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Impacts of climate change on fisheries and aquaculture

Synthesis of current knowledge, adaptation and mitigation options

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Preparation of this document

Preparation of this document started with the appointment of a task team within the FAO Fisheries and Aquaculture Department, led by Manuel Barange (Director) and including Tarûb Bahri (Marine fisheries), Malcolm Beveridge (Aquaculture), Simon Funge-Smith (Inland fisheries), Ari Gudmundsson (Mitigation), Daniela Kalikoski (Poverty nexus), Florence Poulain (Adaptation), Stefania Vannuccini (Supply and demand evolution) and Sylvie Wabbes (Extreme events). The task team designed the draft contents of the Technical Paper, and took responsibility for structuring the different sections. At a later stage the task team took responsibility for commissioning and receiving reviews of the different chapters.

The first workshop of technical experts took place in Rome, at the FAO headquarters on 28 to 29 July 2017, bringing together approximately 30 participants, many of whom were identified as leading contributors. The objectives of this workshop were to design the contents and objectives of a Technical Paper that would provide synthetic information aimed primarily at policymakers, fisheries managers and practitioners, with a view to assisting countries in the development of their Nationally Determined Contributions (NDCs) and complementary needs.

The different chapters were commissioned to international experts, who submitted their first drafts prior to the second workshop of technical experts, held also at FAO in Rome on 15 to 17 January 2018. All chapter leads attended the workshop. At the meeting the chapters were discussed and debated, and the adaptation strategies agreed upon. Extensive conversations were held to ensure consistency of format and messaging, and to identify gaps in knowledge and/or geographical coverage. The experts were then requested to revise and re-submit their drafts for final consideration, and additional chapters were also commissioned.

All the chapters were peer-reviewed before being accepted (see Acknowledgements), and a technical editor (Professor Kevern Cochrane, Rhodes University, South Africa) was appointed to ensure consistency in the use of language and concepts. To ensure uncertainty statements were not only consistent but well-aligned to parallel endeavours, authors and editors were asked to be guided in their statements by the IPCC guidance note on the consistent treatment of uncertainties (Mastrandrea *et al*., 2010). Language editing, formatting and layout were provided by Dawn Ashby (Plymouth Marine Laboratory, UK) and Claire Attwood and Wendy Worrall (Fishmedia, South Africa).

Abstract

The 2015 Paris Climate Agreement recognizes the need for effective and progressive responses to the urgent threat of climate change, through mitigation and adaptation measures, while taking into account the particular vulnerabilities of food production systems. The inclusion of adaptation measures in the fisheries and aquaculture sector is currently hampered by a widespread lack of targeted analyses of the sector's vulnerabilities to climate change and associated risks, as well as the opportunities and responses available. This report provides the most up-to-date information on the disaggregated impacts of climate change for marine and inland fisheries, and aquaculture, in the context of poverty alleviation and the differential dependency of countries on fish and fishery resources. The work is based on model projections, data analyses, as well as national, regional and basin-scale expert assessments. The results indicate that climate change will lead to significant changes in the availability and trade of fish products, with potentially important geopolitical and economic consequences, especially for those countries most dependent on the sector.

In marine regions model projections suggest decreases in maximum catch potential in the world's exclusive economic zones of between 2.8 percent and 5.3 percent by 2050 according to greenhouse gas emission scenario RCP2.6, and between 7.0 percent and 12.1 percent according to greenhouse gas emission scenario RCP8.5, also by 2050. While at the global scale this average is not particularly large, the impacts are much greater at regional scale, because projected changes in catch potential vary substantially between regions. Although estimates are subject to significant variability, the biggest decreases can be expected in the tropics, mostly in the South Pacific regions. For the high latitude regions, catch potential is projected to increase, or show less of a decrease than in the tropics. It is important to note that these projections only reflect changes in the capacity of the oceans to produce fish, and do not consider the management decisions that may or may not be taken in response. It is concluded that the interaction between ecosystem changes and management responses is crucial to minimize the threats and maximize the opportunities emerging from climate change. Production changes are partly a result of expected shifts in the distribution of species, which are likely to cause conflicts between users, both within and between countries.

The vulnerability of marine fisheries to climate change and existing and potential responses to adapt to the changes are examined in more detail for 13 different marine regions covering a range of ecological, social and economic conditions. It is concluded that adaptations to climate change must be undertaken within the multifaceted context of fisheries, with any additional measures or actions to address climate change complementing overall governance for sustainable use. It is recognized that some of these measures will require institutional adaptation.

In relation to inland fisheries the Technical Paper highlights that in the competition for scarce water resources the valuable contributions of inland fisheries are frequently not recognized or undervalued. The Paper assesses country by country impacts and provides indications of whether levels of stress are expected to change and to what extent. Pakistan, Iraq, Morocco and Spain are highlighted as countries that are currently facing high stresses that are projected to become even higher in the future. Myanmar, Cambodia, the Congo, the Central African Republic and Colombia, are among the countries that were found to be under low stress at present and are projected to remain under low stress in the future. The implications of climate change for individuals, communities and countries will depend on their exposure, sensitivity and adaptive

capacity, but in general they can be expected to be significant. Some positive impacts are also identified, like increased precipitation leading to the expansion and improved connectivity between some fish habitats, but to take advantage of them, new investments as well as flexibility in policies, laws and regulations, and post-harvest processes are needed. It is recommended that adaptive management measures be within the framework of an ecosystem approach to fisheries to maximize success.

Short-term climate change impacts on aquaculture can include losses of production and infrastructure arising from extreme events such as floods, increased risks of diseases, parasites and harmful algal blooms. Long-term impacts can include reduced availability of wild seed as well as reduced precipitation leading to increasing competition for freshwater. Viet Nam, Bangladesh, the Lao People's Democratic Republic and China were estimated to be the most vulnerable countries in Asia, with Belize, Honduras, Costa Rica and Ecuador the most vulnerable in the Americas, for freshwater aquaculture. Uganda, Nigeria and Egypt were found to be particularly vulnerable in Africa. In the case of brackish water production, Viet Nam, Egypt and Thailand emerged as having the highest vulnerabilities. For marine aquaculture, Norway and Chile were identified as being the most vulnerable, due to their high production, although China, Viet Nam, the Philippines and Madagascar were also considered to be highly vulnerable. Climate-driven changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, are expected to have long-term impacts in the aquaculture sector at multiple scales. Options for adaptation and resilience building are offered, noting that interactions between aquaculture, fisheries and agriculture can either exacerbate the impacts or help create solutions for adaptation.

The Technical Paper also investigates the impacts of extreme events, as there is growing confidence that their number is on the increase in several regions, and is related to anthropogenic climate change. Climate-related disasters now account for more than 80 percent of all disaster events, with large social and economic impacts. Not all extreme events necessarily result in a disaster, and the extent of their impacts on fisheries and aquaculture will depend on how exposed and vulnerable the socio-ecological systems are as well as their capacity to respond.

An often unrecognized impact of climate change is on food safety, for example through changes in the growth rates of pathogenic marine bacteria, or on the incidence of parasites and food-borne viruses. Climate change may also bring increased risks for animal health, particularly in the rapidly growing aquaculture sector, for example by changing the occurrence and virulence of pathogens or the susceptibility of the organisms being cultured to pathogens and infections. Effective biosecurity plans that emphasize prevention are essential.

In the final sections the Technical Paper recognizes that the impacts of climate change on the fisheries and aquaculture sector will be determined by the sector's ability to adapt. Guidance on the tools and methods available to facilitate and strengthen such adaptation is provided. Because each specific fishery or fishery/aquaculture enterprise exists within unique contexts, climate change adaptations must start with a good understanding of a given fishery or aquaculture system and a reliable assessment of potential future climate change. The Paper provides information on the tools available to inform decision-makers of particular adaptation investments and of the process to develop and implement adaptation strategies. It presents examples of tools within three primary adaptation entries: institutional and management, those addressing livelihoods and, thirdly, measures intended to manage and mitigate risks and thereby strengthen resilience. It is noted that adaptation should be implemented as an ongoing and iterative process, equivalent in many respects to adaptive management in fisheries.

Finally, the contributions of the sector to global emissions of carbon dioxide are presented. Globally, fishing vessels (including inland vessels) emitted 172.3 million tonnes of CO_2 in 2012, about 0.5 percent of total global CO_2 emissions that year. For the aquaculture industry, it was estimated that 385 million tonnes of CO_2 equivalent (CO_2 e) was emitted in 2010, around 7 percent of those from agriculture. While the sector is a small contributor, options for reducing fuel use and greenhouse gas emissions are identified. In the case of capture fisheries, reductions of between 10 percent and 30 percent could be attained through use of efficient engines, larger propellers, as well as through improving vessel shapes or simply by reducing the mean speed of vessels. There are also opportunities to reduce greenhouse gas emissions in aquaculture, which include improved technologies to increase efficiency, use of renewable energy sources, and improving feed conversion rates, among others.

The Technical Paper highlights the multifaceted and interconnected complexity of fisheries and aquaculture, through which direct and indirect impacts of climate change will materialize. Efforts to adapt to and mitigate climate change should be planned and implemented with full consideration of this complexity. Failure to do so would increase inefficiency and maladaptation, exacerbating rather than reducing impacts.

Finally, the Technical Paper is a reminder of the critical importance of fisheries and aquaculture for millions of people struggling to maintain reasonable livelihoods through the sector. These are the people who are most vulnerable to the impacts of climate change, and particular attention needs to be given to them while designing adaptation measures if the sector is to continue to contribute to meeting global goals of poverty reduction and food security.

Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. & Poulain, F., eds. 2018.
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Contents

Foreword

By 2050 humans will face the challenge of having to provide food and livelihoods to a population likely to exceed nine billion people. This challenge is well reflected in the United Nations Agenda 2030 for Sustainable Development, a global commitment to end poverty and hunger and to ensure that economic, social and technological progress occurs in harmony with nature, through the sustainable management of natural resources.

An additional consideration to the above challenge is that it will have to be met at a time when the effects of climate change will be increasingly prominent. The two cannot be separated and, indeed, the 2015 Paris Climate Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) explicitly recognizes the fundamental priority of safeguarding food security and ending hunger when taking climate action.

One of the novelties of the Paris Climate Agreement is the inclusion of a long-term adaptation goal – *to increase the ability to adapt to the adverse impacts of climate change and foster climate resilience …/… in a manner that does not threaten food production* – alongside the goal for mitigation. It also notes that the level of adaptation needed will be determined by the success of mitigation activities. To implement the Agreement member states are required to prepare, communicate and maintain successive Nationally Determined Contributions (NDCs), submitted every five years to the UNFCCC secretariat. The next round of NDCs (new or updated) is to be submitted by 2020.

This FAO Technical Paper emerges from the above challenges, first in recognition of the significant role that fisheries (both marine and inland) and aquaculture play in addressing them. The fisheries and aquaculture sector supports the livelihoods of between 10 percent and 12 percent of the world's population, and in the last five decades its production has significantly outpaced population growth (FAO, 2016), thus increasing its contribution to food security and nutrition (HLPE, 2014). Second, while the fisheries and aquaculture sectors are included in the NDCs of approximately 60 countries, the level of ambition is typically low, partially because of the difficulty of making explicit sectoral commitments when climate change projections remain highly uncertain.

In 2009, and in response to a request from the twenty-seventh session of the Committee on Fisheries (COFI), the FAO Fisheries and Aquaculture Department undertook a scoping study to identify the key issues in relation to climate change and fisheries through three comprehensive technical papers (Cochrane *et al*., eds., 2009). Nine years later the political framework has dramatically evolved, the evidence has increased exponentially, as has the importance of marine and ocean matters in climate change circles. For example, in 2016 the Intergovernmental Panel on Climate Change (IPCC) commissioned a Special Report on Oceans and the Cryosphere in a Changing Climate (SROCC), to report in 2019.

This Technical Paper is intended to update the Cochrane *et al*., eds. (2009) Technical Paper, and be of fundamental use to countries in their NDC development and implementation, including resource mobilization efforts. In this context it is significant to note that Article 9 of the Paris Climate Agreement stipulates that financial resources will be provided to assist developing country Parties with respect to their mitigation and adaptation obligations.

It is often mentioned that the fisheries and aquaculture sector is extremely dynamic and used to dealing with change, as historical patterns of changes in marine resources demonstrate (Baumgartner, Soutar and Ferreira-Bartrina, 1992), but the magnitude and uni-directionality of future climate-driven changes demand greater preparedness in responding to the changes. For example the Fifth Assessment Report of the IPCC concludes, with high confidence, that global marine species redistribution and marine biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity by the mid-twenty-first century (IPCC, 2014). Biodiversity reductions in sensitive areas, such as northern latitudinal basins, are also expected in freshwater ecosystems (Comte and Olden, 2017). Preparedness is indeed essential to translate changes into opportunities, while the opposite leads to maladaptation and unfulfilled prospects. Furthermore, the IPCC notes that adaptation is place- and context-specific, with no single approach for reducing risks being appropriate across all settings (IPCC, 2014). Understanding the direction, speed, intensity and place of change is thus a prerequisite to effective adaptation.

A fundamental principle in the preparation of this Technical Paper was that the report would not provide a comprehensive review of all the available evidence of, and possible responses to climate change, but that it would be a synthetic volume aimed primarily at policymakers, fisheries managers and practitioners, with a view to assisting countries in the development of their NDCs. The work (see Preparation of this document) was tailored around two technical workshops in Rome (July 2017 and January 2018), and engaged over 100 contributors.

The Technical Paper recognizes the importance of contextualizing the topic of climate change in fisheries and aquaculture in terms of poverty alleviation and the existing policy commitments such as UN Agenda 2030 and the Paris Climate Agreement (Chapter 2), and the current and expected socio-economic dependencies of the sector (Chapter 3). It was designed to include marine (Chapters 4 to 17) and inland (Chapters 18, 19, 26) capture fisheries, as well as aquaculture (Chapters 20 to 22), recognizing that the level of evidence and responses at global, regional and national scales differs between subsectors. While model projections for marine catch potential were computed for all countries, with the time and resources available it was not possible to provide dedicated chapters for all regions. However, every effort was made to ensure reasonably comprehensive geographical coverage that would provide good representation of the types of changes, impacts and responses that are taking place in the sector as a whole. Figure 1 illustrates the geographical areas covered by the marine fisheries projections and the regional chapters. While inland fisheries are addressed for all the major fish producers, Figure 1 also illustrates the location of the eight major river basins discussed in detail in Chapter 19. Aquaculture impacts are discussed according to their vulnerability and adaptation options, supported by case studies, in Chapter 21.

It was also agreed to consider disasters and extreme events (Chapter 23) and health and food safety hazards (Chapter 24) in addition to the impacts of long-term patterns of change. All these pieces of evidence were translated into effective and explicit adaptation (Chapter 25) and mitigation (Chapter 27) strategies and tools, also taking into consideration the potential adaptations to climate change from other sectors (Chapter 26).

It is hoped that the Technical Paper will be used extensively in the development of programmes of work, particularly in relation to adaptation measures to climate change in the sector, by UN agencies, national institutions and NGOs.

The different chapters were commissioned to international experts, who submitted their drafts prior to the second expert workshop, held in Rome on 15 to 17 January 2018. At the workshop the chapters were discussed and debated, and the options and measures available for adaptation agreed upon. The experts were then requested to revise and re-submit their drafts for final consideration. All the chapters were peer-reviewed before being accepted, and a technical editor was appointed to ensure consistency in the use of language and concepts. To ensure any uncertainty statements presented in the chapters were not only consistent but well-aligned to parallel endeavours, authors and editors were guided by the IPCC guidance note on the consistent treatment of uncertainties (Mastrandrea *et al*., 2010).

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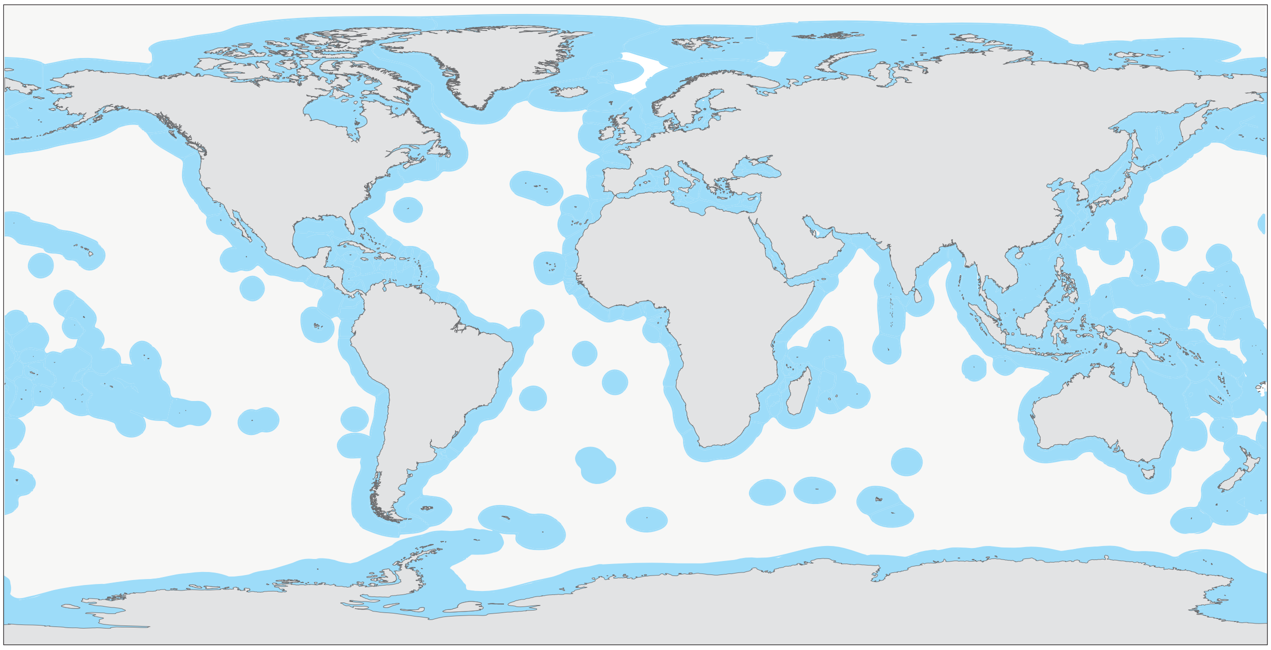
FIGURE 1

Conceptual map of the geographic areas covered by the Technical Paper. Figure 1a. Country projections of marine fisheries catch presented in Chapter 4. Pressures on inland fisheries in 26 subregions and 149 individual countries are presented in Chapter 19. Country by country analysis of aquaculture is presented in Chapter 21. Figure 1b. Areas covered by the marine regional fisheries Chapters 5 to 17; the map also shows the location of the eight major river basins, the fisheries of which were assessed in the case studies presented in Chapter 19

a



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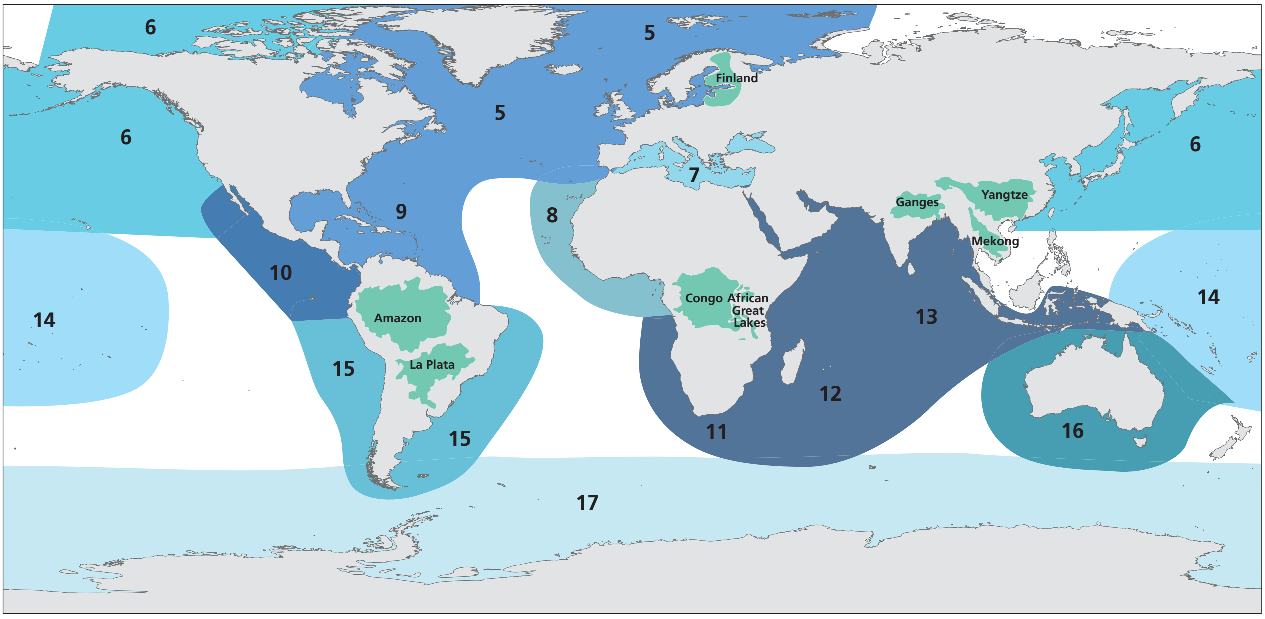

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Abbreviations and acronyms

AC	alternating current
ACCE	Antarctic Climate Change and the Environment (report)
AEUS	Atlantic Equatorial Upwelling System
AL	Agulhas leakage
AMO	Atlantic Multi-decadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AM	adaptation measure
APECOSM-E	Apex Predators ECOSystem Model
APF	Antarctic Polar Front
AR4	Fourth Assessment Report (of the IPCC)
AR5	Fifth Assessment Report (of the IPCC)
BAU	business-as-usual
BBB	building back better
BCC	Benguela Current Commission
BCLME	Benguela Current Large Marine Ecosystem
BMP	Better management practice
CAMLR Convention	Convention on the Conservation of Antarctic Marine Living Resources
CBF	culture-based fisheries
CC4FISH	Climate Change Adaptation in the Eastern Caribbean Fisheries Sector Project
CCA	climate change adaptation
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCI	Caribbean Challenge Initiative
CCLME	Canary Current Large Marine Ecosystem
CCS	Canary Current System
CCS	California Current System
CD	capacity development
CEAFM	community-based ecosystem approach to fisheries management
CECAF	FAO Fishery Committee for the Eastern Central Atlantic
CIL	cold intermediate layer
CLME+	Caribbean and North Brazil Shelf Large Marine Ecosystem
CMIP5	Climate Model Intercomparison Project version 5
CO_2	carbon dioxide
CO_2 e	CO_2 equivalent
COI	*Commission de l'Océan Indien* / Indian Ocean Commission
CPUE	catch per unit effort
CSR	corporate social responsibility
CVCA	climate vulnerability and capacity analysis

CVIs	community social vulnerability indices
DBEM	Dynamic Bioclimate Envelope Model
DC	direct current
DEC	daily energy consumption
DFO	Department of Fisheries and Oceans (Canada)
DHC	direct human consumption
DO	dissolved oxygen
DRM	disaster risk management
DWFNs	distant water fishing nations
EAA	ecosystem approach to aquaculture
EAC	East Australia Current
EAF	ecosystem approach to fisheries
EAP	East Asia/Pacific
EBS	Eastern Bering Sea
EBUS	eastern boundary upwelling systems
ECR	Economics of Climate Resilience (report)
EEZ	exclusive economic zone
EMPRES Food Safety	(FAO) Emergency Prevention System for Food Safety
ENSMN	ensemble mean
ENSO	El Niño-Southern Oscillation
ESM	Earth system models
EU	European Union
EUS	epizootic ulcerative syndrome
EWS	early warning system
FAD	fish aggregating device
FAO	Food and Agriculture Organization of the United Nations
FCR	feed conversion rates
FEWER	Fisheries Early Warning and Emergency Response (modules)
FFA	(Pacific Islands) Forum Fisheries Agency
FM	fishmeal
FMFO	fishmeal and fish oil
FO	fish oil
FUI	fuel use intensity
GAPS	Global Agriculture Perspectives System
GCLME	Guinea Current Large Marine Ecosystem
GCM	general circulation model (also referred to as “global climate model”)
GCS	Guinea Current System
GFCM	General Fisheries Commission for the Mediterranean
GFDL–ESM	Geophysical Fluid Dynamic Laboratory Earth System Model
GHG	greenhouse gas
GIS	geographic information systems
GOA	Gulf of Alaska
GOM	Gulf of Mexico

GRPS	Global Risks Perception Survey
H_2S	hydrogen sulphide
HAB	harmful algal bloom
HACCP	Hazard Analysis and Critical Control Points
HCS	Humboldt Current System
HDI	Human Development Index
IATTC	Inter-American Tropical Tuna Commission
IC	internal combustion
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICE	internal combustion engine
ICES	International Council for the Exploration of the Sea
ICZM	integrated coastal zone management
IHHNV	Infectious hypodermic and haematopoietic necrosis virus
IIOE–2	International Indian Ocean Expedition – 2 programme
IMF	International Monetary Fund
INFOSAN	International Food Safety Authorities Network
IOD	Indian Ocean Dipole
IODE	Oceanographic Data and Information Exchange
IOTC	Indian Ocean Tuna Commission
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institute Pierre-Simon Laplace Climate Model
IPSL–CM5	Institute Pierre-Simon Laplace Climate Earth System Model
IRM	iterative risk management
IUU	illegal, unreported and unregulated (fishing)
LC	Leuwin Current
LDC	least developed countries
LED	light emitting diode
LIFDC	low-income food-deficit country
LME	large marine ecosystem
LMR	living marine resources
L-W	lose-win
MeHg	methylmercury
MH	metal halide
MOC	meridional overturning circulation
MPA	marine protected area
MPI–ESM	Max Planck Institute Earth System Model
MRC	Mekong River Commission
MSY	maximum sustainable yield
NACW	North Atlantic Central Water
NAFO	Northwest Atlantic Fisheries Organization
NAOMZ	North Atlantic oxygen minimum zone
NAPA	National Adaptation Programme of Action
NAP	National Adaptation Plan/National Action Plan
NASCO	North Atlantic Salmon Conservation Organization

NBC	North Brazil Current
NDCs	Nationally Determined Contributions
NEAFC	North East Atlantic Fisheries Commission
NEPAD	New Partnership for Africa's Development
NETP	Northeast Tropical Pacific
NGO	non-governmental organization
NMFS	National Marine Fisheries Service (United States of America)
NOAA	National Oceanic and Atmospheric Administration (United States of America)
NPP	net primary productivity
NPTZ	North Pacific Transition Zone
OA	ocean acidification
OIE	*Office International des Epizooties*
OMZ	oxygen minimum zone
OSPESCA	Central America Fisheries and Aquaculture Organization
PA	Paris Agreement
PaV1	*Panulirus argus* Virus 1
PCAC	Pacific Central American Coastal
PDNA	post-disaster needs assessment
PDF	probability density function
PDO	Pacific Decadal Oscillation
PES	payment for ecosystem services
PFTs	plankton functional types
PI	potential impacts
PICES	North Pacific Marine Science Organization
PICTs	Pacific island countries and territories
pIOD	positive Indian Ocean Dipole
PIOMAS	Pan-Arctic Ice Modeling and Assimilation System
PLD	pelagic larval duration
PNA	Parties to the Nauru Agreement
PPCR	Programme for Climate Resilience project
PRA	participatory rural appraisal
PV	photovoltaic
RAS	recirculating aquaculture system
RASFF	Rapid Alert System for Food and Feed
RBM	robust decision-making
RCP	representative concentration pathway
REDD+	reducing emissions from deforestation and forest degradation
RFB	regional fishery body
RFMO	regional fisheries management organization
ROA	real option analysis
RRA	rapid rural appraisal
SA	South and Southeast Asian
SADC	Southern African Development Community

SAFMC	South Atlantic Fishery Management Council
SAM	Southern Annular Mode
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCAR	Scientific Committee for Antarctic Research
SCTR	Seychelles-Chagos Thermocline Ridge
SDG	Sustainable Development Goal
SE USA	southeast shelf of the United States of America
SI–CCME	Strategic Initiative for the Study of Climate Impacts on Marine Ecosystems
SIDS	small island developing states
SIOFA	South Indian Ocean Fisheries Agreement
SLR	sea level rise
SPAGS	spawning aggregation site
SPC	Oceanic Fisheries Programme of the Pacific Community
SPF	small pelagic fish
SPS Agreement	Agreement on the Application of Sanitary and Phytosanitary Measures Agreement
SREX	IPCC Special report on managing the risks of extreme events and disasters to advance climate change adaptation
SS	storm surge
SSF	small-scale fisheries
SSF Guidelines	(FAO) Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication
SSP	shared socio-economic pathway
SSS	sea surface salinity
SST	sea surface temperature
SWIOFC	Southwest Indian Ocean Fisheries Commission
TAC	total allowable catch
TAR	Third Assessment Report (of the IPCC)
TCU	total cumulative upwelling
TEK	traditional ecological knowledge
TPP	temperature preference profile
TSV	Taura syndrome virus
TURFs	territorial use rights in fisheries
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations Office for Disaster Risk Reduction
VA	vulnerability assessment
VDS	vessel day scheme
VMS	vessel monitoring system
WACs	West African countries
WB	World Bank
WBC	western boundary current
WCA	Western Central Atlantic
WCPFC	Western and Central Pacific Fisheries Commission
WCPO	Western and Central Pacific Ocean

WECAF	Western Central Atlantic Fishery Commission
WECAF–CFRM	WECAF Caribbean Regional Fisheries Mechanism
WEF	World Economic Forum
WESS	United Nations World Economic and Social Survey
WIO	Western Indian Ocean
WIOMSA	Western Indian Ocean Marine Science Association
WMO	World Meteorological Organization
WRI	World Resources Institute
WSSV	white spot syndrome virus
WTO	World Trade Organization
W-W	win-win
Ωar	Aragonite saturation

Chapter 1: Climate change and aquatic systems

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KEY MESSAGES

- The warming of the climate system is unequivocal. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished and sea level has risen. The uptake of additional energy in the climate system is caused by the increase in the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs).
- CO_2 concentrations have increased by 40 percent since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. It is thus extremely likely that human influence has been the dominant cause of the observed warming since the mid-twentieth century.
- The ocean has absorbed 93 percent of this additional heat and sequestered 30 percent of the emitted anthropogenic CO_2. Over the period 1901 to 2010, global mean sea level also rose by 0.19 m.
- Aquatic systems that sustain fisheries and aquaculture are undergoing significant changes as a result of global warming and projections indicate that these changes will be accentuated in the future.
- A range of scenarios for atmospheric concentrations of GHGs are used to model and project future climates; most of these scenarios indicate that a large fraction of anthropogenic climate change is irreversible for centuries to come even after complete cessation of anthropogenic CO_2 emissions.
- In many regions, climate change is affecting precipitation and melting of snow and ice, altering hydrological systems and affecting water resources in terms of quantity and quality. Projections show that rainfall can be expected to increase in equatorial areas and decrease elsewhere.
- Temperature of water bodies is increasing across the globe, which results in more pronounced stratification of the water column, with more dramatic consequences for freshwater systems than for oceans because of their shallowness and lower buffering capacity.
- Dissolved oxygen levels decrease with increased temperature, and oxygen minimum zones in the oceans have expanded over the last decades, both in coastal and offshore areas. This trend is expected to continue.
- Global and local ocean circulation is changing, with a weakening of patterns such as the Gulf Stream and the California Current upwelling, and an increase in upwelling in other areas, such as in the Canary, the Humboldt and the Benguela Current systems. Responses are still heterogeneous and predictions have low confidence.
- The absorption of increasing amounts of anthropogenic CO_2 by the oceans results in acidification of waters, with potentially detrimental impacts on shell-forming aquatic life; water acidity has increased by 26 percent since the industrial revolution and this trend will continue, especially in warmer low- and mid-latitudes.

- Primary production in the oceans has been projected to decrease by three percent to nine percent by 2100; in freshwater systems observations vary depending on the area, but overall, forecasts are highly uncertain for both marine and freshwater systems because primary production is an integrator of changes in light, temperature and nutrients.

1.1 INTRODUCTION

Since 1988 the Intergovernmental Panel on Climate Change[1] (IPCC) has been providing regular, evidence-based updates on climate change and its political and economic impacts. These updates comprehensively synthesize the internationally accepted consensus on the science of climate change, its causes and consequences. Based largely on the 5th IPCC Assessment Report (AR5), and recent scientific literature, this chapter provides an overview of the major impacts of climate change on the dynamics of aquatic systems (oceans, seas, lakes and rivers), and particularly on the aspects that relate to aquatic food production, i.e. fisheries and aquaculture. While more detailed information on the impacts of climate change on these food production systems is available in subsequent chapters of this publication, this chapter focuses specifically on providing basic information on the underlying drivers of climate change and on how they translate into biophysical changes in aquatic systems. Its purpose is to contextualize the different chapters and set up a knowledge baseline that avoids the need for repetition in subsequent chapters.

1.2 OBSERVED CHANGES IN THE CLIMATE SYSTEM

Information on the climate system is based on multiple lines of evidence, which include direct and indirect observations and historical reconstructions going back thousands of years as well as more recent instrumental observations, conceptual and numerical models, including radiative and heat budgets. Based on analysis of these data, and notwithstanding the uncertainties associated with knowledge and data gaps, the IPCC AR5 concluded that the warming of the climate system was unequivocal, and that many of the observed changes since 1950 are unprecedented compared with preceding decades to millennia. At the global level, the Earth's average surface temperature has increased by more than 0.8 °C since the middle of the nineteenth century, and is now warming at a rate of more than 0.1 °C every decade (Hansen *et al*., 2010). Heat waves are more frequent now, even though the reliability of data and level of certainty vary across continents (Hartmann *et al*., 2013).

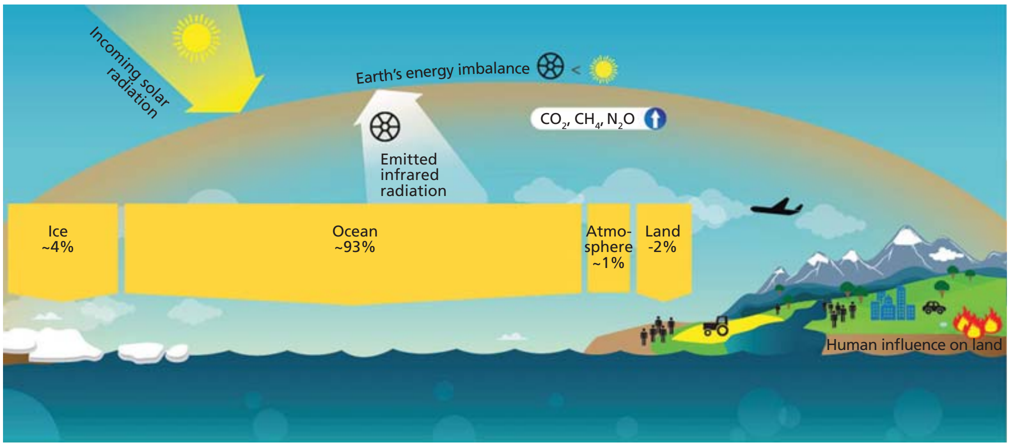
The largest contribution to this warming is believed to be from the increase in atmospheric concentration of GHGs, such as CO_2, methane CH_4 and nitrogen dioxide NO_2. GHGs act like a thermal blanket around the planet and are responsible for allowing life on Earth to exist (IPCC, 2014). The exponential increase in the emission of GHGs since the industrial revolution has resulted in atmospheric concentrations of these gases that are unprecedented in the last 800 000 years. For example, atmospheric CO_2 concentrations increased from 278 ppm in the middle of the eighteenth century to around the current level of 400 ppm (See Figure 6.25 in Ciais *et al*., 2013). The IPCC AR5 has also concluded that it is extremely likely that humans have been the dominant cause of the observed warming since the mid-twentieth century, through

[1] The IPCC is the international body for assessing the science related to climate change, set up in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The IPCC periodically issues special reports on specific themes, as well as global assessment reports based on published scientific information and taking stock of the most recent scientific evidence of climate impacts and proposed adaptation and mitigation responses. These reports are intended for policymakers and constitute the scientific basis for the international negotiations within the United Nations Framework Convention on Climate Change (UNFCCC). http://www.ipcc.ch

the association of GHG emissions with gas and oil combustion, deforestation, and intensive agriculture.

Only one percent of the additional heat caused by anthropogenic climate change is retained in the atmosphere, whilst 93 percent has been absorbed by the global ocean. The remaining three to four percent is absorbed by the melting of ice and snow (Figure 1.1). The ocean's heat buffer is thus enormous and any small change in the balance of heat between ocean and atmosphere would have huge impacts on global air temperature (Reid, 2016). In addition to its thermal capacity, the ocean has also sequestered about 25 percent of the CO_2 released as a result of anthropogenic activities (Le Quéré *et al.*, 2018), playing a crucial role in the regulation of the Earth's climate.

FIGURE 1.1
Flow and storage of energy in the Earth's climate system



Source: Reid, 2016.

BOX 1.1
El Niño Southern Oscillation

The El Niño-Southern Oscillation, or ENSO, is the interaction between the atmosphere and ocean in the tropical Pacific that results in three to seven year periodic oscillations in the temperature of surface waters of the equatorial Pacific, between particularly warm and cold temperatures, referred to as El Niño and La Niña respectively. The release of heat from the ocean to the atmosphere during El Niño events is known to cause changes in global atmospheric circulation, cyclone and hurricane patterns, monsoons, and heat and precipitation patterns, with associated drought and flooding episodes (Reid, 2016). The effects are felt worldwide, with consequences for marine and freshwater systems throughout the food web, including species sustaining fisheries.

The interactions between anthropogenic climate change and ENSO cycles have challenged scientists for decades. Since the publication of the IPCC AR5, there have been a number of modelling studies that have shown an increasing frequency of extreme El Niño events as a result of climate change (e.g. Cai *et al.*, 2014, 2015; Wang *et al.*, 2017). It is significant, in this context, that the 1982/83, 1997/98 and most recent 2015/16 El Niño events were not just the most intense in the modern observational record but also the most peculiar, exhibiting unusual characteristics distinct from any other observed events (Santoso, Mcphaden and Cai, 2017).

1.3 FUTURE CHANGES IN THE CLIMATE SYSTEM

In order to assess and forecast future possible changes in the climate system, the IPCC uses a hierarchy of climate models that simulate changes based on a set of scenarios of anthropogenic forcing. These scenarios take the form of representative concentration pathways (RCPs), which simulate possible ranges of heat or radiative forcing values in the year 2100, relative to pre-industrial values (+2.6 W/m^2, +4.5 W/m^2, +6.0 W/m^2, and +8.5 W/m^2, respectively[2]). The four RCPs are based on certain socio-economic assumptions (possible future trends e.g. population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy), which provide flexible descriptions of possible futures. RCP2.6 is consistent with an emissions pathway that leads to very low GHG concentration levels and is thus a "peak-and-decline" scenario. RCP4.5 and RCP6.0 reflect two stabilization scenarios in which total radiative forcing is stabilized shortly after 2100 with differential speed, while RCP8.5 is characterized by increasing GHG emissions over time, representative of scenarios in the literature that lead to high GHG concentration levels (van Vuuren *et al*., 2011).

It is estimated for all RCP scenarios except for RCP2.6 that global atmospheric temperature change for the end of the twenty-first century is likely to exceed 1.5 °C relative to the average of the 1850 to 1900 period. It is likely to exceed 2 °C for RCP6.0 and RCP8.5, but more likely not to exceed 2 °C for RCP4.5. Warming is forecast to continue beyond 2100 under all RCP scenarios except RCP2.6, although there will be interannual-to-decadal variability and regional heterogeneity (IPCC, 2014). A large fraction of anthropogenic climate change is considered to be irreversible for centuries to come, and possibly even millennia, even after a complete cessation of anthropogenic CO_2 emissions (IPCC, 2014; Solomon *et al*., 2009) (Figure 1.2).

1.4 IMPLICATIONS FOR AQUATIC SYSTEMS

1.4.1 Hydrological cycle and rainfall patterns

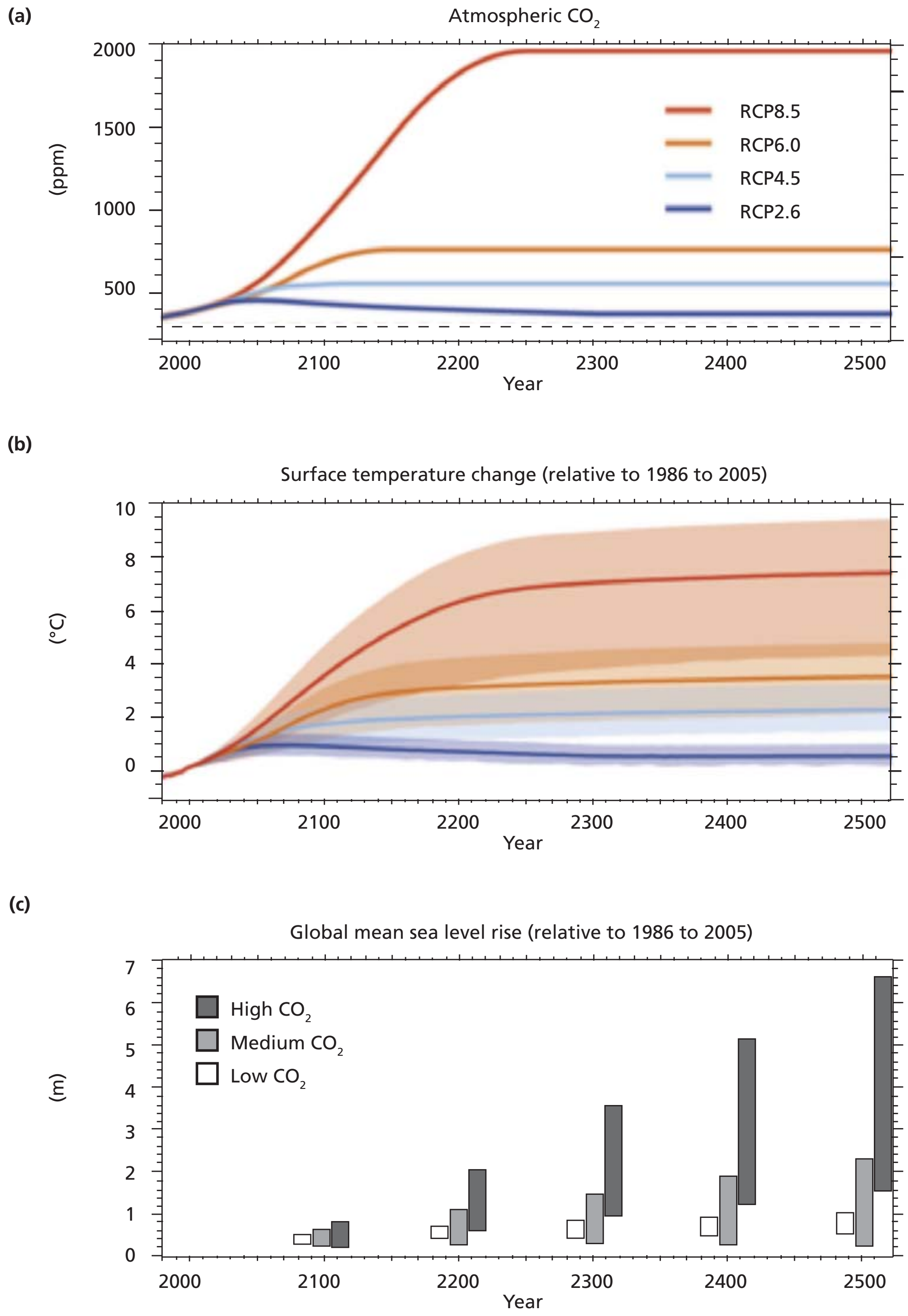
The warming of the climate has significant implications for the hydrological cycle. Changing precipitation, temperature and climatic patterns and the melting of snow and ice affect the quantity, quality and seasonality of water resources, leading to inevitable changes in aquatic ecosystems. Climate change is already causing permafrost warming and thawing in high-latitude regions, and in high-elevation regions it is driving glacier shrinkage, with consequences for downstream water resources (IPCC, 2014 – AR5 synthesis report p. 51). In the marine systems, the melting of the Arctic sea ice has the potential to disrupt or slow down the global ocean conveyor belt (Liu *et al*., 2017; also see ocean circulation section below).

Observed precipitation changes since 1901 vary across regions with some such as the mid-latitude land areas of the Northern Hemisphere showing likely increases while others have shown decreases, but with low confidence (Hartmann *et al*., 2013). However, models indicate that zonal mean precipitation is very likely to increase in high latitudes and near the equator, and decrease in the subtropics (Ren *et al*., 2013). In California, in the Mediterranean basin, as well as in the already arid zones, droughts are expected to be longer and more frequent, and there will be reductions in river flows. As discussed in Chapter 19, precipitation changes at the regional scale will be strongly influenced by natural variability.

[2] W/m^2= Watts per square metre

FIGURE 1.2

(a) Atmospheric CO_2 and (b) projected global mean atmospheric (surface) changes for the four RCPs up to 2500 (relative to 1986 to 2005). The dashed line on (a) indicates the pre-industrial CO_2 concentration. (c) Sea level change projections according to GHG concentrations (low: below 500 ppm as in RCP2.6; medium: 500 ppm to 700 ppm as in RCP4.5; high: above 700 ppm and below 1500 ppm as in RCP6.0 and RCP8.5). The bars represent the maximum possible spread



Source: IPCC, 2014

In the twentieth century, global river discharges have not demonstrated changes that can be associated with global warming. However, as most large rivers have been impacted by human influences such as dam construction, water abstraction and regulation, it is difficult to be conclusive. Despite uncertainties, it is expected that the contribution of snowmelt to river flows will increase in the near future (Jha *et al.*, 2006; Pervez and Henebry, 2015; Siderius *et al.*, 2013). Changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins.

The frequency and intensity of heavy precipitation events over land are also likely to increase in the short-term, although this trend will not be apparent in all regions because of natural variability. There is low confidence in projections of changes in the intensity and frequency of tropical cyclones in all basins to the mid-twenty-first century (Kirtman *et al.*, 2013).

1.4.2 Water temperature

Anthropogenic forcing has made a substantial contribution to the upper ocean warming (above 700 m) that has been observed since the 1960s (Cheng *et al.*, 2017), with the surface waters warming by an average of 0.7 °C per century globally from 1900 to 2016 (Huang *et al.*, 2015). Ocean temperature trends over this period vary in different regions but are positive over most of the globe, although the warming is more prominent in the Northern Hemisphere, especially the North Atlantic. The upper ocean (0 m to 700 m) accounts for about 64 percent of the additional anthropogenic energy accumulated in oceans and seas. Upper ocean warming is expected to continue in the twenty-first century, especially in the tropical and Northern Hemisphere subtropical regions, whereas in deep waters the warming is expected to be more pronounced in the Southern Ocean. The trend in sea surface temperature already exceeds the range in natural seasonal variability in the subtropical areas and in the Arctic (Henson *et al.*, 2017). Best estimates of mean ocean warming in the top 100 m by the end of the twenty-first century are about 0.6 °C (RCP2.6) to 2.0 °C (RCP8.5), and about 0.3 °C (RCP2.6) to 0.6 °C (RCP8.5) at a depth of about 1 000 m compared to the 1986 to 2005 average (IPCC, 2014).

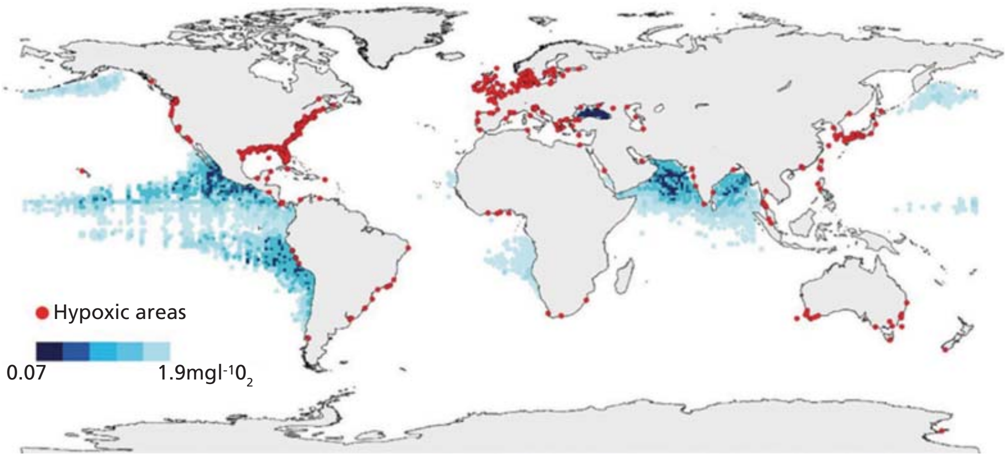
For freshwater systems, an increase of water temperature is expected to occur in most areas, as a result of an increase of air temperature. This is linked to the relatively shallow nature of surface freshwaters and their susceptibility to atmospheric temperature change. Harrod *et al.* (Chapter 18, this volume) analysed a set of river basins on all continents and found that an increase of up to 1.8 °C in water temperature is expected, with geographical heterogeneities, including areas where the increase is expected to be minor, such as in the Lower Mekong river basin. There is a high confidence that rising water temperatures will lead to shifts in freshwater species' distributions and exacerbate existing problems in water quality, especially in those systems experiencing high anthropogenic loading of nutrients (IPCC, 2014).

1.4.3 Oxygen content

Dissolved oxygen is an important component of aquatic systems. Changes in its concentrations have major impacts on the global carbon and nitrogen cycles (IPCC, 2014). The average dissolved oxygen concentration in the ocean varies significantly, ranging from super-saturated Antarctic waters to zero in coastal sediments where oxygen consumption is in excess of supply over sufficient periods of time. A large variety of such systems exist, including the so-called oxygen minimum zones (OMZs) in the open ocean, coastal upwelling zones, deep basins of semi-enclosed seas, deep fjords, and other areas with restricted circulation (Figure 1.3), but the discovery of widespread decreases in oxygen concentrations in coastal waters since the 1960s, and the expansion of the tropical OMZs in recent decades (IPCC, 2014) has raised concerns. GHG-driven global warming is the likely ultimate cause of this ongoing deoxygenation in many parts of the open ocean (Breitburg *et al*., 2018). Ocean warming, which reduces the solubility of oxygen in water, is estimated to account for approximately 15 percent of current total global oxygen loss and more than 50 percent of the oxygen loss in the upper 1 000 m of the ocean. Intensified stratification is estimated to account for the remaining 85 percent of global ocean oxygen loss by reducing ventilation. Modelling simulations show that the global volume of OMZs is expected to increase by 10 percent to 30 percent by 2100, depending on the oxygen concentration threshold considered. Beyond 2100, the trend could reverse with a decrease of global volume of OMZs (Fu *et al*., 2018). However, modelling results are associated with a high uncertainty because of the discrepancy between observations and modelled trends (Bopp *et al*., 2013).

Oxygen influences biological and biogeochemical processes at their most fundamental level, but the impacts are very dependent on widely varying oxygen tolerances of different species and taxonomic groups. In particular, the presence and expansion of low oxygen in the water column reduces vertical migration depths for some species (e.g. tunas and billfishes), compressing vertical habitat and potentially shoaling distributions of fishery species and their prey (Eby and Crowder 2002; Chapter 12, this volume).

FIGURE 1.3
Coastal sites where anthropogenic nutrients have exacerbated or caused O_2 declines to <2 mg/litre (<63 µmol/litre) (red dots), as well as ocean oxygen minimum zones at 300 m of depth (blue shaded regions)



Source: Breitburg *et al*., 2018.

1.4.4 Ice coverage

Over the period 1979 to 2012 the average annual extent of Arctic sea ice decreased at a rate of 3.5 percent to 4.1 percent per decade, and the extent of perennial sea ice (summer minimum) decreased by 11.5 percent ± 2.1 percent per decade. It is also very likely that the average annual extent of Antarctic sea ice increased by 1.2 percent to 1.8 percent per decade over the same period (Vaughan *et al*., 2013). Almost all glaciers worldwide have shrunk: between 2003 and 2009, most of the ice loss was from glaciers in Alaska, the Canadian Arctic, the periphery of the Greenland ice sheet, the Southern Andes and the Asian Mountains (Vaughan *et al*., 2013). In the near future, as global mean surface temperature continues to rise, it is very likely that there will be further shrinking and thinning of Arctic sea ice cover and decreases in the northern high-latitude springtime snow cover and near surface permafrosts. On the other hand, there is low confidence in projected short-term decreases in the Antarctic sea ice extent and volume (Bindoff *et al*., 2013).

Melting of ice and snow coverage and reduction of mountain glaciers contribute to water levels and flows in aquatic systems. Sea level rise is a direct consequence of ice melting and, as discussed below, is expected to have impacts in the long-term, whereas the reduction of mountain glaciers will have an impact on river flow and lake levels over the short term, until their likely disappearance in the medium-term.

1.4.5 Sea level

In the recent past, sea level has increased by an average of 3.1 mm/year as a result of climatic and non-climatic factors (Dangendorf *et al*., 2017). The rate of increase shows a high variability across regions, with values up to three times the global average in the Western Pacific or null or negative values in the Eastern Pacific. Sea level has already risen by a global mean of 0.19 m over the period 1901 to 2010. It is estimated that between 2000 and 2100, the projected global mean sea level rise (SLR) will very likely (90 percent probability) reach between 0.5 m and 1.2 m under RCP8.5, 0.4 m to 0.9 m under RCP4.5, and 0.3 m to 0.8 m under RCP2.6 (Kopp *et al*., 2014). There is a high certainty that the sea level will rise in 95 percent of the ocean area; however, there will be a significant regional heterogeneity in the SLR and thus in its consequences (IPCC, 2014).

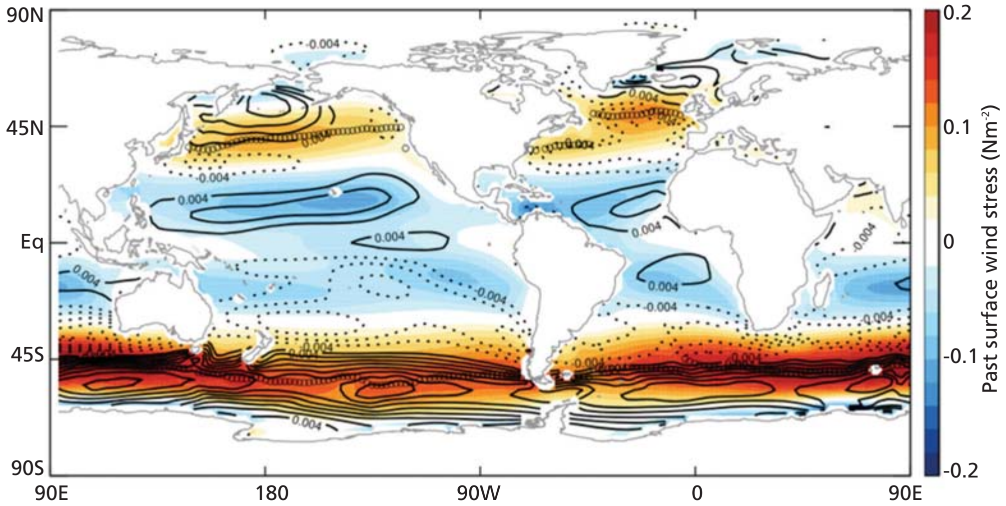
1.4.6 Ocean circulation

Ocean circulation redistributes heat and freshwater across the globe, influencing local climates. A significant part of this redistribution is done by the meridional overturning circulation (MOC), responsible for much of the ocean's capacity to carry excess heat from the tropics to middle and high latitudes, and for the ocean's sequestration of carbon. While the timing of changes is still under debate, partially because of its observed short-term variability (Cunningham *et al*., 2007), it appears clear that the Atlantic meridional overturning circulation (AMOC) is progressively weakening, resulting in a cooling of sea surface temperature in the subpolar Atlantic Ocean and a warming and northward shift of the Gulf Stream (Caesar *et al*., 2018; Thornalley *et al*., 2018). While it is very likely that the AMOC will overall continue to weaken over the twenty-first century, with significant inter-decadal variability, the rate and magnitude of weakening is very uncertain. This is mostly because the predictability of the AMOC varies among models and their realism cannot be easily judged in the absence of a sufficiently long record of observation-based AMOC values. Whether the AMOC will undergo an abrupt transition or collapse after the twenty-first century is an open question and a strong candidate for further research and understanding of the dynamical behaviour of coupled climate models; their predictability, inherent biases, improved parameterizations and confidence of validation of their results against past and continuing observations (Collins *et al*., 2013; Liu *et al*., 2017; Sgubin *et al*., 2017). There is also low confidence in assessing the evolution of the AMOC beyond the twenty-first century because of the limited number of analyses and equivocal results. The consequences of the AMOC weakening would include a disruption of climate patterns in the subtropical Atlantic that would translate into an increased storminess and frequency of heat waves, as well as a warming of tropical Atlantic waters.

Western boundary currents transporting heat poleward from the tropics (Gulf Stream, Kuroshio Current and Somali Current in the Northern Hemisphere; Agulhas Current, Brazil Current and East Australia Current in the Southern Hemisphere) and formed in response to large-scale wind forcing have a strong influence on regional climate and storm tracks. Apart from the Gulf Stream, which is expected to weaken together with the AMOC, all the western boundary currents are likely to intensify as a result of wind shifts and tropical atmospheric changes in connection with GHG concentrations (Figure 1.4). This would favour the formation of severe storms and would affect the climate of the coastal areas in the vicinity of these currents (Yang *et al*., 2016).

FIGURE 1.4

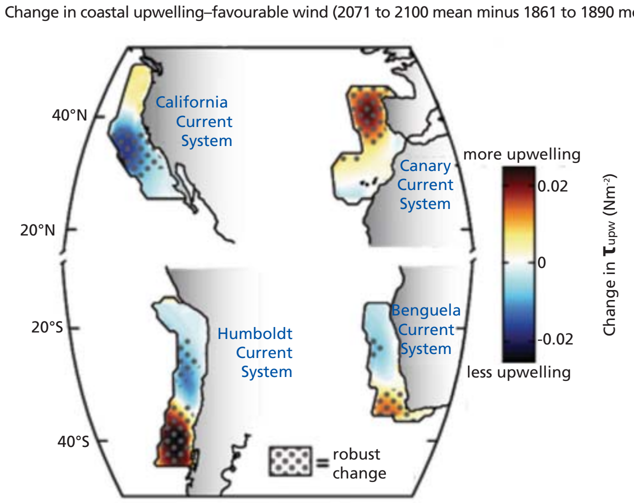
The historical (shading) and projected change (contours) from 1979 to 2005 to 2070 to 2099 in annual mean surface zonal wind stress evaluated as the multimodel mean of CMIP5[3] historical simulations and projections with the RCP8.5 high emissions scenario



The black circles denote the location of the maxima in climatological wind stress at each longitude in the historical period. The contours represent anomalies, i.e. projections minus historical data: the bold lines represent positive anomalies with an interval of 0.004 N/m² (Newtons per square metre, pressure unit) with the zero line omitted, whereas the dashed lines represent negative anomalies with an interval of -0.004 N/m². The models used are as in Simpson et al. (2014). *Source:* Simpson, Shaw and Seager (2014).

FIGURE 1.5

Illustration of upwelling intensification hypothesis. Change in coastal upwelling-favourable winds (τ_{upw}) between two periods: 2071 to 2100 average minus 1861 to 1890 average



Source: Rykaczewski *et al*., 2015.

[3] The Coupled Model Intercomparison Project (CMIP) is a standard experimental protocol for studying the output of coupled atmosphere–ocean general circulation models. CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. CMIP5 refers to the fifth phase of the project. https://cmip.llnl.gov/index.html

BOX 1.2

Eastern boundary upwelling systems: global pattern and patchy responses

Major coastal upwelling zones exist along the edges of eastern boundary currents of the Pacific and Atlantic Oceans (Figure 1.5). In these eastern boundary upwelling systems (EBUS), alongshore winds interact with the earth's rotation to force surface waters offshore. These waters are then replaced with nutrient-rich deeper waters (upwelled), making EBUS some of the most productive of the world's marine ecosystems. According to a widely debated theory, under global warming coastal upwelling would generally strengthen as a result of differential warming between land and ocean, which would intensify upwelling-favourable winds (Bakun, 1990). However, the warming of the global ocean surface is also expected to increase thermal stratification, which would limit the depth from which water is upwelled, and thus the amount of nutrients brought to the near surface (Jacox and Edwards, 2011). How the impacts of climate change on wind and stratification interact, and their relative importance in different regions and times, remains uncertain and yet remarkably important for the future of a significant portion of global fisheries.

The processing of decades of data indicates that over the past 60 years, winds have intensified in the California, Benguela, and Humboldt upwelling systems and weakened in the Iberian system. In the Canary Current system, the trend is equivocal. Intensification was more evident in higher latitudes, which is consistent with the warming pattern associated with climate change (Sydeman *et al*., 2014). While in general, results of recent projections corroborate Bakun's 1990 upwelling intensification theory (Wang *et al*., 2015), there are regional differences in terms of upwelling intensity and duration, as well as spatial heterogeneity between low and high latitudes and in Northern and Southern Hemispheres (Rykaczewski *et al*., 2015) (Figure 1.5).

In the Humboldt and the Benguela Currents, the duration and intensity of the upwelling is expected to increase with latitude, meaning that subtropical areas will experience more intense and longer upwelling events in the future. In the Canary Current, the same pattern is expected in terms of intensity, with an increase in high latitudes and a decrease in low latitudes. Contradictory information is found on the California Current as regards intensification of the upwelling; recent modelling results indicate that the upwelling might become more intense in spring and less intense in summer (Brady *et al*., 2017). Contradicting theories on the California Current are probably because of the fact that it is strongly influenced by regional processes and natural variability (i.e. El Niño, Pacific Decadal Oscillation, North Pacific Gyre Oscillation).

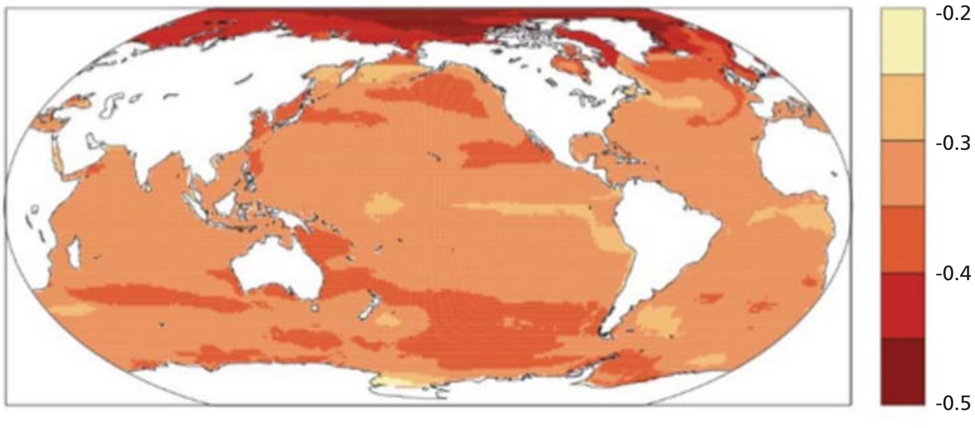
Regarding ocean productivity, the dynamics of the upwelling areas and their interactions with regional processes need to be better understood. On the one hand, upwelling intensification could have a positive impact on nutrient inputs and primary production, while on the other hand it could increase the presence of low oxygen waters in shelf habitats (Bakun *et al*., 2015)

1.4.7 Ocean acidification

Ocean acidification refers to a reduction in the pH of the ocean over an extended period (typically decades or longer) caused primarily by the uptake of atmospheric CO_2. It can also be caused by other chemical additions to or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity. As atmospheric CO_2 concentrations increase, the oceans absorb more CO_2. This causes an increase in the partial pressure of CO_2 (pCO_2) at the ocean surface and a decrease in water pH and in the saturation state of mineral forms of calcium carbonate ($CaCO_3$), referred to as Ωar[4], which is important for all shell-forming aquatic life (Pörtner *et al*., 2014). Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in increasing acidification of the ocean; the pH of ocean surface water has decreased by an average of 0.1, corresponding to a 26 percent increase in acidity (IPCC, 2014; Jewett and Romanou, 2017). Variability in coastal pH, pCO_2 and Ωar is higher in coastal waters than in the open ocean. Lower salinity (resulting from ice melt and/or excess precipitation) exacerbates water acidification by diluting the concentration of substances acting as buffers. There are regional variations in the rate of acidification of surface waters: acidification is already 50 percent higher in the Northern Atlantic than in the subtropical Atlantic, and Arctic waters are acidifying faster than the global average because cold water can absorb more CO_2. In the California Current, corrosive conditions events (in terms of Ωar state) have increased in frequency, severity, duration and spatial extent (Harris, DeGranpre and Hales, 2013).

While oceanic pH is subject to natural variability, especially near sources of freshwater input like rivers and heavily tidal environments, observed trends in global ocean pH already exceed the range in natural seasonal variability over most of the oceans (Henson *et al*., 2017), and are expected to exceed it further in coming years (Gattuso *et al*., 2015). Projections indicate that the volume of ocean water supersaturated in aragonite (where Ωar is greater than 1) will decrease by half (RCP2.6) or even disappear (RCP8.5) by the end of the century. The volume of undersaturated waters (where Ωar is less than 1), which are corrosive to calcium carbonate shells and skeletons, are forecast to increase by 10 percent to 20 percent depending on the scenario considered. Future projections show that this decrease in pH will occur throughout the world oceans, with the largest decreases in surface waters occurring in the warmer low- and mid-latitudes. However, it is the already low Ωar waters in the high latitudes and in the upwelling regions that are expected to become aragonite unsaturated first (Figure 1.6).

FIGURE 1.6
Median model's change in surface pH from 1850 to 2100 resulting from projected changes in ocean acidification of 11 CMIP5 Earth System Models under RCP8.5



Source: Ciais *et al*., 2013.

While the nature and speed of the acidification process are well understood and predicted with high confidence, its consequences over the next few decades are still

[4] If Ωar is less than 1 (Ωar<1), conditions are corrosive (undersaturated) for aragonite-based shells and skeletons. When Ωar>1, waters are supersaturated with respect to calcium carbonate and conditions are favourable for shell formation. Coral growth benefits from Ωar≥3 (IGBP, IOC & SCOR, 2013).

unclear. The type and magnitude of ocean acidification impacts on marine organisms vary with their physiological abilities to adapt to these new conditions, on top of the multiplicity of other stressors the organisms are exposed to. Ocean acidification research is still in the early stages of development and so far, mainly short-term responses in laboratory conditions have been investigated and provide information only on the sensitivity of organisms to a single stressor (McElhany, 2017). There is an emerging trend of scientific research that explores long-term responses and adaptive capacity of marine organisms (Munday, 2017), as well as the impact of combinations of stressors, such as temperature and acidification, or oxygen content and acidification (Gobler and Baumann, 2018). This will yield more insight into likely impacts.

1.4.8 Primary production

Phytoplankton production is the process at the base of the marine food web, controlling the energy and food available to higher tropic levels and ultimately to fish. Earth system model projections of global marine primary production as a result of climate change are uncertain, with models projecting both increases (Taucher and Oschiles, 2011) and declines of up to 20 percent by 2100 (Bopp *et al*., 2013; see also Chapter 4, this volume). This is partly because primary production is an integrator of changes in light, temperature and nutrients, but also because of the uncertainty in the sensitivity of tropical ocean primary production to climate change. Specifically, how climate change will affect El Niño events in the tropical Pacific remains uncertain (Chapter 15, this volume). However, based on the most recent understanding of tropical ocean primary production, it is estimated that global marine primary production will decline by 6 percent ± 3 percent by 2100 (Kwiatkowski *et al*., 2017). Primary production in freshwater lakes has been observed to increase in some Arctic (Michelutti *et al*., 2005) and boreal lakes, but to decrease in Lake Tanganyika in the tropics (O'Reilly *et al*., 2003). In both cases the changes were attributed by the authors to climate change (IPCC, 2014).

1.5 CONCLUSION

This chapter summarizes thematic information on climate change and its consequences for aquatic systems in order to provide the background and to set the context for the chapters that follow. Considering that aquatic systems represent more than two-thirds of the Earth surface, the current level of available information on climate change impacts is relatively low and many of the theories and assumptions are still under debate. However, it is a certainty that oceans play a critical role in climate regulation and in absorbing heat and the increased amounts of CO_2 resulting from anthropogenic activities. Model projections agree that ocean warming, increased stratification and increasing emissions will reduce the ocean's future capacity to absorb CO_2 (Gattuso *et al*., 2015).

Freshwater systems are also strongly connected to climate, as they may influence climate-related atmospheric processes and also be indicators of climate change. The IPCC considered freshwater systems to be among the most threatened on the planet because of the multiple anthropogenic impacts they are subject to. Hydropower infrastructure, water use for irrigation and agricultural land-use result in the fragmentation of water bodies, modification of flow regimes and a progressive disconnection of floodplains and wetlands from the rivers that sustain them. It is expected that these stressors will continue to dominate as human demand for water resources grows, together with urbanization and agriculture expansion (Settele *et al*., 2014), in addition to climate change.

Whether positive or negative, the evolution of aquatic systems under climate change will have implications for the fisheries and aquaculture sector, throughout the value chain. Species productivity and fish growth are already changing with consequences for fishing and farming yields, as a result of shifts in the distribution of fish, alteration of larval transport or thermal tolerance of farmed fish. Operations of fishing and farming activities are also expected to be affected, whether by short-term events such as extreme weather events or medium to long-term changes such as lake levels or river flow that could affect the safety and working conditions of fishers and fish farmers. Food control procedures will undergo major reshaping to protect consumers from potential increase in contaminants and toxin levels resulting from changes in water conditions. These examples of potential implications are further developed in more comprehensive analyses in the subsequent chapters, which examine the evolution of the fisheries and aquaculture sector in the context of climate change, but also in relation to the multiple stressors that it is currently experiencing, whether related to environmental or to anthropogenic activities. The chapters also explain the implications of these changes for fisheries and watershed management and, more importantly, they provide a set of potential solutions, both to adapt to the expected changes and to contribute to climate change mitigation.

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Chapter 2: Understanding the impacts of climate change for fisheries and aquaculture: applying a poverty lens

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> *"No community with a sense of justice, compassion or respect for basic human rights should accept the current pattern of adaptation. Leaving the world's poor to sink or swim with their own meagre resources in the face of the threat posed by climate change is morally wrong."*
>
> **Archbishop Desmond Tutu – Human Development Report 2007/2008[1]**

KEY MESSAGES

- Climate change affects communities and livelihoods in fisheries and aquaculture, and efforts to adapt to and mitigate climate change must therefore be human-centred.
- Climate adaptation strategies must emphasize the need for poverty eradication and food security, in accordance with the Paris Agreement, the United Nations 2030 Agenda for Sustainable Development and other international instruments, such as the *Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication*.
- Measures to eradicate poverty and provide food security for people in fishing and aquaculture communities are also instrumental for climate change adaptation, and should be integrated in the formulation and implementation of national adaptation plans.
- Climate change adaptation for building resilience must be multi-dimensional and multi-sectoral to help people out of poverty and to prevent them from descending further into it.
- Capacity at national, regional and local levels of governance should be mobilized to facilitate adaptation to climate change for the poor and vulnerable.

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[1] http://hdr.undp.org/sites/default/files/reports/268/hdr_20072008_en_complete.pdf

- To address climate change vulnerability, management systems must create opportunities for fishers, fishfarmers and fish-workers to remain flexible, and to be able to sustainably utilize diverse livelihood opportunities.
- Climate change adaptation should empower local stakeholders to allow for meaningful participation of the poor and vulnerable, and safeguard their human rights.
- Climate change adaptation measures must address issues of power imbalances and inequity disadvantaging the poor, as they relate to, for example, gender, labour conditions, tenure rights, market access, migration patterns and stakeholder conflicts.
- The impact of climate change and adaptation measures for the poor and vulnerable must be monitored at different scales and dimensions, focusing both on achievements, best practices and on possible maladaptation.
- There is a need for the countries to put a stronger emphasis on poverty and food security in the context of fisheries and aquaculture within their national determined contributions.

2.1 BACKGROUND: POVERTY IN FISHERIES AND AQUACULTURE

Approximately 11 percent of the world's population (about 767 million people) is living in extreme poverty (World Bank, 2016). In addition to low income, poverty is comprised of factors that together, in many instances, hinder the realization of human rights as originally stated in the *Universal declaration of human rights, the right to food guidelines* (FAO, 2005), the *Voluntary guidelines on the responsible governance of tenure of land, fisheries and forestry in the context of national food security* (FAO, 2012), and the *Voluntary guidelines for sustainable small-scale fisheries in the context of food security and poverty eradication* (SSF Guidelines; FAO, 2015). Among these are food insecurity and malnutrition, poor health, low levels of education, insecure tenure rights, marginalization, and political discrimination. Poor people typically lack representation in governance systems, which makes them vulnerable in ways that affect their overall well-being. In addition to this, their limited integration in the formal economy frequently results in their marginalization from the formal employment system and social programmes[2] (FAO, 2017a). Targeted programmes could better prepare them to respond and adapt to situations which otherwise reduce their abilities to engage in fishing activities, thus further aggravating their poverty and vulnerability.

Small-scale fishing and fishfarming communities[3] in developing countries are often marginalized and at the bottom of the socio-economic ladder. This is even the case in many countries where the overall indicators of human development are relatively good (Jentoft and Midré, 2011). Currently, there are insufficient sector-disaggregated data to calculate the exact share of fishery-dependent people within the above total populations in poverty. However, since more than 90 percent of those employed in the sector are engaged in small-scale fisheries, including processing and marketing, this is also where poverty is most prevalent (Béné, Macfadyen, and Allison, 2007). The situation has in many instances been improved by a combination of state support, public welfare programmes, engagement of civil society organizations, and collective action by the fishing population themselves (FAO, 2016a). Likewise, the recognition of the importance of small-scale fisheries for food security and poverty reduction led to the development and endorsement of the SSF Guidelines (FAO, 2015). Small-scale aquaculture producers and communities do not as yet have a similar instrument, but their contribution to poverty eradication and food security should not be ignored.

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[2] Regional Fisheries Livelihoods Programme for South and Southeast Asia (RFLP) and the Sustainable Fisheries Livelihoods Programme (SFLP) in West Africa

[3] When referring to fisheries and aquaculture communities, it includes both inland and coastal communities, if not otherwise specified.

Both inland and marine fisheries and aquaculture operate at various scales with different degrees of labour intensity (FAO/NACA, 2012). In addition to full- and part-time employment, small-scale fisheries and aquaculture often provide vital supplements to other livelihood activities in times of difficulty or as a recurrent side activity. Fishing as seasonal employment frequently provides those in poverty with an extra income source. As recognized in the SSF Guidelines, small-scale fisheries are typically partly an informal sector, which provides operators with the flexibility needed to make harvesting a food security safety valve (FAO, 2017a). For it to serve such a function, in the context of climate change adaptation, flexibility should not be undermined as an important adaptive mechanism (Cinner *et al.*, 2018).

Adaptive capacity refers to strengthening resilience, reducing vulnerability and achieving robustness i.e. the ability of the system to withstand adverse conditions (IPCC, 2014a; Miller *et al.*, 2010). More specifically, climate resilience refers to the capacity of social, ecological, technical, or infrastructural systems to address challenges while maintaining the same function, structure and overall identity; and to respond to opportunities (IPCC, 2007). Adaptive capacity has a negative correlation with poverty and food insecurity. In other words, poverty can be an obstacle to adaptive capacity, which may be lower in poorer communities and in poor countries (IPCC, 2014b). Achieving adaptive capacity must go hand in hand with ensuring human rights and environmental justice (Schlosberg and Collins, 2014). This is also noted in the Paris Agreement (PA)[4] and its instruments such as the Nationally Determined Contributions (NDCs), as well as in the SSF Guidelines. In order to increase adaptive capacity to climate change, national governments are expected to adopt a legal framework for the mapping of climate change impacts on communities with a view to formulating nationally determined prioritized actions, as stated in the PA. They then need to take into account vulnerable people, places and ecosystems as well as building the resilience of socio-economic and ecological systems, including through economic diversification and sustainable management of natural resources (see Appendix 2.1).

This chapter addresses the specific poverty and vulnerability issues related to climate change in fisheries and aquaculture. It discusses how climate change challenges the resilience of local communities and peoples' capacity to cope and adapt. The chapter also contains an analysis of the extent to which poverty and vulnerability are highlighted in the climate change adaptation agenda at international and national levels with regards to fisheries and aquaculture. Finally, the chapter suggests possible pathways to address the nexus between climate change and poverty.

2.2 HOW ARE CLIMATE CHANGE AND POVERTY RELATED IN FISHERIES AND AQUACULTURE?

Small-scale fishers and small-scale aquaculture are particularly vulnerable to climate change (see e.g. Chapter 18). Their vulnerability is a result of both their geographical location as well as their poverty situation. Being located at the waterfront, fishing and fishfarming communities are exposed to climate related extreme events and natural hazards, such as hurricanes, cyclones, sea level rise, ocean acidification, floods and coastal erosion. Millions of people living in coastal and floodplain lowlands are unable to escape regular flooding. As reported throughout this volume, climate change impacts are harming human and natural systems including infrastructure, disturbing fish stocks, eroding natural resources and endangering species and ecosystems. These impacts also reduce resilience. Climate change is therefore a threat to human health, well-being, and livelihoods.

[4] Article 7(1). The IPCC defines adaptation as: "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2001a, Annex B). The term is not defined in the Agreement or UNFCCC.

The ability of individuals and communities to adapt to climate change depends on their vulnerability, exposure and adaptive capacity. In turn, this is related to their financial and social capital, such as social networks. Their exposure and vulnerability to climate change impacts is also related to the existing infrastructure and institutional framework, including government sponsored social safety programmes. Their adaptive capacity also depends on their ability to acquire assets, such as insurance, technologies, and knowledge (Béné and Friend, 2011; Fankhauser and McDermott, 2014). Those who are poor and vulnerable have fewer opportunities to access these resources, and thus are less able to adapt.

The poverty and vulnerability of fishers and fish-workers are also often linked to and determined by their political marginalization. They typically do not have a voice in the climate adaptation planning process, which reduces their short- and long-term resilience. Unequal power relations, such as the control exerted by intermediaries who buy the fish, provide credit, extend consumption loans, and offer land on which fishers can build their homes, contribute to their vulnerability and poverty status. In these transactions, fishers and fish-workers are easily trapped in a cycle of exploitative deals, which tend to undermine their capacity to respond to additional threats, such as those related to climate change (Kurien, 2014).

Predictions of the future impact of climate change on the poverty and vulnerability of fisheries and aquaculture arise out of climate change models, which indicate, for example, increased fish productivity at high latitudes and decreased productivity at low- and mid-latitudes, with considerable regional variations. By 2050, total maximum catch potential globally has been projected to decrease under climate change by 2.8 percent to 5.3 percent under representative concentration pathway (RCP)2.6 and by 7.0 percent to 12.1 percent under RCP8.5 from present yields, but with substantial variability across national exclusive economic zones (EEZs; see Chapter 4). The likely outcomes of these changes include:

- Shifts in fish distribution and migration behaviour.
- Disrupted traditional fishing patterns which will have to change, at least over a period of time, depending on how fast these shifts occur.
- Change in policies and regulatory systems to deal with climate change effects that will impact on fishing practices (see other chapters). These policies will affect poverty, food security, and equity within and among fisheries communities.
- Mobile, large-scale fleets will be able to better adapt to the shifts in fish distribution than small-scale, community-based fleets.
- Communities at lower latitudes will see their fish landings go down, while communities at higher latitudes will see them go up.
- Poor communities in the tropical south will suffer losses while communities in the north experience higher fishing pressure as fleets move there.

Shifting species distributions may cause fishers and fish-workers to migrate in search of livelihood opportunities elsewhere, where existing tenure systems and rights will be challenged. Fishfarmers have this opportunity to a lesser degree because they are less mobile.

2.3 IS POVERTY A CONCERN IN THE CLIMATE CHANGE ADAPTATION AGENDA IN FISHERIES AND AQUACULTURE?

Having discussed the interaction of poverty and climate change in the context of fisheries and aquaculture, the next two sections draw on this background to explore whether the international climate change regime effectively addresses the nexus between climate change and poverty in fisheries and aquaculture. It starts by analysing the international level, then turns to the national level.

2.3.1 The international level

At the international level, the PA unites all parties in urgently addressing climate change and its impacts through an integrated approach. The Agreement enhances the implementation of the United Nations Framework Convention on Climate Change (UNFCCC) and aims to strengthen the global response to the threat of climate change in the context of sustainable development and efforts to eradicate poverty (Article 2(1), PA) (see Appendix 2.1 of this chapter). Although the PA does not explicitly address fisheries and aquaculture, it inherently speaks to them as it does to other sectors. This is also reflected in several NDCs, as well as submitted National Adaptation Plans (NAPs)[5].

The Agreement emphasizes the intrinsic relationship between climate change actions and the eradication of poverty, as well as with food security and "the fundamental priority" of ending hunger (Preamble, PA). New climate change-related goals, such as the Sustainable Development Goals (SDGs)[6] and the recognition of climate change as a driver of disaster risk in the Sendai Framework for Disaster Risk Reduction[7], are set in recognition of the urgent need to take more ambitious measures to prevent dangerous climate change, whilst also providing for closer integration with action on poverty.

A similar ambition appears in the latest reports by the World Bank (Hallegatte *et al.*, 2016) and the World Economic and Social Survey (WESS, 2016). The reports show that development strategies in the era of climate change require the planning and implementation of stronger and more cohesive transformative policies to reduce inequalities and focus on poverty eradication, food security and nutrition, and social development. Through the provision of resources and shock responsive policies that lower disaster risks and mitigate climate change impacts, communities and individuals can achieve the reduction of rural poverty (WESS, 2016).

The PA emphasizes the importance of securing the finance to achieve these goals (Articles 2 and 9) in an effort to close the adaptation deficit caused by the fact that poor countries are less able to take effective adaptation action, thus rendering them more vulnerable than rich countries (Fankhauser and McDermott, 2014). States should ensure that national laws governing adaptation address vulnerability and resilience (Article 7(9), PA). According to the PA, they also need to present concrete ideas of what building resilience requires in the context of climate change adaptation, and what it would take to implement them in specific contexts such as fisheries and aquaculture.

Responding to these agreements, the climate change adaptation agenda needs to mainstream development strategies at all levels, including at the international level, bearing in mind the Global Goal on Adaptation (Appendix 2.1) set by the PA (Article 7, PA). The Global Goal on Adaptation is reinforced by references to poverty and food security and the need to ensure human rights integration[8]. It emphasizes the strengthening of resilience and the reduction of vulnerability (Article 7, PA), the provision for transparency (Article 7(5) and Article 13, PA) and for public participation (Article 7(5) and Article 12, PA), as well as the call for states to respect, promote and consider human rights in addressing climate change (Preamble, PA).

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[5] National Adaptation Plans (NAP) are "a means of identifying medium- and long-term adaptation needs and developing and implementing strategies and programmes to address those needs". The process to formulate and implement NAPs was formally established at the 16th Conference of Parties (COP16) of the UNFCCC in 2010 under the Cancun Adaptation Framework.

[6] https://sustainabledevelopment.un.org/sdgs

[7] https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf

[8] Knox (2016) at paragraph 68: States must adopt a legal and institutional framework that assists those within their jurisdiction to adapt to the unavoidable effects of climate change.

Furthermore, parties are required to evaluate and respond to vulnerability[9] and take proactive measures to secure resilience and achieve robustness. The agenda must also be gender-responsive, participatory and involve an integrated approach laid down in Article 7(5) PA, and in the Gender Action Plan approved at the 23rd Conference of the Parties of the UNFCC. Furthermore, adaptation responses in fisheries and aquaculture from a gender perspective should be integrated into the formulation and implementation of NAPs and other planning processes (FAO, 2018). Issues such as safety at sea, loss of livelihood, declining food security and coastal inundation fall within this framework. This agenda must be integrated across the various processes set under the international climate change regime (the UNFCCC and the PA), as part of the formulation and delivery of NDCs and as the operational arm to implement the adaptation component, NAPs. These nationally determined programmes should have explicit mechanisms to reach affected communities and individuals, enhancing their adaptive capacity, which simultaneously feeds back into the delivery of development policy at the national level. The contribution of every sector, including fisheries and aquaculture, therefore comes under renewed focus, as does the need to reduce vulnerabilities in all communities facing significant climate change impacts. To support fisheries and aquaculture in the formulation and implementation of NAPs (FAO 2016b), FAO is developing guidelines with the aim to inform those responsible for climate change adaptation processes and draw the attention of policymakers and government officers involved in the NAP planning and the fisheries and aquaculture community.

BOX 2.1

FAO guidelines on addressing fisheries and aquaculture in NAPs

The *Addressing fisheries and aquaculture in National Adaptation Plans - supplementary guidelines* (FAO, forthcoming) provide technical guidance on the integration of fisheries and aquaculture in the formulation and implementation of NAPs and serves as supplementary guidance to FAO's *Addressing agriculture, forestry and fisheries in National Adaptation Plans – Supplementary guidelines* (referred to as "NAP-Ag Guidelines"; Karttunen *et al.*, 2017). It aims to draw the attention of policymakers and government officers responsible for NAP planning and processes generally, as well as fisheries and aquaculture officers at country level, specifically. It collates and analyses relevant information from fisheries and aquaculture to support the sector's ability to take part in national climate change adaptation planning processes.

The fisheries and aquaculture NAP guidance aims to:

- assist fisheries and aquaculture institutions to map their knowledge into the climate change world and language and articulate their needs;
- ensure that the visibility and specificities of fisheries and aquaculture are captured in the process to formulate and implement NAPs;
- support the mainstreaming of fisheries and aquaculture in the NAP implementation; and
- more broadly, support adaptation planning within fisheries and aquaculture.

[9] Social vulnerabilities are as significant as economic vulnerabilities. Therefore innovative interventions are needed to provide protections across the specific set of challenges that fishers face in each national and local context.

The growing calls to focus development on increasing the adaptive capacity of communities in order to increase their resilience to climate change and to reduce poverty are reflected in the Nairobi Programme on impacts, vulnerability and adaptation to climate change. This programme, established under the UNFCCC, continues to provide input on best practices in adaptation (see Subsidiary Body for Scientific and Technological Advice (SBSTA) Draft Conclusions, FCCC/SBSTA/2017/L.7 of 16 May 2017[10]).

With regards to the PA, delivery of national adaptation policies is communicated within NAPs[11] or NDCs (Article 7(10) and (11)). NDCs are intended to reflect each state's common but differentiated responsibilities and respective capabilities, in the light of different national circumstances (Article 4(3)). The acknowledgement that the eradication of poverty is a key consideration (Article 4(1)) signals the importance placed on this international objective (first recital to the Preamble to Decision 1/CP.21). Some NDCs predate the adoption of the PA and therefore the approach taken in some current NDCs may not fully track all the language of the Agreement.[12] Under the PA, NDCs are to be renewed progressively every five years. As parties revise their NDCs, the emphasis placed on addressing food security and poverty can be progressively addressed and expanded.

A degree of differentiation in setting the framework for NDCs allows for the special status of vulnerable countries under the PA (Articles 4(6), 7(6) and the Preamble). Furthermore, the status of NDCs at the national level will be determined by national law, including any specific provision made under national climate change law. Constitutional and human rights protection of interests affected by the delivery, or non-delivery, of the NDC may also be addressed under national, as well as international law, taking into account the call for states to "respect, promote and consider" their human rights obligations in addressing climate change (Preamble to the PA).

2.3.2 The national level

As of September 12, 2017, 155 NDCs had been submitted to the UNFCCC. These describe actions to be implemented in order to mitigate and adapt to climate change. According to the PA, NDCs must address the climate change impacts on communities and livelihoods, and develop well-designed strategies to address them. An analysis of these commitments was conducted to identify if countries' proposed interventions within the fisheries and aquaculture sector were explicitly targeting the poor and most vulnerable[13]. The analysis shows that 49 countries make explicit links to SDG 1 (no poverty) and 101 countries refer to SDG 2 (no hunger) in their NDCs[14], although this does not imply that they are all directly targeting poverty and food security in the fisheries and aquaculture sector. In fact, only seven NDCs refer explicitly to impacts of climate change on food security in the fisheries and aquaculture sector.

This analysis also assessed whether NDCs included pro-poor social policies and actions with regards to fisheries and aquaculture. Each NDC policy or action was then categorized according to several indicators related to poverty and vulnerability in the sector.

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[10] https://unfccc.int/sites/default/files/resource/docs/2017/sbsta/eng/l07.pdf

[11] NAPs were established under the Cancun Adaptation Framework. The earlier NAPA process was designed to identify priority areas for urgent and immediate needs in LDCs.

[12] NDCs are individual and voluntary commitments and goals for post-2020 climate action that both developed and developing countries submitted before or shortly after the COP21 in December 2015. At this time, since this was before parties ratified the Convention, the documents submitted were called intended national determined contributions (iNDCs), however, after the ratification took place, countries either re-submitted their iNDC as their NDC or they decided to submit an NDC different to the iNDC.

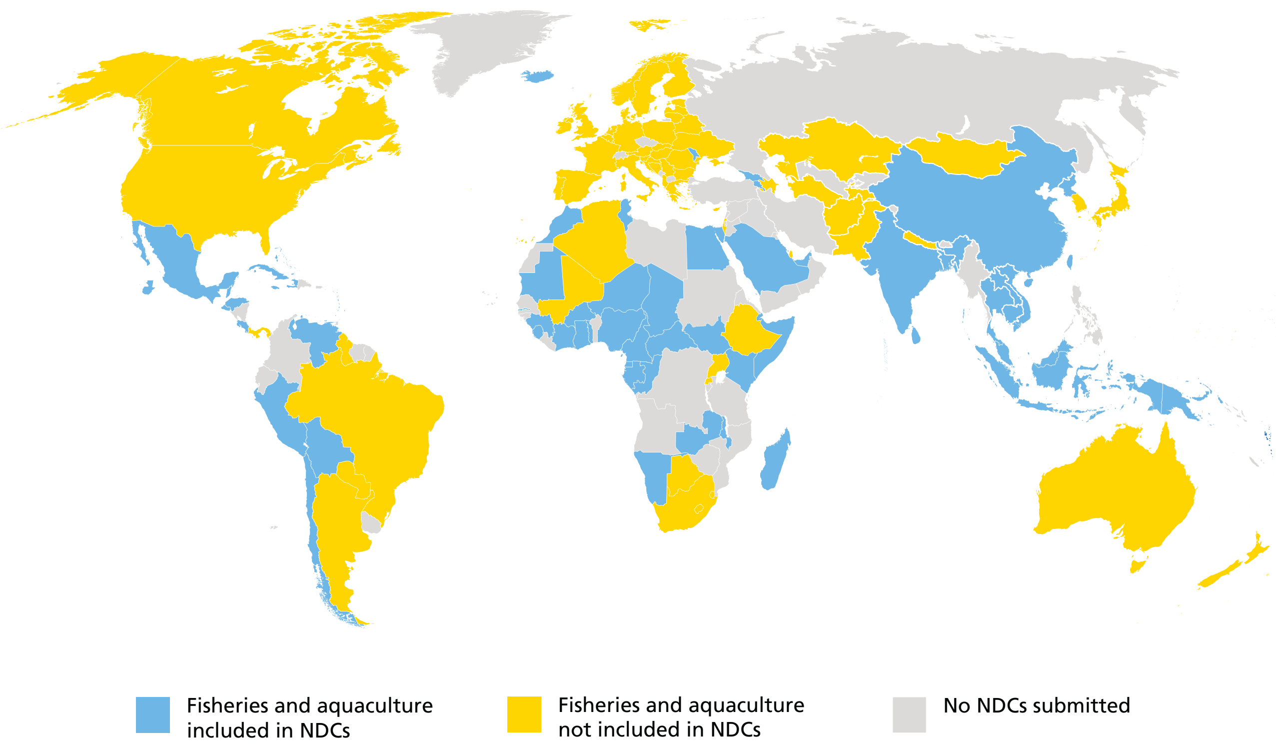
[13] Small-scale fishers are considered the most poor and vulnerable as explicitly recognized in the SSF Guidelines (FAO, 2015).

[14] http://ndcpartnership.org

Out of the 155 NDCs submitted, 87 address fisheries and aquaculture, of which 78 include climate change adaptation measures in the sector (see Figure 2.1). Notably, 23 countries in Asia and 23 in Africa, where the concentration of poverty is most prevalent, include fisheries and aquaculture adaptation measures to climate change in their NDCs.

The analysis also shows that out of the 78 NDCs focusing on climate change adaptation, 55 reported impacts of climate change on their fisheries and aquaculture sector, including impacts on fisheries resources and migration patterns with consequences for the sustainability of the fishery sector, livelihoods, human health and food security, to name some. Particularly, 16 NDCs mention how climate change impacts local communities, including migration and livelihood diversification, decreasing food production as a result of changing fish abundance, and the aggravation of fishers' poverty (see Box 2.2).

FIGURE 2.1
Fisheries and aquaculture reported in the NDCs



Not all countries are visible on this map.

BOX 2.1

Examples of reported impacts of climate change in the NDCs

- Lake Chad's reduction in size from 25 000 km² in 1960 to 2 500 km² today has considerably impacted crop and fish production, and forced inhabitants to migrate to wetter areas (Chad).
- The likely disappearance of more than half the coral cover will affect local populations that are dependent on those resources and who already live in poverty (Djibouti).
- Very significant decrease in agricultural yields, in fishing and aquaculture production, total or partial destruction of social infrastructure (schools, basic health centres) and aggravation of household poverty as well as food insecurity following cyclone events and social conflict caused by water scarcity (Madagascar).
- Communities are experiencing climate change impacts such as eroding shorelines and riverbanks, shortage of water, depleted fisheries stocks, reduced food production, large-scale flooding, increase in outbreaks of vector-borne diseases and sea level rise (Fiji).
- As a result of climate change, in rural outer islands the people have limited access to employment opportunities, effective transport, communication, and community services such as education and health – these factors, combined with a high dependency on subsistence agriculture and coastal fisheries, make rural communities vulnerable (Kiribati).
- Communities' livelihoods and infrastructure are impacted by sea level rise, sea surges, typhoons and rainfall intensity; water and food security issues from changing rainfall patterns and ocean acidification. Community well-being is also affected by rising temperatures, peak wind speeds and changes to ocean circulation patterns (the Marshall Islands).
- Exposure to the cyclical and adverse climate impacts of "El Niño", which affects primary sectors such as fisheries. Likewise, given the vulnerability of the sector and focusing on people and their livelihoods, the vulnerable populations that need to be addressed on a priority basis, include small-scale fishers (Peru).
- The increased coastal erosion, droughts, storms, floods and landslides of the last decade have severely impacted livelihoods (Saint Vincent and the Grenadines).
- Extreme temperatures, erratic rainfall, floods, drought, tropical cyclones, rising sea levels, tidal surges, salinity intrusion and ocean acidification are causing serious negative impacts on the lives and livelihoods of millions of people in Bangladesh, and are gradually offsetting the socio-economic development gained over the past 30 years (Bangladesh).
- The migration of tuna to deeper waters and the coral bleaching affecting the reefs are affecting the livelihoods of people (Maldives).
- Sea level rise, flooding, hurricanes, and other extreme events will affect the country, thus destroying the natural and cultural heritage along the coast (Cuba).
- The damage caused by hurricanes affects the fishing seasons, landing infrastructure and markets, resulting in wastage and loss of fish and revenue to fishers. Climate change, including increasing ocean acidification and changes in sea temperatures, are affecting fisher resources and migration patterns with consequent impacts on the sustainability of the fishery sector, livelihoods, human health and prospects for food security (Dominica).
- The National Adaptation Programme of Action targets particularly vulnerable groups in the coastal zone, such as poor communities in rural areas including farmers and small producers and people whose livelihood mainly depends on the use of natural resources (hunters, fishers, salt producers, etc.) (Guinea).
- The magnitude and frequency of natural hazards are expected to increase, especially impacting the most vulnerable populations in the country, such as indigenous peoples, small-scale fishers, women and children, with negative impacts on livelihoods, cultural identity and traditional and ancestral knowledge (Guatemala).
- Many fisheries- and fishfarming-dependent communities which live in precarious and vulnerable situations because of poverty and their lack of social services and essential infrastructure are already affected by climate change. The consequences felt on sustainability of aquatic ecosystems for fisheries and aquaculture are highly adverse (Sri Lanka).
- Vulnerability to sea level rise, inland flooding and other climate related events cause adverse impacts on the overwhelming majority of coastal populations. Extinction of species such as whales, dolphins and turtles, as well as coral bleaching and migration of some marine species and sea birds are expected (Qatar).

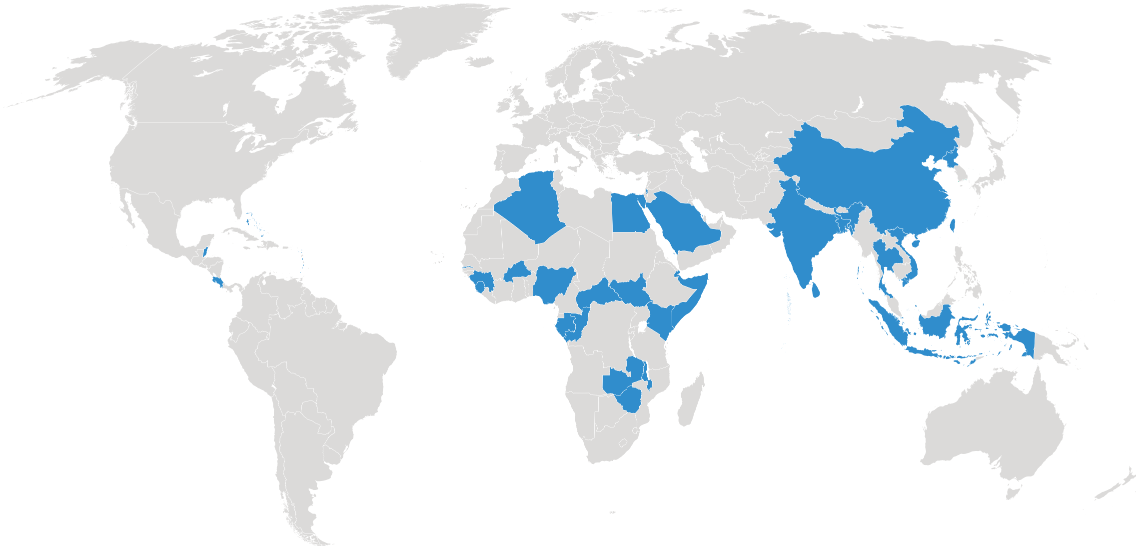
In response to climate change impacts in the sector, 43 NDCs explicitly include some form of social policies. Some of these policies include the promotion of income-generating activities linking climate change adaptation with conservation and poverty alleviation, livelihoods' diversification, early warning systems targeting the poor and vulnerable, and resilience building of coastal economies and the social capital of communities. These policies also aim to strengthen insurance schemes for fishers as well as micro-insurance for the private sector and vulnerable segments of the sector (see examples in Box 2.3).

Out of the 43 NDCs mentioned above, 32 explicitly mention the resilience of the poor and vulnerable in fisheries and aquaculture (see Figure 2.2). It is important to note that many of the adaptation actions related to fisheries and aquaculture mentioned in the NDCs do not concretize how resilience building shall be implemented and who will be targeted. This omission may negatively affect the achievement of poverty eradication and resilience building in the sector.

Some examples provided in this chapter show NDCs making explicit linkages between poverty and climate change (see Box 2.3). These examples show how social policies can set the path for other countries and communities to develop similar strategies. However, the analysis of the strategies to respond to them shows that overall NDCs focus more towards the environmental aspects rather than on local livelihoods and food security. In general, the nexus between climate change and poverty is weakly addressed at the national level (Madhanagopal, 2018; Prowse, Grist and Sourang, 2009). This highlights the need for climate change adaptation strategies to be more human-centred.

It should be recalled that NDCs are subject to a comprehensive five-yearly global stocktake (Article 14(1) PA, see Appendix 1), conducted at the international level to assess collective progress, the first of which will be conducted by 2023. This may be the opportunity to incorporate specific targeted poverty eradication and food security strategies for fisheries and aquaculture into the NDCs.

FIGURE 2.2
Reported pro-poor measures to adapt to climate change in the fisheries and aquaculture sector within NDCs



8 include food security
(Seychelles, Zambia, Guinea, Bahamas, Dominica, Belize, Bahrain, Egypt)

32 include resilience
(Djibouti, Kenya, Mauritius, Seychelles, Zambia, Central African Republic, Sao Tome and Principe, Gambia, Guinea, Nigeria, Sierra Leone, South Sudan, Antigua and Barbuda, Bahamas, Dominica, Grenada, Saint Lucia, Saint Vincent and the Grenadines, Saint Kitts and Nevis, Belize, China, India, Indonesia, Maldives, Singapore, Viet Nam, Cook Islands, Kiribati, Bahrain, Saudi Arabia, Algeria, Egypt)

1 includes gender
(Dominica)

17 include public participation
(Djibouti, Malawi, Mauritius, Seychelles, Somalia, Zambia, Congo, Sao Tome and Principe, Burkina Faso, South Sudan, Grenada, Costa Rica, Bangladesh, Thailand, Democratic People's Republic of Korea, Bahrain, Egypt)

5 include social protection
(Seychelles, Antigua and Barbuda, Dominica, Maldives, Sri Lanka)

7 include decent rural employment
(Central African Republic, Congo, Gabon, Guinea, India, Democratic People's Republic of Korea, Egypt)

2 include access to services
(Maldives, Palestine)

BOX 2.2

Examples of pro-poor social policies related to climate change reported in the NDCs

- Promoting and reviving income-generating activities linked to inland and coastal ecosystems, diversification of means of livelihoods, and improved access to fisheries resources (Central African Republic, the Democratic Republic of the Congo, Gabon, Malawi and Guinea).
- Capacity building in aquaculture and promotion of fish farming (Malawi).
- Protecting and enhancing resilience of coastal and estuarine/riverine economies and livelihoods, and supporting alternative livelihoods, if needed (the Gambia, India, Democratic People's Republic of Korea).
- Supporting and strengthening insurance schemes for fishers to cope with losses resulting from climate variability through minimum monthly income, and to recover the losses and damages induced by climate change on livelihood, properties, infrastructure and fisheries (Seychelles, Dominica, Maldives, Sri Lanka).
- Micro-insurance for private sector and vulnerable segments of society (farmers, fishers and fish-workers, women, and indigenous and vulnerable communities) (Antigua and Barbuda).
- Strengthening early warning systems and capacity building in coastal areas (Seychelles).
- Promoting food security and nutrition through feasibility studies as well as diversification and promotion of climate smart agriculture for fisheries production through the development of agro-ecological fishfarming harvest and post-harvest techniques (Seychelles, Zambia, Guinea).
- Formulating and implementing measures to enhance sustainable food systems that are climate resilient and build robust communities by strengthening their capacity to address risks to food security associated with changing precipitation patterns (the Bahamas, Dominica, Belize, Egypt, Bahrain).
- Promoting reef ecosystem recovery integrated with community building and development (the Bahamas, Dominica, Belize, Egypt, Bahrain).
- Facilitating capacity building through education, awareness and training programmes on climate change risks and resiliency measures in order to strengthen capacity at the community and sectoral level, within municipalities and local authorities, and the private sector (Dominica).
- Integrating the climate funding framework in the national plan and budget to disburse annual allocations for the implementation of mitigation and adaptation projects such as infrastructure and livelihood improvement projects including climate adaptation and livelihood protection (Bangladesh, Maldives).
- Developing a participatory and integrated marine conservation and coastal rehabilitation plan, increasing capacity to manage climate-related health impacts – including through development of health surveillance and early warning systems, systematic climate risk assessment and effective disease prevention and response measures to climate change related health consequences, and building regional climate resilience by serving as a knowledge hub to foster regional cooperation and exchange experiences on adaptation (Thailand).

2.4 FILLING THE GAP: COPING WITH CLIMATE CHANGE AND POVERTY

The content analysis of the NDCs suggests that a stronger emphasis on the impacts of climate change on poverty and food security is needed with regards to fisheries and aquaculture. The next global stocktake to assess the collective progress of the NDCs will take place in 2023, which will be an opportunity to incorporate specific targeted poverty eradication and food security strategies to fill this gap. The following ten key elements, taken from a global literature review of state-of-the-art approaches linking poverty reduction and resilience building undertaken for this chapter, suggest a pathway to address the poverty and climate change nexus:

Enabling national legal and policy-making frameworks are crucial for climate change adaptation. National pro-poor policies can help in lifting communities out of poverty through the targeted provision of services, among others, and to prevent the relapse of communities into poverty from climate change impacts. There is a need to assess to what extent rural development policies actually support small-scale fishers and fisheries communities, and to what extent they address the human dimension impacts of climate change in the sector. Also, the national institutional framework for emergency response and disaster risk reduction is an instrument to lift fisheries communities out of poverty. National reviews should examine the mandate and expertise of all fisheries agencies to assess the extent to which they are required to take climate change into account in making regulatory decisions. As a matter of national discretion, states could consider whether such agencies should be placed under a legal duty to ensure fulfilment of their NDC and NAP so far as relevant to fisheries and aquaculture.

National alignment of the climate change agenda to the SDGs is needed. Tackling climate change through a poverty lens is a key strategy for moving people out of poverty, and for preventing them from descending into it (Krishna, 2010), while at the same time, bringing people out of poverty is essential for making people and communities more capable of dealing with the impacts of climate change. Any strategy aimed at achieving the SDGs must in itself be environmentally friendly, with a minimum carbon footprint. Also related are improving education, awareness raising, and human and institutional capacity on climate change mitigation. Moreover, building capacity for climate change adaptation in least developed countries and small island developing states is important since they are particularly vulnerable.

A holistic, human-centred approach to be resilient is a route to enhance lives by saving livelihoods. Poverty eradication in the climate change context is not only essential in its own right, but as a means of enhancing the resilience of people and communities. Socio-economic development and climate change adaptation must go hand-in-hand. Climate change is a contributor to food insecurity and poverty, while at the same time, poverty and food insecurity reduce the capacity to adapt to climate change. Therefore, both issues need to be tackled simultaneously, and in an integrated fashion. This requires that climate change adaptation strategies are brought to the level of the affected people themselves, and their communities, where the impacts of climate change are felt and where actions are in urgent demand. This demand calls for a multidimensional and integrated approach to both poverty and climate change.

Adding adaptation measures into poverty reduction strategies is crucial to address the impacts of climate change on the poor and vulnerable. Adaptation strategies that simultaneously target poverty and food insecurity are needed at an international and national scale, and at all levels of governance. Notably, adaptive capacity must also include the local context, as this determines local communities' capacity to respond pro-actively on opportunities or challenges induced by climate change (Charles, 2012).

More specifically, climate change adaptation must provide answers to "'of what,' 'to what,' and 'for whom'" questions (Whitney *et al.*, 2017). Addressing these questions should create a more transparent, enabling environment, including policies, which will permit the targeting of specific populations and specific objectives.

In the absence of pro-poor targeted interventions, climate change adaptation measures may reinforce the poverty cycle. This is for instance the case if the poor have no other option than to perpetuate the degradation of natural resources (Tandon, 2012). This is known as the resource dependency trap or cycle (Jentoft and Midrè, 2011), which climate change adaptation must aim to defeat. It is important to recognize that poor and vulnerable communities are at both the receiving and delivering end of climate change adaptation. They not only need external support but also their own collective adaptive capacity to become proactive. This would have to be done through a multidimensional and multi-sectoral approach that includes 1) social protection, 2) development approaches, and 3) resilience building programmes. The first two of these enable people to escape poverty, while the last prevents vulnerable people from descending into it (FAO, 2017b). Also important is to draw on multiple-disciplinary perspectives and knowledge bases, including indigenous and local knowledge, in order to reflect and learn from the full human experience of climate change (Allison and Bassett, 2015).

Social protection schemes that are risk-informed and shock-responsive, are key to reducing the impacts of climate change on the poor (Winder *et al.*, 2017). People without substantial or diversified resources are likely to be the most affected, as climate-related hazards can exacerbate their pre-existing, economic and social vulnerabilities. Poor and vulnerable fishers and fish-workers may have no other choice than to sell off productive assets, take their children out of school, and migrate (Béné, Devereux and Roelen, 2015; FAO, 2017b). This indicates the importance of insurance schemes, cash transfers, disability benefits, pensions, unemployment benefits, food transfers, among others (FAO, 2017a), to give people a better capacity and opportunity to adapt to climate change impacts (Winder *et al.*, 2017). The SDGs targeting the poor and vulnerable, recognize that social protection has a role in poor people's asset accumulation through cash transfers and micro-credit (FAO, 2017b). It also reduces the risk that people take on when they invest in new opportunities (Hallegatte and Rozenberg, 2017).

Recognizing the roles that women play in securing essential community functions and services (including employment, food security, and household responsibilities), and in building and representing their communities, is essential both in terms of poverty reduction and climate change response. Women are mostly engaged in post-harvest work, as their work is centred on fish landing sites or local markets, where they are in charge mainly of selling and processing the fish. Given the marginalization of fishing communities, coupled with the lack of access to credit and capacity development experienced by women in the post-harvest sector, they are placed in a disadvantaged position. Climate change adaptation should not undermine women's tenure rights in fisheries communities. Hence, the adaptive capacity of communities to climate change, as well as their resilience and well-being, are raised through women's social and economic empowerment, entrepreneurship and leadership, and women should therefore be a beneficiary of capacity building as stated in the SSF Guidelines. The Gender Action Plan approved at the 23rd Conference of the Parties of the UNFCCC adopted a new roadmap to incorporate gender equality and women's empowerment in climate change discourse and actions. It aims to increase the participation of women in all UNFCCC processes and seeks to create awareness of and support for the development and effective implementation of gender-responsive climate policy at the regional, national and local levels.

Climate change adaptation in the fisheries and aquaculture sector is a governance challenge, where the actors at different levels and sectors of government, civil society, academia and community organizations would need to engage in an interactive process through which pathways and policies are defined and implemented (Bavinck *et al.*, eds, 2011; FAO, 2018; Kooiman *et al.*, 2005). One may assume that climate change policies and actions may be as contentious in this area as in other areas of environmental policy and change, including in fisheries and aquaculture management. Given the complexity of climate change and poverty issues, there is a need for building partnerships to facilitate cooperation, coordination and policy coherence. There is also a need for strengthening and building institutions that establish shared and differential responsibilities and mandates. These governance mechanisms must reflect the holistic approach to climate change and poverty eradication, and secure equity while building resilient and robust communities.

Governance mechanisms should empower communities in order for them to become more resilient and robust, by facilitating collective action. This may be done, for instance, through community-based co-management arrangements, to strengthen their institutions and adaptive capacity (Cinner *et al.*, 2018). Governance mechanisms must also build institutional capacity at higher ecological and social scales (Whitney *et al.*, 2017). The state and civil society organizations have a role to help communities to become better equipped to adapt to climate change. In particular, these actors have a responsibility to develop resilience programmes and policies specifically targeting the poor and vulnerable in fisheries and aquaculture. Likewise, the WESS (2016) emphasizes that in the absence of far-reaching pro-poor transformative policies the goal of building climate resilience will remain elusive, and that poverty and inequalities will likely increase.

2.5 RECOMMENDATIONS

Drawing on the above key general elements of a "way forward", the following specific points are suggested to enable a better linking of NDCs and the international climate regime to the fisheries and aquaculture sector, in the context of poverty and food insecurity:

- Given the importance of fisheries and aquaculture to poverty reduction and food security in many countries, there is a need for those countries to include, within the NDCs, their concerns and the adaptation requirements of their fishing and fishfarming communities. As specified in the PA, climate efforts are to take place on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty. Furthermore, the new standards introduced in the Agreement should assist states in avoiding maladaptation[15].
- To avoid maladaptation, insurance schemes need to be encompassed by development programmes that entail social safety nets to protect the chronic and those in extreme poverty by increasing their resilience and robustness. This could include, for example, insurance through cash plus services[16]. Such programmes should also protect the not-so-poor from falling into poverty because of natural hazards. Global

[15] Defined by the IPCC as adaptation that increases rather than reduces vulnerability (IPCC, 2001b, p.990). Maladaptation refers to increased impacts of climate change on vulnerable areas and communities as a result of poorly designed and implemented policies to cope with climate change. Examples of maladaptation include promoting development in risk prone areas, as well as taking actions based on short-term political decisions, neglecting of known climatic variability, imperfect foresight, insufficient information, and over-reliance on insurance mechanisms.

[16] Strategies in which coherence and coordination between agricultural and social protection interventions can be strengthened. Cash plus encompasses a wide range of "plus" activities and linkages with the ultimate aim to integrate programmes across sectors and address different dimensions of poverty to more effectively support the poorest groups with the hope of inducing synergistic impacts (FAO, 2017b).

insurance programmes that help countries to cope with massive natural disasters and/or pandemics that affect more than one country would also be needed.

- Countries should, where appropriate, explicitly link their mitigation and adaptation measures to their national policies on sustainable development in the fisheries and aquaculture sectors. These should all be inclusive and pro-poor, as indicated in the SSF Guidelines, recognizing the differential impact that climate change may have on fisheries and aquaculture communities.
- Poverty and food insecurity represent a violation of human rights as recognized in the PA and other international instruments, such as the SSF Guidelines. Therefore, when taking actions to address climate change, national and international law should specifically include legal and other measures to protect and support the lives and livelihoods of fishers, fishfarmers, fish-workers as well as their communities.
- Most NDCs do not specify mechanisms supporting the most vulnerable and poor to deal with shock and impacts of climate change, neither generally nor particularly with regards to fisheries and aquaculture. The NDCs should focus on priorities and actions that fill this gap in future revisions. In a fisheries and aquaculture context, this largely means directing policy measures at small-scale fisheries and small-scale fishfarming.
- In addition to emphasizing ecological and natural aspects of climate change adaptation, NDCs would need to take social, economic, and institutional aspects into account. It is particularly important to assess the situation for those who are poor and vulnerable in fisheries and aquaculture. One implication of targeting the poor and vulnerable is to make policies that strengthen the resilience and robustness of local communities. In all of this, it is crucial to be gender sensitive, and to fully engage women in these processes.
- Building resilience through collective action will require cooperation and coordination of climate related policies and actions. Therefore, communities need to be empowered legally, organizationally and with knowledge. Government agencies and civil society organizations have important roles to play in this regard. In particular, support could be provided to community-based fisheries management organizations to enable their direct involvement in assessment of vulnerability and of measures to secure climate resilience, including those addressed in the NDC.
- Climate change-induced disasters in fisheries and aquaculture communities require an immediate humanitarian response in terms of relief, and robust infrastructure such as shelters. In a longer-term, these events also require efforts to create opportunities for people to build stronger, and more prosperous, communities and by that to become more self reliant. Communities must possess the capacity (assets, knowledge and skills) for climate related collective action. They also need the enabling institutional environment (such as legislation and mandates) to make their own adaptation decisions.
- Climate change adaptation strategies must be developed and implemented in cooperation with affected communities and their organizations through transparent processes, allowing for meaningful participation of fisheries stakeholders, including the poor and vulnerable in the fisheries and aquaculture sector. In order to ensure the latter, states should develop relevant indicators, keeping sex disaggregated data to track the impacts of climate change on poor and vulnerable groups and geographical areas. Key issues of the fisheries and aquaculture sector should be part of the formulation and implementation of National Adaptation Plans in the countries.

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APPENDIX 2.1
Table of provisions of the Paris Agreement of particular relevance to addressing poverty, reducing vulnerability and promoting resilience

The aim of the PA: **Article 2(1)**	The Agreement …aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by: a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change; b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.
Mitigation and the NDCs: **Article 4(1) and (2)**	1. In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty. 2. Each Party shall prepare, communicate and maintain successive Nationally Determined Contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions.
The global goal on adaptation: **Article 7**	1. Parties hereby establish the global goal on adaptation of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal referred to in Article 2. 2. Parties recognize that adaptation is a global challenge faced by all with local, sub-national, national, regional and international dimensions, and that it is a key component of and makes a contribution to the long-term global response to climate change to protect people, livelihoods and ecosystems, taking into account the urgent and immediate needs of those developing country Parties that are particularly vulnerable to the adverse effects of climate change. … 5. Parties acknowledge that adaptation action should follow a country-driven, gender-responsive, participatory and fully transparent approach, taking into consideration vulnerable groups, communities and ecosystems, and should be based on and guided by the best available science and, as appropriate, traditional knowledge, knowledge of indigenous peoples and local knowledge systems, with a view to integrating adaptation into relevant socio-economic and environmental policies and actions, where appropriate. 9. Each Party shall, as appropriate, engage in adaptation planning processes and the implementation of actions… which may include… c) The assessment of climate change impacts and vulnerability, with a view to formulating nationally determined prioritized actions, taking into account vulnerable people, places and ecosystems…and e) Building the resilience of socio-economic and ecological systems, including through economic diversification and sustainable management of natural resources… 10. Each Party should, as appropriate, submit and update periodically an adaptation communication, which may include its priorities, implementation and support needs, plans and actions, without creating any additional burden for developing country Parties. 11. The adaptation communication …shall be… submitted and updated periodically, as a component of or in conjunction with other communications or documents, including a national adaptation plan, a nationally determined contribution…and/or a national communication…
The global stocktake and adaptation: **Article 7(14)**	14. The global stocktake shall: a) Recognize adaptation efforts of developing country Parties; b) Enhance the implementation of adaptation action taking into account the adaptation communication; c) Review the adequacy and effectiveness of adaptation and support provided for adaptation; and d) Review the overall progress made in achieving the global goal on adaptation.

Loss and damage: **Article 8**	1. Parties recognize the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events and slow onset events, and the role of sustainable development in reducing the risk of loss and damage. 2. The Warsaw International Mechanism for Loss and Damage associated with climate change impacts shall be subject to the authority and guidance of the Conference of the Parties serving as the meeting of the Parties to this Agreement and may be enhanced and strengthened… 4. …areas of cooperation and facilitation to enhance understanding, action and support may include: a) Early warning systems; b) Emergency preparedness; c) Slow onset events; d) Events that may involve irreversible and permanent loss and damage; e) Comprehensive risk assessment and management; f) Risk insurance facilities, climate risk pooling and other insurance solutions; g) Non-economic losses; and h) Resilience of communities, livelihoods and ecosystems…
Scaled up financial support: **Article 9(4)**	The provision of scaled-up financial resources should aim to achieve a balance between adaptation and mitigation, taking into account country-driven strategies, and the priorities and needs of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change and have significant capacity constraints, such as the least developed countries and small island developing states…
Public participation and access to information: **Article 12**	Parties shall cooperate in taking measures…to enhance …public awareness, public participation and public access to information, recognizing the importance of these steps with respect to enhancing actions under this Agreement
Transparency: **Article 13**	1. In order to build mutual trust and confidence and to promote effective implementation, an enhanced transparency framework for action and support…is … established. 5. The purpose of the framework for transparency of action is to provide a clear understanding of climate change action in the light of the objective of the Convention as set out in its Article 2, including clarity and tracking of progress towards achieving Parties' individual [NDCs], and Parties' adaptation actions under Article 7, including good practices, priorities, needs and gaps, to inform the global stocktake... 6. The purpose of the framework for transparency of support is to provide clarity on support provided and received by relevant individual Parties …and, to the extent possible, to provide a full overview of aggregate financial support provided, to inform the global stocktake...
The global stocktake: **Article 14(1)**	1. The Conference of the Parties serving as the meeting of the Parties to this Agreement shall periodically take stock of the implementation of this Agreement to assess the collective progress towards achieving the purpose of this Agreement and its long-term goals…It shall do so in a comprehensive and facilitative manner, considering mitigation, adaptation and the means of implementation and support, and in the light of equity and the best available science.

Chapter 3: Understanding the impacts of climate change for fisheries and aquaculture: global and regional supply and demand trends and prospects

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KEY MESSAGES

- Fisheries and aquaculture play a key role in provision of food security and livelihoods of millions of people for their social, economic and nutritional benefits.
- The sector is crucial in numerous coastal, riverine, insular and inland regions, with fishing- and aquaculture-dependent people often located in places that are at particularly high risk of extreme events.
- There has been a major expansion in fish production, trade and consumption over the last decades, but more recently, while still expanding, a slowdown in growth rates is being experienced.
- The sector is globalized through trade, but production (especially in the case of inland fisheries and aquaculture) is concentrated in certain countries/regions.
- Developing countries, in particular in Asia, have a growing share of production and trade, with a high percentage of small-scale/artisanal fishers and fish farmers playing a part.
- Fish plays a major role as a source of nutrients and micronutrients.
- Fish is highly traded in different product forms, with trade relevant as an income generator and for broadening fish consumption.
- Climate change is expected to have geopolitical and economic consequences, with influences on food security.
- A scenario prepared to analyse the potential future development of food and agricultural markets indicates that population growth is expected to put pressure on fish markets and lead to higher food fish prices.
- Higher prices should have a detrimental effect on fish consumption, with an overall decrease in per capita food fish consumption at world level; at the same time higher prices should stimulate those that earn income from fisheries and aquaculture to increase their productivity and efficiency.

3.1 INTRODUCTION

This chapter is structured into three main sections that explore 1) the global overview on the role of fish[1] in food security through an analysis of the current main trends in the fisheries and aquaculture sector; 2) the possible impacts of climate change on fish consumption and trade; and 3) the prospects for fish demand, prices and net trade to 2050.

3.2 ROLE OF FISH IN FOOD SECURITY

Food security exists when "all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Fisheries and aquaculture contribute in a significant way to food security and to the livelihoods of millions of people, as a creator of employment, supplier of nutritious food, generator of income and economic growth through harvesting, processing and marketing fish. Several countries, including many less advanced economies, depend on these sectors for their social, economic and nutritional benefits. The maps shown in Figure 3.1A–H provide an overview of the key players according to the different components of the sector[2]. Detailed information on fisheries and aquaculture production (Table 3A); fisheries and aquaculture production by FAO major fishing areas (Table 3B); apparent food fish consumption (Table 3C); and trade in fish and fish products (Table 3D) is presented at the end of this chapter.

Although fisheries and aquaculture may represent a limited share of the overall national economy or labour force (Figure 3.1D) and the consumption of their products can be small compared to other food at national level, they can be crucial for numerous coastal, riverine, insular and inland regions, including many small islands developing states (SIDS), which depend heavily on these sectors. Most of the people directly employed, on a full-time, part-time or occasional basis, as fishers and fish farmers (about 60 million people in 2016, of whom 32 percent – or over 19 million people – are engaged in aquaculture) are artisanal and small-scale producers, with the bulk of them in Asia (85 percent in 2016). Worldwide, about 200 million people are directly and indirectly employed along the value chain, from harvesting to distribution. Women play an important role in this workforce and represent about 14 percent of the people employed in the primary sector (FAO, 2018) and half of them if the secondary sector is included (Montfort, 2015). These activities support the livelihoods of many additional millions of people, with fishing-dependent people often located in places that are at particularly high risk of extreme events.

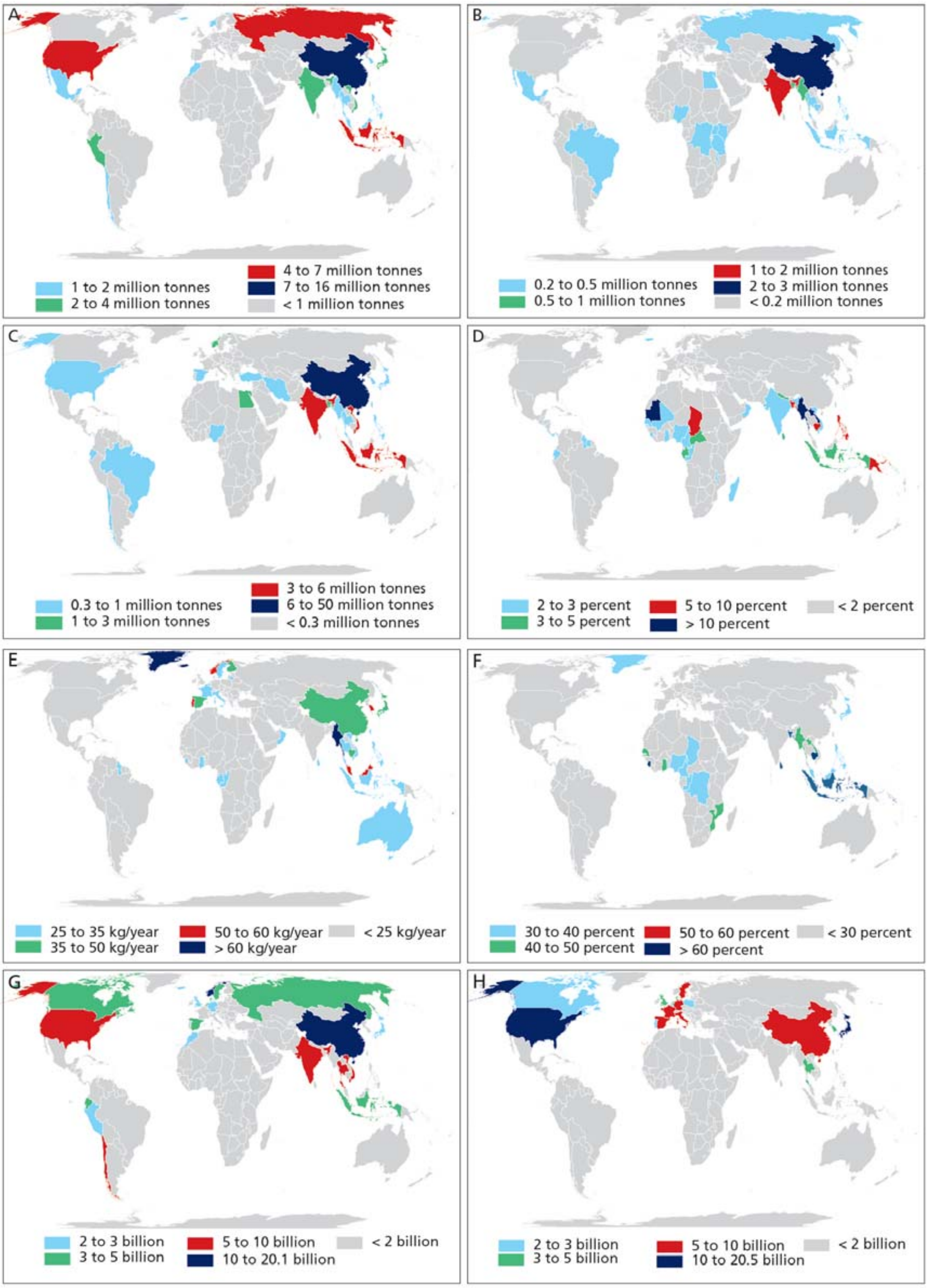
The fishery and aquaculture sectors have been significantly expanding in recent decades, with an increase in overall production, trade and consumption (Table 3.1 and Figure 3.2). This expansion has been characterized by many transformations, including changes in the source of fish production, being increasingly dependent on aquaculture, and in the key producers and traders, with a consistent growth of the role of developing countries in these sectors.

[1] Unless otherwise specified, throughout this chapter, the term "fish" indicates finfish, crustaceans, molluscs and other aquatic animals (including sea cucumbers, sea urchins, sea squirts and jellyfish), but excludes aquatic mammals, reptiles, seaweeds and other aquatic plants. In this chapter, the term "food fish" refers to fish destined for human consumption, thus excluding fish for non-food uses. The source of fisheries and aquaculture data, if not otherwise stated, is FAO. Information on the different formats, tools and products through which users can access FAO fisheries and aquaculture statistics is available at: http://www.fao.org/fishery/statistics

[2] A limited but consistent number of countries is presented in each map. Their respective shares compared to the world differ because of the different levels of concentration present in production or trade.

FIGURE 3.1A–H

Key players in the fisheries and aquaculture sectors



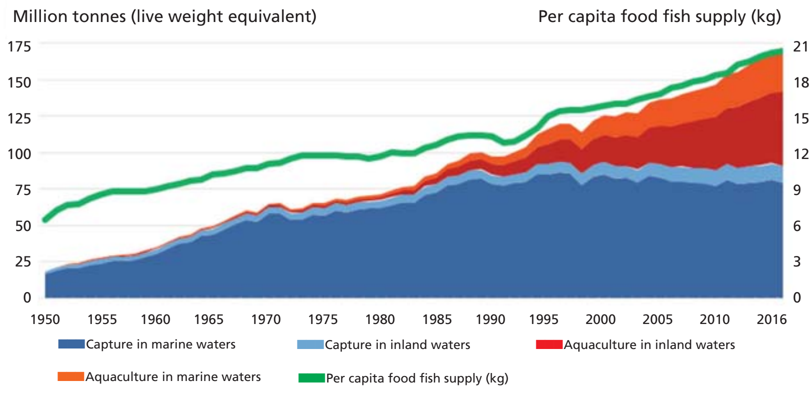
A: Capture fisheries production in marine waters by top producers* – over 1 million tonnes – in 2016. *Representing 74 percent of the world total.
B: Capture fisheries production in inland waters by top producers* – over 0.2 million tonnes – in 2016. *Representing 82 percent of the world total.
C: Aquaculture production by top producers* – over 0.3 million tonnes – in 2016. *Representing 95 percent of the world total.
D: Share of employment of fishers and fish farmers in total labour population – over 2 percent – in 2016. Source of Labour population: World Bank.
E: Per capita fish consumption by top consumers – over 25 kg/year – in 2013.
F: Contribution of fish to animal protein supply, share – over 30 percent – in 2013.
G: Top exporters* of fish and fish products – over USD 2 billion – in 2016. *Representing 76 percent of the world total.
H: Top importers* of fish and fish products – over USD 2 billion – in 2016. *Representing 78 percent of the world total.
Note: due to the typology and size of the maps, the role of SIDS is not fully represented in the figure.
See footnote 2 for the approach followed in the number of countries shown in the maps.

TABLE 3.1
World trends in fisheries and aquaculture

	Average							
	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2015	2016
	Million tonnes (live weight equivalent)							
Total production	**26.8**	**49.0**	**66.4**	**85.9**	**110.7**	**134.3**	**158.5**	**170.9**
Capture fisheries	**25.6**	**47.0**	**62.9**	**77.8**	**88.9**	**90.8**	**90.7**	**90.9**
Inland waters	2.6	3.8	4.9	5.7	7.1	9.3	11.1	11.6
Marine waters	23.0	43.2	58.0	72.1	81.9	81.6	79.5	79.3
Aquaculture	**1.1**	**1.9**	**3.5**	**8.1**	**21.8**	**43.5**	**67.8**	**80.0**
Inland waters	0.6	0.9	1.7	4.6	12.6	25.7	43.0	51.4
Marine waters	0.6	1.0	1.8	3.5	9.2	17.7	24.9	28.7
Trade volume	**…**	**…**	**…**	**26.1**	**39.3**	**51.4**	**58.7**	**59.1**
Share of trade as a percentage of total production	*…*	*…*	*…*	*30%*	*36%*	*38%*	*37%*	*35%*
Utilization of fish production	**26.8**	**49.0**	**66.4**	**85.9**	**110.7**	**134.3**	**158.5**	**170.9**
Human consumption	22.2	32.8	46.4	60.6	81.8	109.2	137.8	151.2
Non-food uses	4.6	16.2	19.9	25.3	29.0	25.1	20.7	19.7
	kg (live weight equivalent)							
Per capita food fish consumption	**8.1**	**9.9**	**11.5**	**12.5**	**14.3**	**16.8**	**19.3**	**20.3**
From capture	7.7	9.3	10.7	10.9	10.5	10.1	9.8	10.8
From aquaculture	0.4	0.6	0.9	1.6	3.8	6.7	9.5	9.6

Excluding whales, seals, other aquatic mammals and aquatic plants. Totals may not match because of rounding.

FIGURE 3.2
World fisheries and aquaculture production and apparent consumption



Note: Excluding whales, seals, other aquatic mammals and aquatic plants. Per capita food fish supply on secondary vertical axis (at right).

3.2.1 Production

Total fisheries and aquaculture production reached an all-time record in 2016 at about 171 million tonnes (Table 3A), of which 53 percent was from capture fisheries and 47 percent from aquaculture. Of this total, 108 million tonnes were produced in marine waters (73 percent from capture fisheries and 27 percent from aquaculture) and 63 million tonnes in inland waters (82 percent from aquaculture and 18 percent from capture fisheries). The total first sale value of fisheries and aquaculture production in 2016 was estimated at USD 362 billion of which USD 232 billion was from aquaculture production.

Being the main source of production (46 percent in 2016, but 87 percent in the 1950 to 1980 period), capture fisheries in marine waters have always played a key role in the sector and are very relevant to the economy and well-being of coastal communities and the dominant method of production for a number of species. At a global level, after several decades of sustained growth, marine capture fisheries have been rather stable since late 1980s at around 80 million tonnes, with some interannual fluctuations in the range of three to four million tonnes higher and lower.

During recent decades, a growing share of capture fisheries production in marine waters has been caught by developing countries (from 29 percent in the 1950s to 71 percent in 2016). In 2016, Asian countries were the main producers, accounting for 54 percent, followed by countries in North and South America (20 percent) and Europe (17 percent). China was the major national producer followed by Indonesia, the United States of America, the Russian Federation and Peru (Figure 3.1A). These five countries were responsible for about 44 percent of the world's capture fisheries production in marine areas in 2016. A large number of species are caught every year, with the number and specific species varying from region to region. In 2016, finfish represented 84 percent of the total production in marine capture fisheries, with small pelagics as the main group.

Major differences can be noticed when analysing the harvest of marine capture fisheries by FAO major fishing areas (Table 3A). While in the 1950s more than 50 percent of the production was caught in the Atlantic Ocean, in the last decade the largest share of marine capture fisheries production originated from the Pacific (60 percent as average in 1996 to 2016), with the Northwest Pacific as the main fishing area in 2016, followed by the Western Central Pacific, Northeast Atlantic, eastern Indian Ocean and the Southeast Pacific. In recent years, while catches in the Northwest Pacific and Northeast Pacific have shown an increasing trend, those in other temperate areas have experienced a declining trend for several years. A decrease in catches by distant-water fishing nations produced a recent contraction in production in the Southwest Atlantic and the Southwest Pacific. Catches in tropical areas have experienced a growing trend, mainly due to increase in production of large and small pelagics (FAO, 2018).

Production differs from area to area as a result of several factors, including the level of development of the countries surrounding those areas, the fisheries management measures being adopted, the composition of the species being caught, the amount of the illegal, unreported and unregulated (IUU) fishing, as well as the status of stocks. For example, for some fishing areas, annual variations are the result of the high proportion of small pelagic fish in total catches, which are prone to large fluctuations, and can also be particularly affected by climatic variability and change, as for example with catches of anchoveta (*Engraulis ringens*) off South America. As for the status of resources, on the basis of FAO's analysis of assessed commercial marine fish stocks (FAO, 2018), the share of fish stocks estimated as being fished at biologically unsustainable levels has been increasing in recent decades, from 10 percent in 1974 to 33.1 percent in 2015. This increase has occurred despite notable progress in achieving sustainable fisheries experienced in some areas and fisheries thanks to stricter management measures, which have allowed the recovery of certain stocks. Conversely, the fish stocks fished within biologically sustainable levels have declined from 90.0 percent in 1974 to 66.9 percent in 2015, of which about seven percent are underfished. While the underfished stocks declined constantly from 1974 to 2015, the maximally sustainable fished stocks declined from 1974 to 1989, and increased to 59.9 percent in 2015. In 2015, among the 16 major fishing areas assessed, the Mediterranean and Black Sea, Southeast Pacific and Southwest Atlantic had the highest percentages of stocks fished at unsustainable levels, whereas the Eastern Central Pacific, Northeast Pacific, Northwest Pacific, Western Central Pacific and Southwest Pacific had the lowest (FAO, 2018). The scope for discovery of new fisheries resources seems very limited and, therefore, it is not expected that production from capture fisheries in marine waters will increase unless proper management of resources allows overfished stocks to recover and ensures that all stocks are exploited at levels of fishing that maximize sustainable yields. However, many other factors are also affecting the sustainability of the resources, ranging from habitat destruction, overfishing, eutrophication, acidification of the water, pollution, species introductions and other human interventions (transportation, oil and gas extraction, etc.), all of which interact with climate change and can impact the future of the sector.

Even if representing only 13 percent of capture fisheries production and seven percent of total fisheries and aquaculture production in 2016, capture fisheries in inland waters represent an important sector in many countries and regions, especially in land-locked countries and low-income countries, where this production represented 75 percent and 49 percent, respectively, of their total fishery and aquaculture output in 2016 (Table 3A). Particularly in these countries, this sector plays a key role in food security and poverty alleviation, sustaining the livelihoods of many communities, especially those living near lakes and rivers, and represents an important, and in some cases essential, source for domestic fish consumption. With the exception of a few fisheries oriented for export purposes, most of the production from inland waters is of a small-scale nature, including many subsistence fisheries, the products of which are consumed locally, with 95 percent of the inland fishery production being harvested by developing countries. Despite the sector being increasingly exposed to environmental pressures including water abstraction and poor water quality, damming, over-exploitation and pollution, inland catches increased at an annual growth rate of 1.7 percent during the last decade to peak at 11.6 million tonnes in 2016, in part as a result of stock enhancement practices such as stocking. This general trend masks considerable variations between continents, regions and countries, with more sustained growth being experienced in Asia, Africa and Central America. In 2016, Asia confirmed its key role, accounting for 66 percent of world inland fisheries catches, while Africa had a share of 25 percent. China is by far the major producer, with a share of about 20 percent of total production in 2016, followed by India (13 percent), Bangladesh (9 percent) and Myanmar (8 percent) (Figure 3.1B). Overall, in 2016, more than 82 percent of the production was concentrated in 18 countries, each with an annual output of over 150 000 tonnes. Finfish represented over 92 percent of the inland fisheries catches in 2016.

Despite the total increase of inland water catches, total production for inland fisheries is often considered to be underestimated, and thus undervalued, because of problems of unreporting and unreliability. (FAO, 2016; Welcomme, 2011). The lack of reporting is mainly caused by the diffuse and small-scale nature of inland fisheries, with most of the catches going directly into domestic consumption (Welcomme, 2011). It is also believed that while the increases in recorded catches experienced during the last decades in some individual fisheries are real, others are also the result of an improvement in reporting (Welcomme, 2011) and assessment.

With capture fisheries production having been relatively stable since the late 1980s, most growth in production from the sector as a whole has been from aquaculture, to peak at 80.0 million tonnes in 2016. Whereas aquaculture provided only four percent of total production in the 1950s, this share increased to 19 percent in the 1990s and to 47 percent[3] in 2016. Aquaculture in inland waters has been the major driver of growth of the sector, representing 64 percent of the total aquaculture production in 2016 (Table 3B). Asian countries, and in particular China, have played a major role in this growth and represented, respectively, more than 89 percent and 62 percent of world aquaculture production in 2016. Other major producers were India and Indonesia and

[3] If aquatic plants are included, aquaculture has overtaken capture fisheries production since 2013. In 2016, total aquaculture production of aquatic plants was 30.1 million tonnes, valued at USD 11.7 billion.

these three countries together represented 75 percent of global aquaculture production in 2016 (Figure 3.1C). Despite this concentration of production, aquaculture has experienced growth across the world, with the unequal rates reflecting differences in local policy, management objectives, site opportunities and environmental factors. Aquaculture production is highly diversified, with a large number of species cultured in fresh, brackish and marine environments for both domestic and export markets. In 2016, about 30 percent of aquaculture production consisted of non-fed species, a percentage that has been decreasing in the last decade. Although some higher value species such as shrimps and salmon are highly traded, a significant share of aquaculture consists of low-value freshwater species destined mainly for domestic consumption. In some rural areas, in particular in Asia, this activity is carried out by small-scale farmers, typically in ponds and in rice fields and often through integrated farming.

At world level, aquaculture has expanded and intensified at annual growth rates of 11.3 percent in the 1980s, 10.0 percent in the 1990s, but then slowing down to 6.2 percent in the 2000s and 5.2 percent in 2010 to 2016, even if still remaining one of the fastest growing food sectors in the world. This slowdown is because of a variety of factors, including increasing environmental regulation, animal diseases related to intensive production practices, a shortage of suitable new production locations, and a contraction of demand in key markets.

3.2.2 Utilization and consumption

Fish production is very heterogeneous in terms of species and product forms, with marked differences within and between continents, regions, and countries in utilization for both food and non-food purposes and in the processing methods. In recent decades the share utilized for direct human consumption has increased significantly, up from 67 percent in the 1960s to 88 percent (or over 151 million tonnes) in 2016. The remaining 20 million tonnes in 2016 was destined for non-food products, of which 74 percent was for the manufacture of fishmeal and fish oil, while the rest was utilized for other purposes.

An important role for fish and fish products in global food security is in nutrition as they are important sources of nutrients and micronutrients such as vitamins, minerals (zinc, iron, iodine and selenium) and omega-3 fatty acids. Even small quantities of fish can provide a significant positive nutritional impact compared to plant-based diets, or where the total protein intake level is low. This is often the case in many low-income food-deficit countries (LIFDCs) and least-developed countries. Fish proteins are very important in the diets of many other countries, and essential in many, particularly SIDS, where fish is often the most important source of dietary proteins. At the global level, fish accounts for about 17 percent of the world population's intake of animal proteins, but this share can be 50 percent or higher in some SIDS, as well as in Bangladesh, Cambodia, the Gambia, Ghana, Indonesia, Sierra Leone and Sri Lanka (Figure 3.1F). World apparent food fish consumption[4] has increased remarkably during the last six decades outpacing population growth (3.2 percent per year vs 1.6 percent from 1961 to 2016), with per capita fish consumption going from 9.0 kg in 1961[5] to 20.3 kg in 2016, with a slight slowdown of growth being experienced in the last few years. The expansion in demand has been driven by a combination of population growth, rising incomes and urbanization, and facilitated by the strong expansion of food fish production, reductions in wastage, improved and more efficient processing, storage and distribution channels.

[4] Food fish consumption is calculated in live weight equivalent as production, minus non-food uses and exports, plus imports and plus/minus stocks. It refers to the apparent consumption, i.e. the amount available to be consumed, which for a number of reasons (including waste at the household level) is not equal to food intake.

[5] 1961 is the first year for which FAO data on food balance sheets for fish and fishery products are available.

Despite the overall increase in the availability of fish to most consumers, marked differences exist between and within countries and regions in terms of quantity and variety consumed at per capita level and the subsequent contribution to nutritional intake. For total food fish supply, Asia consumes more than two-thirds of the total, while Oceania and Africa have the lowest share. Nevertheless, although annual per capita food fish consumption has grown steadily in developing regions and in LIFDCs, it is still considerably lower than in more developed regions (Table 3C). A growing share of food fish consumption originates from aquaculture production, with a milestone reached in 2013 when the aquaculture sector's contribution to the supply of fish available for human consumption overtook that of wild-caught fish for the first time. In 2016, the share of aquaculture products in total food fish available for human consumption was 53 percent.

As a result of the high geographical concentration of production, international trade has played an important role in broadening fish consumption by providing wider choices to consumers and creating global markets for several species. A sizeable and growing share of food fish consumed in Africa (about 40 percent) and in North America and Europe (over 70 percent) consists mainly of imports, owing to steady demand, including for non-locally produced species, accompanied by static or declining domestic fish production. Notwithstanding the statistics for Africa, overall in developing countries, fish consumption tends to be based on locally available products and be driven more by supply than by demand. However, fueled by rising domestic income, consumers in emerging economies are experiencing a diversification in the types of available fish through an increase in fishery imports.

3.2.3 Trade

A sizeable share of total fish production (about 35 percent, live-weight equivalent in 2016) is exported, reflecting the sector's degree of openness and integration into international trade. It is estimated that some 78 percent of fish and fish products are exposed to international trade competition (Tveterås *et al.*, 2012). Fish and fishery products are among the most traded food commodities worldwide, with a wide range of species, increasingly including farmed ones, and products being exported. The fisheries and aquaculture sectors operate in an increasingly globalized environment, with fish that can cross national boundaries several times before final consumption, being produced in one country, processed in a second and consumed in a third. Trade of fish and fish products has increased remarkably in recent decades along with increases in production and demand and more efficient processing methods and improved distribution channels. From a mere USD 8 billion in 1976, fishery trade peaked at USD 148 billion in 2014 and it is expected to have reached a new record at about USD 152 billion in 2017, with a growth of seven percent over the USD 143 billion in 2016. However, during the last few years, trade of fish and fish products has experienced reduced growth rates and declined in 2009 and 2015. This slowdown is not an isolated phenomenon as it is also occurring in agriculture and global merchandise trade.

In 2016, developing countries had a share of 54 percent in total fish export trade value and about 59 percent in quantity (live weight equivalent) (Table 3D). Their fish net-export revenues (exports minus imports) are higher than those of all other agricultural commodities combined. In addition, in recent years, developing countries have increased imports of fish and fish products to supply their processing sectors for further re-export and to meet rising domestic consumption. Developed countries have always dominated fish imports, although with a declining share in recent years (88 percent share of world imports in 1976 and 71 percent in 2016). Their imports originate from both developed and developing countries and shape the market, giving many producers an incentive to produce, process and export. Since 2002, China is the leading exporter of fish and fish products and since 2011 the third main importer. In

2016, other major exporters were Norway, Viet Nam and Thailand (Figure 3.1G). The European Union represents the largest single market for fish and fish products, followed by the United States of America and Japan (Figure 3.1H). In 2016 their combined imports accounted for about 64 percent of total import value of fish and fish products. In terms of net trade, Oceania, the developing countries of Asia and the Latin America and the Caribbean region are net fish exporters. Europe and North America are characterized by a fish trade deficit, while Africa is a net importer in volume terms but a net exporter in terms of value (Table 3D), reflecting the higher unit value of exports. Table 3.2 provides an overview of the trade flows for import values (in percentages) by continent and regions.

TABLE 3.2
Trade flows of imports of fish and fish product by partners – 2016 values (percentage)

	Partners					
Importers	**Africa**	**Asia**	**Europe**	**Northern America**	**Latin America & Caribbean**	**Oceania**
Africa	27	26	37	1	7	2
Asia	4	50	19	12	11	4
Europe	8	14	63	5	9	1
Northern America	1	48	10	19	21	2
Latin America & Caribbean	2	31	8	7	51	1
Oceania	2	68	9	4	4	13

Many factors affect trade of fish and fish products, including import tariffs (usually lower in developed countries because of their dependence on imports to satisfy domestic consumption, but still high in many developing countries), non-tariff measures, market-based measures such as ecolabels or trade-tightening policies such as import regulations to prevent IUU fish entering markets.

3.3 POSSIBLE KEY IMPACTS OF CLIMATE CHANGE ON FISH CONSUMPTION AND TRADE

Several chapters of this publication analyse the expected impact of climate change on fish supply, an impact that is complex to determine and is affecting different regions with varying intensity and characteristics. In addition, climate change is expected to have different typologies of consequences, with influences not only on fish supply. The impacts can be particularly relevant for those countries more dependent on fisheries and aquaculture and which could be vulnerable because of the important contribution of these sectors to employment, supply, income and nutrition in those countries.

Climate change is expected to have an effect on availability and circulation of goods from aquatic production, with the distribution of several species predicted to change as a result of changing conditions. These shifts in species may affect the accessibility to fish resources, in particular for small-scale fishers, the fishing techniques and practices applied and as a consequence the nutritional habits of local communities, as well as the practices of producers, exporters and consumers. The changes in distribution of fish resources can also put international fisheries agreements and governance under pressure. Trade and its patterns can also be impacted, having consequences for countries more dependent on trade in fish and fish products for tax revenues and foreign exchange earnings, and with a potential impact on their food security. Consumption can also be affected by these shifts either in a positive or negative way, by making available on domestic markets species more or less favoured by local consumers. The repercussions on consumption are expected to be more serious for communities dependent on fishing and aquaculture, which rely on fish for food and livelihoods (Barange *et al.*, 2014) and in particular for those living near climate-sensitive environments like low-lying coastal areas and water-stressed regions. The consequences could be exacerbated in cases of dependency on certain species impacted by climate change, for consumption or export, in particular in the absence of support through targeted policies on adaptation to climate variability and change.

Climate change is expected to alter aquatic food prices, by affecting not only the availability of aquatic resources and the global supply, but also the cost of goods, infrastructure and services required in aquatic food production, processing and distribution activities. It has been estimated that the projected changes in temperature and precipitation on food production will contribute to an increase in global food prices by 2050 (Porter *et al.*, 2014). For example, the highest emission scenario studied in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) has been estimated to increase crop prices by between two percent and 35 percent when compared to a no-climate change scenario in 2050 (Nelson *et al.*, 2014). This could be applicable to fish prices as well, especially in the case of reduced availability in domestic markets or as a consequence of shocks caused by unexpected extreme events. Higher fish prices can weaken demand and consumption of these products, which could have a major impact on food security and malnutrition, particularly among the most vulnerable households. In the case of countries dependent on imports for their consumption, higher prices could reduce demand, in particular among less affluent consumers.

3.4 PROSPECTS FOR FISH DEMAND, PRICES AND NET TRADE TO 2050

The future evolution of the fisheries and aquaculture sector is also very much linked to challenges posed to food systems, not only by climate change, but also by socio-economic trends. The world population is expected to reach nearly 10 billion people in 2050, a trend that, on its own, raises concerns about how to feed the world in the future. At the same time income growth in low- and middle-income countries may well imply dietary changes towards higher consumption of animal protein and thus of fish and fish products. Moreover, structural changes in the economy (e.g. variations in the relative importance of the sectors, reallocation of production factors across sectors and geographic areas and changes in their productivity), together with urbanization and migration, challenge food systems further because they imply modifications in consumption patterns, in the way food chains are organized (e.g. higher demand for processed food) and to distribution channels.

In order to understand future trends better and help to address forthcoming challenges, forward-looking studies can be useful to provide insights on the likely paths of development and constraints in food supply and demand, and to determine regional vulnerabilities and changes in comparative advantages in trade and price effects.

3.4.1 Scenario assumptions and methodology

In this report, a scenario was prepared to analyse a potential future development in fish demand, prices and trade by 2050 and to sketch challenges for the fisheries and aquaculture sectors if the future evolves according to socio-economic, technological and environmental trends similar to those that have been exhibited historically.

The global population is expected to grow, albeit at slower growth rates than in the past 50 years, by some 2.3 billion people by 2050 and to reach 9.7 billion people, as Table 3.3 suggests (UN DESA, 2015). High-income countries are expected to reach their maximum population size by 2040 and to maintain it thereafter, whereas low- and middle-income countries would see a slowdown in their population increase after 2050. Asia, the most populous continent, is expected to reach its population peak between 2050 and 2060. The only region where the maximum population size should not be reached within this century is Africa. While the region's growth rate will continue to decelerate, its population is expected to reach more than 2.2 billion by 2050 and is set to continue to expand beyond the end of the twenty-first century.

TABLE 3.3
Population by region and income group

	Billion people			Average annual growth rate (percent)	
	2012	2030	2050	2013 to 2030	2031 to 2050
High-income	1.2	1.3	1.3	0.4	0.1
East Asia & Pacific (EAP)	2.0	2.2	2.2	0.5	0.0
EAP excluding China	0.6	0.8	0.8	0.9	0.4
China	1.4	1.4	1.3	0.2	-0.2
South Asia	1.7	2.1	2.3	1.2	0.6
East Europe & Central Asia	0.4	0.4	0.4	0.2	-0.1
Latin America & Caribbean	0.6	0.7	0.8	0.9	0.4
Near East & North Africa	0.3	0.5	0.6	1.6	1.0
sub-Saharan Africa	0.9	1.5	2.2	2.5	2.1
World	**7.1**	**8.5**	**9.7**	**1.0**	**0.7**

Note: countries are grouped into high and middle and low-income ones based on the World Bank July 2016 list of economies. Low- and middle-income countries are arranged into geographic groups. Data for China do not include data for Taiwan Province of China.
Source: FAO global perspectives studies, based on data from UN DESA, 2015.

Economic growth follows the so-called SSP3[6] scenario (Table 3.4), in which global GDP grows at an annual rate of 2.2 percent between 2012 and 2050 (Shared Socioeconomic Pathways, 2016). In this scenario, high-income countries are assumed to see the smallest increase in their GDP per capita, whereas Asia and in particular China, the highest. Despite their relatively higher economic growth, none of the low- and middle-income countries are assumed to reach levels of GDP per capita similar to those that high-income countries have currently. This alone suggests that convergence between the low- and middle-income countries and the high-income ones will be only modest, implying that no significant change in current consumption patterns is assumed to occur throughout the simulation period.

TABLE 3.4
GDP per capita, per region and income group

	GDP per capita (USD at 2012 exchange rates)			Average annual growth rate in GDP per capita (percent)	
	2012	2030	2050	2013 to 2030	2031 to 2050
High-income	41 688	55 178	66 319	1.6	0.9
East Asia & Pacific (EAP)	5 331	13 655	17 880	5.4	1.4
EAP excluding China	3 368	6 841	9 757	4.0	1.8
China	6 262	17 319	22 895	5.8	1.4
South Asia	1 391	2 840	3 877	4.0	1.6
East Europe & Central Asia	9 336	16 276	20 613	3.1	1.2
Latin America & Caribbean	9 647	14 178	16 795	2.2	0.9
Near East & North Africa	4 698	7 523	10 233	2.7	1.6
sub-Saharan Africa	1 740	2 807	3 829	2.7	1.6
World	**10 467**	**15 138**	**17 349**	**2.1**	**0.7**

Source: FAO global perspectives studies, based on data from the system of national accounts, for the periods 1990 to 2013 (UN, 2016); the SSP database version 1.1, OECD projections of GDP (Shared Socioeconomic Pathways, 2016).

[6] SSP = shared socioeconomic pathway

The impacts of climate change, and demand and supply drivers on food and agriculture[7] were simulated with the model Global Agriculture Perspectives System (GAPS)[8]. GAPS identifies fish and fish products as a separate commodity, sourced from capture and aquaculture sectors combined, and it only takes into consideration the amount utilized for human consumption.

Projections of aquaculture production up to 2026 rely on the projections included in the *OECD-FAO Agricultural Outlook 2017-2026* publication (OECD–FAO, 2017), while for subsequent years up to 2050, supplies were calculated by applying gradually slowing down annual average growth rates in line with the 2012 to 2026 trends. Regarding capture fisheries, changes in potential catch of fish by 2050 in all exclusive economic zones (EEZ) were based on updates from Cheung *et al.* (2010) according to the emission scenario representative concentration pathway (RCP) 8.5. The percentage variations between 2000 and 2050 were first translated into changes per country according to the size of each EEZ, and assumed to be distributed evenly to all years between 2012 (the base year used in the report) and 2050 through linear interpolation. The combined production data indicate that major growth in the sector is expected to originate from aquaculture.

3.4.2 Food and fish demand

Per capita food consumption depends on income and prices and is subject to historical trends on food mix preferences. High-income countries are projected to expand their per capita DEC at a slower pace than in the past 50 years and to reach saturation levels similar to those projected in Alexandratos and Bruinsma (2012), whose projections were anchored around similar assumptions on population and economic growth, that is to slightly below 3 500 kcal/person/day in 2012 (FAO *et al*., 2017). In low- and middle-income countries, per capita calorie consumption is expected to grow until 2030 at a faster pace than in high-income countries given their higher per capita economic growth (Table 3.4) and to reach levels as in Alexandratos and Bruinsma (2012), who projected their calorie intake to reach nearly 3 000 kcal/person/day by 2050.

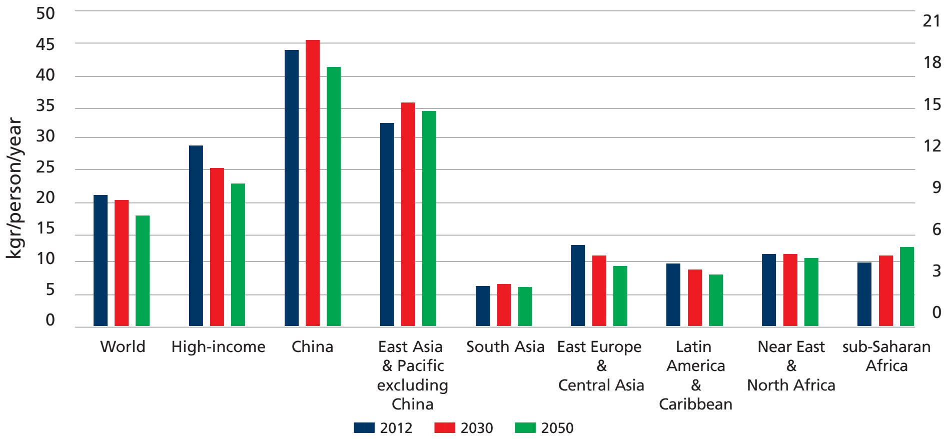
Globally annual per capita food fish consumption is projected to decrease slightly although at the very slow pace of 0.5 percent per year between 2012 and 2050 (from 21 kg/person in 2012 to 18 kg/person in 2050). However, notable differences are expected between regions, and according to the time period, as shown in Figure 3.3.

High-income countries are projected to see a decline of per capita food fish demand of 0.6 percent per year between 2012 and 2030, a result that is in line with the evolution of consumption of animal products and of continuation of historical preferences when it comes to the food mix. FAO (2017) suggests that there is already a dietary shift to less animal-based products and to more fruit and vegetables.

[7] The term agriculture is meant in a broader sense and it refers to crop, livestock, fisheries and forestry activities that are relevant for food production.

[8] Version 1.0 of this model is described in Kavallari *et al*. (2016) but is different from the one used in this report regarding the countries, commodities and activities covered and the way food demand is represented.

FIGURE 3.3
Actual (2012) and simulated (2030, 2050) per capita food fish consumption



Source: FAO Global Perspectives Studies based on simulations with the GAPS model.

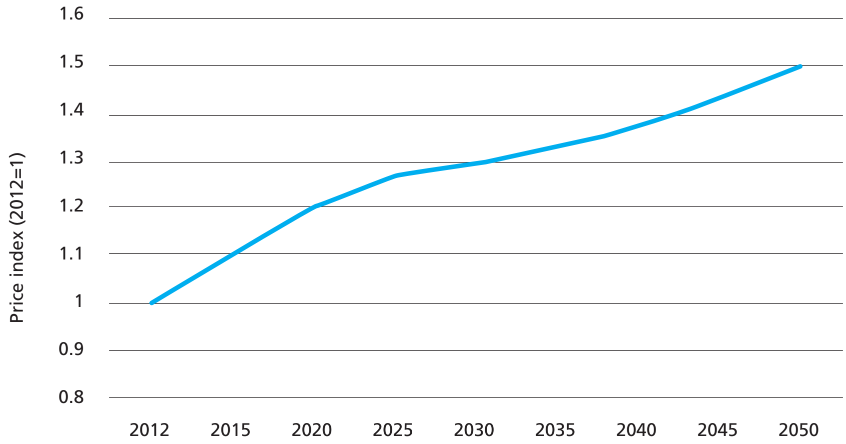
In low-and middle-income countries food fish consumption is expected to increase between 2012 and 2030 motivated by the income growth (Table 3.4). Only in regions where consumer preferences are more oriented towards meat consumption instead of fish, such as Latin America and Eastern Europe and Central Asia, a small decrease in per capita food fish intake of around ten percent is projected. China, as well as East Asia and the Pacific, are expected to increase their food fish intake the most when compared to the rest of the world and are projected to reach an annual per capita food fish consumption of some 46 kg and 36 kg, respectively, in 2030. The period 2030 to 2050 is assumed to be characterized by a slower income growth in all regions allowing price increases to be felt more and to counteract the positive effects that income growth during 2030 to 2050 has on per capita food demand. As a result, per capita food fish consumption is expected to drop during this period in all regions between four percent (in East Asia and Pacific excluding China) and 14 percent (in Eastern Europe and Central Asia) with the exception of sub-Saharan Africa. Consumers in sub-Saharan African countries are assumed to be more reactive to income changes than in other regions and so income growth leads to a slight increase of animal protein intake, including fish.

3.4.3 Prices and trade

Despite the small decrease in the per capita food fish consumption worldwide expected by 2050, population growth is anticipated to add substantial pressure in markets and generate an overall increase of demand for food fish products[9]. Higher demand is expected to lead to a growth of world market prices (Figure 3.4). While the higher prices should have a detrimental effect on food fish consumption for consumers more reactive to price changes, at the same time they should stimulate people that earn income from fisheries and aquaculture to increase their productivity and efficiency. The increase of prices is projected to slow down after 2025, following the slowdown in population growth.

[9] Other demands for fish are for non-food purposes, such as for example pharmaceutics, but being negligible compared to food demand, are not analysed in the fish scenario. Fishmeal and fish oil, which are derived commodities when processing fish, are not considered.

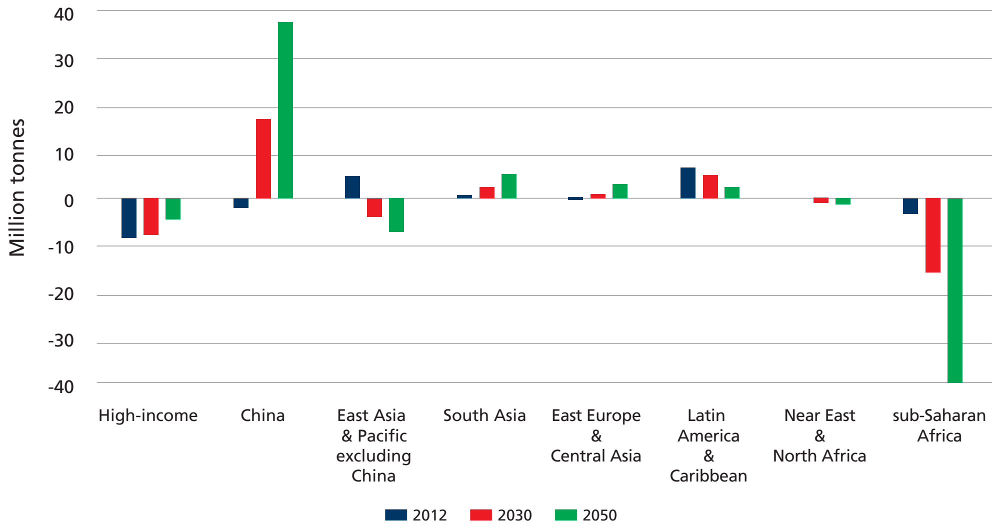
FIGURE 3.4
Simulated world fish price changes



Source: FAO Global Perspectives Studies based on simulations with the GAPS model.

Changes in demand, together with domestic supply, define the net international trade of food fish products of each country and region as illustrated in Figure 3.5.

FIGURE 3.5
Food fish: net trade position



Notes: net trade is given as supply minus aggregate demand; a positive (negative) value implies a net export (import) position.
Source: FAO Global Perspectives Studies based on simulations with the GAPS model.

Most notable are the opposite changes in the net food fish trade positions of China and of sub-Saharan Africa. The decrease in per capita food fish demand together with the slowdown of population growth is expected to result in a surplus in China and lead the country to become the largest net exporter of food fish products by 2050. sub-Saharan Africa is the region with the highest population expansion by 2050 and the only region with an expected increasing per capita food fish demand until 2050 because of the assumed income growth underlying the simulation. These developments lead to an increase of its food fish imports from three million tonnes in 2012 to almost 39 million tonnes in 2050. The East Asia and the Pacific region (excluding China) is projected to see its net trade position reversing, becoming a net food fish importer by the first half of the simulation period as a result of the expansion of its population and higher demand. Its net food fish imports are projected to increase further between 2030 and 2050 suggesting that domestic supply will not be sufficient to meet demand. This is, however, aligned with the price effects discussed above, given that the population in the region will grow (albeit at a slower rate during 2030 to 2050 than 2012 to 2030) resulting in higher food demand (despite reduced per capita fish consumption discussed in the previous section). Analogous are the effects in Latin America and the Caribbean although in this region the changes in food fish demand and supply are not projected to result in a change of the trade position from net exporter to net importer. All other regions, as a result of the slowdown of population growth and of per capita food fish demand, are projected to improve their food fish trade balances and see a reduction in their net imports and an increase of their net exports.

The above projections on fish demand, prices and net trade are based on specific assumptions including those on the future macroeconomic environment and population, absence of abnormal fish related disease outbreaks, a lack of market shocks and continuation of historical trends in food preferences. Should one of these assumptions change, the resulting fish projections would be affected. For example, the potential growth of per capita food fish consumption in sub-Saharan Africa described above will depend on the effective economic growth of the region. This will be a key factor to drive a substantial increase in its food fish imports, despite the expected increasing prices, which will be necessary to meet the potential additional demand. If this does not occur, there is likely to be an alarming risk in terms of food security because of the major role played by fish in the region through the provision of very valuable micronutrients and proteins.

3.5 CONCLUSIONS

The social and economic contributions of the fisheries and aquaculture sectors, including processing and trade, are relevant, complex, and growing. These sectors play a key role in world food security, as a source of nutritious food and as a contributor to economic growth and development, income and livelihood to millions of people. This role can be crucial at local or community levels, in particular for fishing and fish farming-dependent people living along coastal and other riparian land often located in places that are at particularly high risk of extreme events.

During the last six decades, the fisheries and aquaculture sectors have undertaken major changes in their structure and dynamics, and with an overall expansion in production, trade and consumption. The sustainability and productivity of these sectors face a number of challenges and, while still expanding, a slowdown in growth rates has been experienced in recent years. The future prospects of these sectors will depend on their capacity to deal with different challenges, both globally and locally, in terms of social and economic pressures on natural resources and ecosystems, including environmental degradation and, increasingly, water scarcity and quality, and availability of areas for aquaculture. Climate change and extreme weather events can be expected to act as a further source of specific challenges and compounding threats to the sustainability of aquaculture and of marine and inland fisheries. The impacts, both positive and negative, will depend on the region and latitude, and are expected to affect not only fish production but the entire value chain, with effects also on prices, trade and consumption of fish and fish products, by changing competitiveness and patterns. Climate-induced changes will require adaptation at all stages of the fisheries and aquaculture value chain, including the resilience of vulnerable coastal and riparian communities and their livelihoods to threats, from producers, processors, marketers, exporters, and importers as they search for supplies to meet the world's growing demand for fish and fish products.

Economic, demographic and policy factors will be crucial in shaping future demand, supply and consumption. Rising income levels and a growing global population that is increasingly urbanizing, especially in populous developing countries, will require a substantial expansion of production through the coming decades. In addition to increasing consumption levels, growing incomes and urbanization are also expected to generate changes in lifestyle habits and dietary structure, typically from a traditional staple-based diet to a more protein-rich, diversified diet, with fish potentially playing a major role in this regard. A scenario prepared to analyse the potential future development of food and agriculture indicates that population growth is expected to put pressure on fish markets and lead to higher fish prices. The price increases may become higher as altered by climate change, via changes in global and regional fish supply, and also via the cost of goods, infrastructure and services required for fishing and aquaculture. These higher prices risk weakening fish demand and consumption, which could have a major impact on food security and malnutrition of countries or populations dependent on these sectors, particularly among the most vulnerable households.

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TABLE 3A

Fisheries and aquaculture production in 2016

	Total fisheries and aquaculture production				Share of total production				Share of world total production
	Capture marine areas	Capture inland areas	Aquaculture production	Total production	Capture marine areas	Capture inland areas	Aquaculture production	Total production	
	Million tonnes (live weight)				Percentage				
World	**79.3**	**11.6**	**80.0**	**170.9**	**46.4**	**6.8**	**46.8**	**100.0**	**100.0**
Africa	**6.4**	**2.9**	**2.0**	**11.3**	**57.0**	**25.4**	**17.6**	**100.0**	**6.6**
Eastern Africa	0.6	1.4	0.2	2.2	28.6	62.3	9.1	100.0	1.3
Middle Africa	0.8	0.5	0.0	1.2	61.9	37.6	0.5	100.0	0.7
Northern Africa	1.8	0.3	1.4	3.4	51.5	8.1	40.4	100.0	2.0
Southern Africa	1.1	0.0	0.0	1.1	99.0	0.3	0.6	100.0	0.7
Western Africa	2.1	0.8	0.4	3.3	65.5	23.0	11.5	100.0	1.9
Americas	**15.7**	**0.6**	**3.3**	**19.6**	**79.9**	**3.1**	**17.1**	**100.0**	**11.5**
Northern America	6.0	0.1	0.6	6.7	89.6	0.8	9.6	100.0	3.9
Caribbean	0.2	0.0	0.0	0.3	86.6	1.4	12.0	100.0	0.2
Central America	1.7	0.2	0.4	2.3	74.8	9.0	16.1	100.0	1.3
South America	7.7	0.3	2.3	10.4	74.5	3.3	22.2	100.0	6.1
Asia	**42.5**	**7.7**	**71.5**	**121.8**	**34.9**	**6.3**	**58.8**	**100.0**	**71.2**
Central Asia	-	0.1	0.0	0.1	-	66.7	33.3	100.0	0.1
Eastern Asia	20.9	2.4	50.8	74.0	28.2	3.2	68.6	100.0	43.3
South-Eastern Asia	14.9	2.4	11.8	29.1	51.2	8.1	40.7	100.0	17.0
Southern Asia	5.8	2.8	8.5	17.2	33.7	16.5	49.8	100.0	10.0
Western Asia	1.0	0.1	0.4	1.4	68.8	4.7	26.5	100.0	0.8
Europe	**13.3**	**0.4**	**2.9**	**16.6**	**79.7**	**2.6**	**17.7**	**100.0**	**9.7**
Eastern Europe	4.7	0.4	0.3	5.4	87.5	6.5	6.0	100.0	3.2
Northern Europe	5.9	0.0	1.7	7.7	76.9	0.6	22.5	100.0	4.5
Southern Europe	1.4	0.0	0.6	2.1	69.6	0.8	29.6	100.0	1.2
Western Europe	1.1	0.0	0.3	1.5	79.2	1.8	19.0	100.0	0.8
Oceania	**1.4**	**0.0**	**0.2**	**1.6**	**86.1**	**1.1**	**12.8**	**100.0**	**1.0**
Australia & New Zealand	0.6	0.0	0.2	0.8	74.1	0.2	25.7	100.0	0.5
Melanesia	0.5	0.0	0.0	0.5	95.7	3.4	0.9	100.0	0.3
Micronesia	0.3	0.0	0.0	0.3	99.9	0.0	0.1	100.0	0.2
Polynesia	0.0	0.0	0.0	0.0	99.4	0.1	0.4	100.0	0.0
Developed countries	23.0	0.5	4.5	28.1	82.1	1.9	16.0	100.0	16.4
LDC	4.8	4.4	3.7	13.0	37.0	34.1	28.9	100.0	7.6
Other developing countries	51.4	6.7	71.8	129.9	39.6	5.1	55.3	100.0	76.0
LIC	1.5	1.8	0.3	3.6	42.9	49.3	7.9	100.0	2.1
LIFDC	8.2	5.2	8.8	22.2	37.0	23.3	39.7	100.0	13.0
LLDC	-	1.3	0.4	1.7	-	75.2	24.8	100.0	1.0
NFIDC	12.3	5.1	5.6	23.0	53.5	22.3	24.2	100.0	13.4
SIDS	1.6	0.0	0.0	1.7	95.9	1.3	2.8	100.0	1.0

LDC: Least developed countries;
LIC: Low-income countries;
LIFDC: Low-income food-deficit countries;
LLDC: Land-locked developing countries;
NFIDC: Net food-importing developing countries;
SIDS: Small island developing states.

TABLE 3B
Fisheries and aquaculture production by FAO major fishing areas

	Million tonnes					Share of world total (%)					Average annual rate of growth (%)			
	1950–1969	1970–1989	1990–2009	2010–2015	2016	1950–1969	1970–1989	1990–2009	2010–2015	2016	1950–1969	1970–1989	1990–2009	2010–2016
CAPTURE IN MARINE WATERS	**33.1**	**65.1**	**81.7**	**79.5**	**79.3**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**6.17**	**1.83**	**0.04**	**0.53**
Pacific, Northwest (61)	8.3	18.1	20.9	21.5	22.4	25.1	27.8	25.6	27.1	28.3	5.52	3.62	-0.42	1.13
Pacific, Western Central (71)	1.7	5.2	9.6	12.0	12.7	5.2	7.9	11.8	15.1	16.1	10.36	3.45	2.15	1.70
Atlantic, Northeast (27)	7.7	10.8	10.1	8.5	8.3	23.2	16.6	12.4	10.7	10.5	3.23	-0.52	0.01	-0.80
Indian Ocean, Eastern (57)	0.7	2.1	4.8	6.2	6.4	2.2	3.2	5.9	7.8	8.1	6.69	5.62	3.34	1.13
Pacific, Southeast (87)	4.7	8.6	14.0	8.6	6.3	14.0	13.2	17.1	10.8	8.0	24.26	0.51	-0.98	-3.43
Indian Ocean, Western (51)	0.9	2.1	4.0	4.5	4.9	2.7	3.2	4.8	5.7	6.2	4.69	4.40	1.37	2.47
Atlantic, Eastern Central (34)	0.8	3.1	3.7	4.4	4.8	2.3	4.8	4.5	5.5	6.0	10.30	2.61	0.07	0.99
Pacific, Northeast (67)	1.0	2.5	2.9	3.0	3.1	3.0	3.8	3.5	3.7	3.9	5.99	1.13	-2.02	4.05
Atlantic, Northwest (21)	3.2	3.3	2.3	1.9	1.8	9.7	5.1	2.8	2.4	2.3	3.57	-1.48	-2.42	-2.15
Atlantic, Southeast (47)	1.4	2.5	1.5	1.5	1.7	4.4	3.9	1.9	1.9	2.1	10.43	-0.76	-0.89	3.64
Pacific, Eastern Central (77)	0.5	1.3	1.6	1.9	1.7	1.5	2.1	2.0	2.4	2.1	-0.44	4.40	1.52	-2.61
Atlantic, Southwest (41)	0.4	1.4	2.2	2.0	1.6	1.2	2.1	2.7	2.6	2.0	6.63	6.22	0.09	-1.99
Atlantic, Western Central (31)	0.9	1.8	1.7	1.3	1.6	2.7	2.7	2.1	1.7	2.0	5.04	1.44	-1.13	4.04
Mediterranean and Black Sea (37)	0.8	1.5	1.5	1.3	1.2	2.5	2.3	1.9	1.6	1.6	1.33	2.03	0.35	-2.35
Pacific, Southwest (81)	0.1	0.4	0.8	0.6	0.5	0.2	0.7	0.9	0.7	0.6	7.33	10.14	-1.84	-3.46
Atlantic, Antarctic (48)	0.0	0.3	0.2	0.2	0.3	0.1	0.4	0.2	0.3	0.3	…	0.03	-6.43	3.39
Arctic Sea (18)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	…	…	…	-33.27
Indian Ocean, Antarctic (58)	…	0.1	0.0	0.0	0.0	…	0.1	0.0	0.0	0.0	…	53.60	-6.32	1.61
Pacific, Antarctic (88)	…	0.0	0.0	0.0	0.0	…	0.0	0.0	0.0	0.0	…	…	`8.69	0.93
CAPTURE IN INLAND WATERS	**3.2**	**5.3**	**8.2**	**11.1**	**11.6**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**4.47**	**1.57**	**2.52**	**0.89**
Asia - Inland waters (4)	1.6	2.7	5.1	7.4	7.7	50.1	50.1	62.2	66.7	66.3	5.66	1.61	3.65	0.58
Africa - Inland waters (1)	0.6	1.3	2.1	2.7	2.9	19.1	24.6	25.9	24.7	24.6	5.99	2.50	1.67	1.50
Europe - Inland waters (5)	0.1	0.2	0.4	0.4	0.4	3.4	3.8	4.8	3.5	3.8	2.13	9.44	-2.37	2.42
America, South - Inland waters (3)	0.1	0.3	0.4	0.4	0.3	3.2	4.9	4.4	3.3	2.9	4.51	4.49	1.36	-1.96
America, North - Inland waters (2)	0.1	0.2	0.2	0.2	0.3	4.2	3.5	2.4	1.6	2.2	1.42	3.71	-1.13	6.51
Oceania - Inland waters (6)	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	5.16	16.96	-1.27	0.42
Former USSR area - Inland waters (7)	0.6	0.7	…	…	…	20.0	12.8	…	…	…	1.44	…	…	…
AQUACULTURE	**1.5**	**5.8**	**32.6**	**67.8**	**80.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**7.44**	**8.61**	**7.92**	**5.22**
Asia - Inland waters (4)	0.6	2.5	17.7	40.0	47.8	40.0	44.3	54.3	58.9	59.7	9.34	10.02	8.68	5.71
Pacific, Northwest (61)	0.3	1.4	9.1	16.3	18.8	21.2	25.0	27.7	24.1	23.5	11.54	9.49	7.90	4.25
Pacific, Western Central (71)	0.1	0.4	1.5	3.1	3.8	7.6	6.3	4.7	4.6	4.7	5.97	7.17	6.54	4.79
Atlantic, Northeast (27)	0.2	0.5	1.2	2.0	2.1	13.9	8.9	3.6	2.9	2.6	4.08	3.76	4.53	3.28
Africa - Inland waters (1)	0.0	0.0	0.4	1.5	2.0	0.4	0.6	1.2	2.2	2.4	7.73	12.34	14.29	7.41
Pacific, Southeast (87)	0.0	0.0	0.5	1.3	1.5	0.0	0.4	1.6	2.0	1.9	9.15	36.63	12.25	7.70
America, South - Inland waters (3)	0.0	0.0	0.2	0.6	0.7	0.0	0.1	0.6	0.9	0.9	…	35.53	14.92	5.75
Indian Ocean, Western (51)	…	0.0	0.1	0.3	0.6	…	0.1	0.3	0.5	0.8	…	46.47	7.86	25.60
Indian Ocean, Eastern (57)	0.0	0.1	0.3	0.5	0.5	0.9	1.1	0.9	0.8	0.6	10.47	4.06	11.85	-0.61
Europe - Inland waters (5)	0.1	0.3	0.5	0.5	0.5	4.6	4.6	1.5	0.7	0.6	9.40	8.68	-2.13	1.10
Mediterranean and Black Sea (37)	0.0	0.1	0.3	0.4	0.5	0.4	1.1	0.9	0.6	0.6	7.68	10.78	5.36	3.24
America, North - Inland waters (2)	0.0	0.1	0.4	0.4	0.4	0.7	2.3	1.2	0.6	0.5	8.05	11.01	2.34	1.11
Pacific, Eastern Central (77)	…	0.0	0.1	0.2	0.2	…	0.0	0.2	0.3	0.3	…	…	14.22	4.66
Pacific, Southwest (81)	0.0	0.0	0.1	0.1	0.2	0.5	0.3	0.3	0.2	0.2	4.11	8.24	7.39	2.23
Atlantic, Western Central (31)	0.1	0.1	0.1	0.1	0.2	3.7	1.6	0.3	0.2	0.2	5.59	-1.16	6.50	-0.28
Pacific, Northeast (67)	0.0	0.0	0.1	0.1	0.1	2.4	0.6	0.3	0.2	0.2	-1.17	2.75	4.04	2.88
Atlantic, Northwest (21)	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.3	0.2	0.2	1.91	14.64	8.18	0.91
Atlantic, Southwest (41)	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1	…	25.54	21.88	-2.55
Atlantic, Eastern Central (34)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	…	7.78	16.04	7.14
Oceania - Inland waters (6)	…	0.0	0.0	0.0	0.0	…	0.0	0.0	0.0	0.0	…	…	2.77	5.64
Atlantic, Southeast (47)	…	0.0	0.0	0.0	0.0	…	0.0	0.0	0.0	0.0	…	…	1.54	8.43
Former USSR area - Inland waters (7)	0.1	0.2	…	…	…	3.6	3.0	…	…	…	1.25	…	…	…

TABLE 3C
Apparent food fish consumption (2013)

	Total food fish supply	Share of world total	Per capita food fish consumption	Share of fish in total animal protein consumed
	Million tonnes live weight	Percentage	Kg live weight	Percentage
World	142.1	*100.0*	19.8	*16.8*
Africa	11.2	*7.9*	10.1	*18.4*
Eastern Africa	1.9	*1.3*	5.1	*12.2*
Middle Africa	1.5	*1.0*	10.8	*31.4*
Northern Africa	2.9	*2.0*	13.8	*15.1*
Southern Africa	0.4	*0.3*	6.2	*5.2*
Western Africa	4.6	*3.2*	13.8	*32.4*
Americas	14.0	*9.9*	14.4	*7.2*
Northern America	7.7	*5.4*	21.7	*7.6*
Caribbean	0.4	*0.3*	9.0	*10.3*
Central America	1.9	*1.3*	11.3	*9.4*
South America	4.0	*2.8*	9.8	*5.8*
Asia	99.6	*70.1*	23.2	*23.0*
Central Asia	0.1	*0.1*	2.2	*1.7*
Eastern Asia	62.9	*44.3*	38.8	*24.0*
South-Eastern Asia	21.9	*15.4*	35.3	*41.7*
Southern Asia	12.8	*9.0*	7.3	*15.2*
Western Asia	2.0	*1.4*	8.0	*7.1*
Europe	16.2	*11.4*	21.9	*11.3*
Eastern Europe	5.1	*3.6*	17.2	*11.0*
Northern Europe	2.5	*1.8*	24.9	*11.1*
Southern Europe	4.6	*3.2*	29.2	*14.1*
Western Europe	4.1	*2.9*	21.5	*9.6*
Oceania	1.0	*0.7*	25.2	*10.9*
Australia & New Zealand	0.7	*0.5*	26.1	*9.3*
Melanesia	0.2	*0.1*	20.8	*17.2*
Micronesia	0.0	*0.0*	33.0	*55.4*
Polynesia	0.0	*0.0*	41.5	*22.1*
Developed countries	31.1	*21.9*	24.7	*12.0*
LDC	11.5	*8.1*	12.8	*26.0*
Other developing countries	99.5	*70.0*	19.9	*18.6*
LIC	3.7	*2.6*	6.1	*16.0*
LIFDC	19.3	*13.6*	7.3	*15.7*
LLDC	1.9	*1.3*	4.2	*7.0*
NFIDC	17.1	*12.0*	12.1	*19.0*
SIDS	1.1	*0.8*	16.0	*15.1*

LDC: Least developed countries;
LIC: Low-income countries;
LIFDC: Low-income food-deficit countries;
LLDC: Land-locked developing countries;
NFIDC: Net food-importing developing countries;
SIDS: Small island developing states

TABLE 3D

Trade in fish and fish products in 2016

	Exports*	Imports	Net-exports	Exports*	Imports	Exports*	Imports	Net-exports	Exports*	Imports
	Value (USD billion)			Share in world percent		Quantity (million tonnes live weight)			Share of world trade percent	
World	**142.5**	**135.6**	**6.9**	**100.0**	**100.0**	**59.8**	**59.1**	**0.7**	**100.0**	**100.0**
Africa	**6.4**	**5.5**	**0.9**	**4.5**	**4.1**	**4.2**	**4.9**	**-0.6**	**7.0**	**8.2**
Eastern Africa	1.3	0.7	0.6	0.9	0.5	0.7	0.7	-0.1	1.1	1.2
Middle Africa	0.1	0.9	-0.8	0.1	0.6	0.0	0.7	-0.7	0.1	1.2
Northern Africa	2.3	1.3	1.1	1.6	0.9	1.4	0.8	0.5	2.3	1.4
Southern Africa	1.3	0.4	0.8	0.9	0.3	1.1	0.3	0.8	1.8	0.5
Western Africa	1.4	2.2	-0.8	1.0	1.6	1.0	2.3	-1.2	1.8	3.8
Americas	**27.7**	**27.7**	**0.0**	**19.4**	**20.4**	**12.8**	**8.5**	**4.3**	**21.3**	**14.4**
Northern America	11.3	23.4	-12.0	8.0	17.2	3.8	5.9	-2.1	6.3	9.9
Caribbean	0.3	0.5	-0.3	0.2	0.4	0.1	0.3	-0.2	0.1	0.5
Central America	2.3	1.2	1.0	1.6	0.9	0.8	0.8	-0.1	1.3	1.4
South America	13.8	2.6	11.3	9.7	1.9	8.2	1.5	6.7	13.7	2.6
Asia	**54.5**	**43.7**	**10.8**	**38.2**	**32.2**	**22.4**	**23.6**	**-1.2**	**37.4**	**40.0**
Central Asia	0.1	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.1
Eastern Asia	26.4	32.6	-6.2	18.5	24.0	10.3	15.9	-5.5	17.3	26.9
South-Eastern Asia	19.4	7.3	12.1	13.6	5.4	9.6	5.1	4.5	16.0	8.7
Southern Asia	7.1	0.7	6.5	5.0	0.5	1.8	0.7	1.1	3.0	1.2
Western Asia	1.5	3.2	-1.7	1.1	2.3	0.6	1.9	-1.2	1.1	3.1
Europe	**50.9**	**56.9**	**-6.0**	**35.7**	**41.9**	**19.3**	**21.4**	**-2.1**	**32.2**	**36.1**
Eastern Europe	6.4	5.6	0.7	4.5	4.1	3.4	3.0	0.4	5.7	5.1
Northern Europe	27.3	15.9	11.4	19.2	11.7	9.2	5.8	3.4	15.4	9.8
Southern Europe	7.2	16.6	-9.5	5.0	12.2	2.4	5.8	-3.4	4.1	9.9
Western Europe	10.1	18.7	-8.7	7.1	13.8	4.2	6.7	-2.4	7.1	11.3
Oceania	**3.0**	**1.8**	**1.2**	**2.1**	**1.3**	**1.2**	**0.8**	**0.4**	**2.0**	**1.3**
Australia & New Zealand	2.3	1.6	0.6	1.6	1.2	0.7	0.6	0.0	1.1	1.1
Melanesia	0.5	0.2	0.3	0.3	0.1	0.3	0.1	0.2	0.5	0.2
Micronesia	0.3	0.0	0.2	0.2	0.0	0.2	0.0	0.2	0.3	0.0
Polynesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Developed countries	66.6	96.4	-29.8	46.0	70.9	24.8	31.7	-6.9	41.4	53.6
LDC	3.1	1.1	2.0	2.2	0.8	2.0	1.4	0.6	3.4	2.3
Other developing countries	72.9	38.2	34.7	51.8	28.3	33.0	26.0	7.0	55.2	44.1
LIC	1.1	0.7	0.4	0.7	0.4	0.6	0.9	-0.3	1.0	1.5
LIFDC	9.1	3.4	5.7	6.1	2.5	3.2	3.5	-0.3	5.4	5.9
LLDC	0.2	0.5	-0.3	0.2	0.5	0.1	0.7	-0.6	0.2	1.2
NFIDC	10.2	4.0	6.1	7.4	3.2	8.1	3.7	4.4	13.6	6.2
SIDS	2.7	2.3	0.4	1.9	1.8	1.3	1.0	0.3	2.2	1.8

LDC: Least developed countries;
LIC: Low-income countries;
LIFDC: Low-income food-deficit countries;
LLDC: Land-locked developing countries;
NFIDC: Net food-importing developing countries;
SIDS: Small island developing states.
*Re-exports included.

Chapter 4: Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century

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KEY MESSAGES

- Total maximum catch potential in the world's exclusive economic zones (EEZs)[1] (excluding those bordering semi-enclosed seas) was projected by applying two distinct approaches to likely decrease under climate change by 2.8 percent to 5.3 percent and 7.0 percent to 12.1 percent by 2050 relative to 2000 under the "strong mitigation" (RCP2.6) and "business-as-usual" (RCP8.5) greenhouse gas emission scenarios, respectively. The projected decrease in catch under RCP8.5 becomes 16.2 percent to 25.2 percent by the end of the twenty-first century.
- The projected changes in maximum catch potential varied substantially across EEZs in different regions, with EEZs in tropical countries showing the largest decrease, mostly in the South Pacific regions. Catch potential in the temperate Northeast Atlantic is also likely to decrease in the mid-term (2050s).
- The projected changes in catch potential in the high latitude regions are much more variable between models, time periods and EEZs because of the high variabilities in projected oceanographic changes between different Earth system models.

4.1 MODELLING APPROACHES TO PROJECT CLIMATE CHANGE IMPACTS ON MARINE LIVING RESOURCES

Driven by greenhouse gas emission from human activities, the ocean is getting warmer, more acidic, and its oxygen content is declining; these changes cause large-scale changes in marine biodiversity (Pörtner *et al.*, 2014). The changes in ocean conditions are expected to continue to alter patterns of global marine primary productivity (Bopp *et al.*, 2013) and biodiversity (Jones and Cheung, 2015), with consequences for the potential fisheries catches, impacting food security in the twenty-first century (Cheung, Reygondeau and Frölicher, 2016; Golden *et al.*, 2016; Lam *et al.*, 2016).

Models of climate impacts on living marine resources have been developed to project future scenarios of changes in global fisheries resources under climate change. These models generally have three components: 1) a coupled ocean-atmospheric physical and biogeochemical model (or Earth system model), 2) a living marine resources model and 3) a fishing model (Cheung *et al.*, 2016).

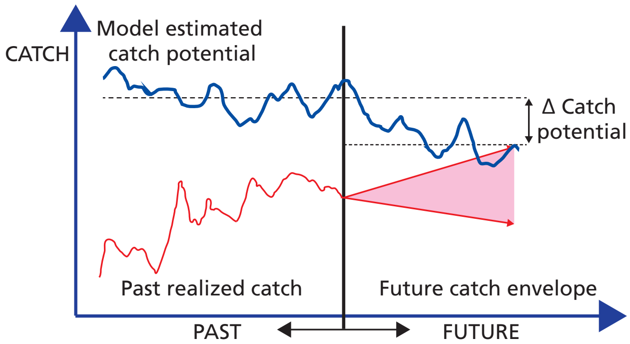
[1] The designations employed and the presentation of information in the EEZ maps in this chapter do not imply the expression of any opinion whatsoever on the part of FAO cocerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers or boundaries.

An Earth system model represents the interactions between the biological, chemical, and physical processes of terrestrial, atmospheric and ocean systems. It projects past and future changes in ocean properties across a three-dimensional grid (representing latitude, longitude, depth) under scenarios of greenhouse gas emissions (Asch *et al.*, 2016). The key projected ocean properties that are commonly used to assess climate impacts on living marine resources include sea water temperature, oxygen concentration, pH and net primary production (Cheung, Reygondeau and Frölicher, 2016).

Living marine resources (LMR) models represent the dynamics of marine ecosystems under changing ocean conditions. Published global-scale LMR modelling approaches broadly include size-based (e.g. Blanchard *et al.*, 2012), species-based (e.g. Cheung, Reygondeau and Frölicher, 2016) and functional group-based (e.g. Christensen *et al.*, 2015) models. These LMR models project future changes in biomass of upper trophic level consumers or exploited fish stocks under scenarios of changing ocean conditions. Such projections are commonly undertaken by driving changes in physiological processes (e.g. respiration and growth) and/or ecological (e.g. primary production, consumption, habitat suitability) with changes in ocean conditions.

A fishing component is integrated with the LMR model to calculate the potential future fish catch. Specifically, in the LMR model, biomass is removed by applying a fishing mortality term, which provides an estimated maximum catch potential, a proxy of maximum sustainable yield (MSY) of the resource. This is not the same as the realized catch, which depends not only on the ecosystem productivity but also the level of fishing (modelled through fishing mortality rate). The relationship between potential and realized catch is not simple, as shown in Figure 4.1 and explained here. The estimated catch potential (both in the past and in the future) is the result of simulating the exploitation of the resource at an ideal MSY level, taking into consideration the change in ecosystem productivity over time (and in the future as driven by climate change). The future realized catch (red line in Figure 4.1) cannot exceed the estimated potential catch in the model in the long-term, as this is an ecosystem-driven upper limit. However, short-term catches could exceed potential catch although such catch would not be sustainable. Moreover, catch potential can exceed current realized catches if, for example, these are below MSY as a result of inefficient management or because stock rebuilding measures are in place. In other words, a future change in catch potential compared to the present does not have to be mirrored with an identical change in realized catch compared to current catch, as management practices are not fully considered in the model. Indeed, the fishing mortality in the catch potential estimation may be a simple assumption of fishing rate based on empirical or theoretical estimation (as used in these simulations), or it may be modelled through fishing fleet dynamics that represent the interactions between bioeconomics of the fishing fleets and resource abundance (Christensen *et al.*, 2015; Galbraith, Carozza and Bianchi, 2017).

FIGURE 4.1
Conceptual diagram illustrating the relationship between estimated catch potential, and its change over time driven by climate considerations and realized catch



The red triangle indicates the possible realized catch in an envelope limited by ecosystem productivity (catch potential) and driven by management measures depending on future fishing scenarios.

4.2 SCENARIOS OF THE MARINE ENVIRONMENTAL CONDITIONS FOR FISHERIES UNDER MITIGATED AND UNMITIGATED CLIMATE CHANGE

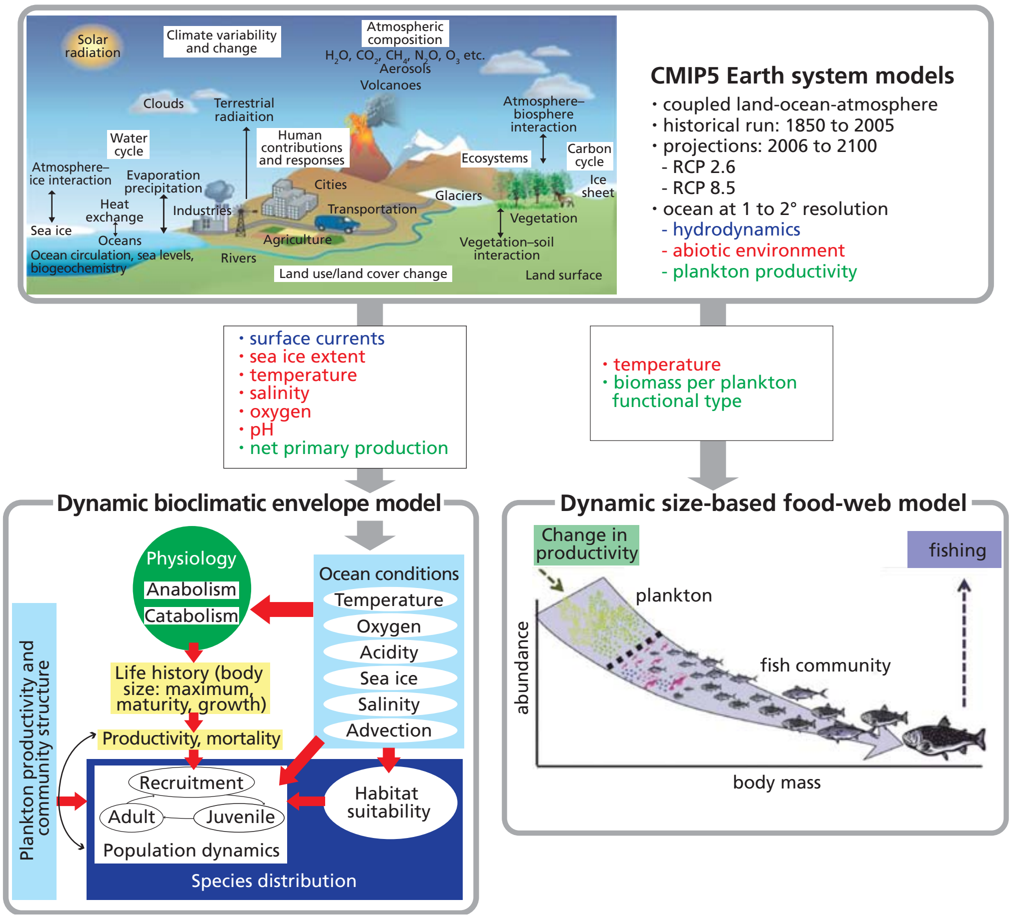
In order to constrain the envelope of response of the marine environment to climate change, the two most contrasting scenarios of greenhouse gas representative concentration pathways (RCPs) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) are applied to drive the projections of the impact on potential fish catches over this century in the EEZs across the globe. The scenario RCP8.5 assumes an increase in radiative forcing of 8.5 W/m^2 at the end of this century with respect to pre-industrial conditions, corresponding to the highest greenhouse gas emissions in the range of RCP scenarios, and is expected to lead to a global mean surface temperature increase of about 4.5 °C resulting in largely unmitigated climate change. The lowest emission scenario (RCP2.6, assuming a 2.6 W/m^2 increase in radiative forcing) represents a stringent mitigation of climate change with an expected increase of global mean surface temperatures below 2 °C (Meinshausen *et al.*, 2011). For the marine environment the impacts of climate change at the global scale have been investigated widely in the scientific literature (e.g. Barange *et al.*, 2014; Gattuso *et al.*, 2015) indicating substantial but geographically diverse risks for ecosystem services, including fisheries, at levels of greenhouse gas concentrations beyond RCP2.6. More specifically, for the two main environmental drivers of change in fisheries potential, global average ocean surface temperature and primary production, the estimated changes under mitigated climate change have shown a consistent picture of ocean warming and decreasing marine primary production across a variety of Earth system models (ESMs). According to Bopp *et al.* (2013), unmitigated climate change conditions will lead to an increase of sea surface temperature of 2.7 °C to ±0.72 °C, while marine primary production has been estimated to decrease by 6 percent ± 3 percent by Kwiatkowski *et al.* (2017) using an emergent relationship between the sea surface temperature anomaly in the tropical Pacific and global marine primary production. While these signals are comparatively robust at the global level, future changes show a much more heterogeneous picture at the regional level. Hence, to get an estimate of the heterogeneity of responses at the smaller scale, projected changes were evaluated across all EEZs. This showed temperature decreases in individual EEZs as large as 6 °C under RCP8.5 and 2.5 °C under RCP2.6, while the change in surface phytoplankton concentration ranges from -19 mg/m^3 to +5 mg/m^3 across different EEZs for scenario RCP8.5 and from -11 mg/m^3 to +2 mg/m^3 for RCP2.6 indicating a high potential for substantial heterogeneity in the system response at the higher trophic levels. The representation of geographical areas applied in this chapter is based on the EEZ definitions of marine regions[2] excluding any disputed areas or joint regimes as well as semi-enclosed seas that are not well represented by the ESMs.

4.3 BRIEF DESCRIPTION OF THE CLIMATE-LMR MODELS FOR THE PROJECTIONS IN THIS CHAPTER

In this chapter, the projected changes in potential fisheries catches are based on two LMR models with different structures (Figure 4.2). The first approach is a species-based dynamic bioclimate envelope model (Cheung *et al.*, 2016) while the second approach uses a dynamic size-based food web model (Blanchard *et al.*, 2012). Both models are driven by outputs from a selection of different Earth system models made available as part of the fifth phase of the Coupled Model Intercomparison Project (CMIP5). The Earth system models were nominally run over the period 1850 to 2005 under historical forcing, and over the period 2006 to 2100 under the RCP2.6 and RCP8.5 greenhouse gas scenarios.

[2] http://marineregions.org/ (version 9)

FIGURE 4.2
Schematic diagram showing the simulation of future changes in potential fisheries catches under climate change scenarios using the two climate-LMR models: a dynamic bioclimate envelope model and size-spectrum model



4.3.1 Dynamic bioclimate envelope model (DBEM)

Outputs were used from a subset of three Earth system models made available as part of CMIP5: the Geophysical Fluid Dynamic Laboratory Earth System Model 2G (GFDL ESM 2G), the Institute Pierre-Simon Laplace Climate Model (IPSL-CM5A-MR) and the Max Planck Institute Earth System Model (MPI-ESM-MR). We used one single realization of each model. The models were selected based on the availability of variables from the CMIP5 database (Cheung, Reygondeau and Frölicher, 2016). The feasible performance of these model systems has been assured in the context of the CMIP5 initiative (Laufkötter *et al.*, 2015, Kwiatkowski *et al.*, 2017 and references therein), while the process representation and parameterization among these models reflects the structural uncertainty involved in these projections. Examples of these structural uncertainties include differences in spatial resolution, representation of lower trophic level systems such as the number of phytoplankton functional groups, and their linkages with other components of ocean biogeochemistry. The Earth system model outputs that are used to drive the DBEM include: seawater temperature (surface and bottom), oxygen concentration (surface and bottom), hydrogen ion concentration (surface and bottom), net primary production (depth integrated), salinity (surface and bottom), sea ice extent and surface advection. All model data have been regridded onto a 0.5° x 0.5° grid using a bilinear interpolation method.

The DBEM was used to simulate changes in distribution, abundance and catches of 910 exploited marine fishes and invertebrates. The overall components of the DBEM are:

1. The current distributions of commercially exploited species, representing the average pattern of relative abundance in recent decades (i.e. 1970 to 2000), were produced using an algorithm developed by the *Sea Around Us*[3]. The algorithm predicts the relative abundance of a species on a 0.5° latitude × 0.5° longitude grid based on the species' depth range, latitudinal range, known FAO statistical areas and polygons encompassing their known occurrence regions. The distributions were further refined by assigning habitat preferences to each species, such as affinity to shelf (inner, outer), estuaries, and coral reef habitats.
2. An index of habitat suitability for each species in each spatial cell from temperature (bottom and surface temperature for demersal and pelagic species, respectively), bathymetry, specific habitats, salinity and sea ice with 30 year averages of outputs from 1971 to 2000 from Earth system models. DBEM estimated the temperature preference profile (TPP) of each species by overlaying the estimated distribution of the species with annual seawater temperature and calculated the area-corrected distribution of relative abundance across temperature for each year from 1971 to 2000, subsequently averaging annual TPPs. The estimated TPP was used to predict the thermal physiological performance of a species (aerobic scope) in each area.
3. Population carrying capacity in each spatial cell is a function of the unfished biomass of the population, the habitat suitability and net primary production. We assumed that the average of the top ten annual catches was roughly equal to the maximum sustainable yield of the species.
4. DBEM calculates a characteristic weight representing the average mass of the individuals of a population in a given spatial cell. The model simulated how changes in temperature and oxygen content would affect growth and body size of the individuals using a sub-model derived from a generalized von Bertalanffy growth function.
5. The model simulated changes in relative abundance and biomass of a species based on changes in population carrying capacity, intrinsic population growth, and the advection-diffusion of the adults and larvae of the population driven by ocean conditions projected from the Earth system models. Movement and dispersal of adults and larvae were modelled through an advection-diffusion-reaction equation for larvae and adult stages. Larval movement is partly determined by the predicted pelagic larval duration. Population growth was represented by a logistic function.
6. Maximum catch potential from each population was predicted by applying a fishing mortality rate at the level required to achieve maximum sustainable yield to the biomass at that time.
7. Trophic interactions between exploited species are not represented in the model.

For each simulation, changes in total annual maximum catch potential by 2050 (2046 to 2055) and 2095 (2091 to 2100) relative to catch potential in 2000 (1996 to 2005) under RCP2.6 and RCP8.5 in each of the EEZs of the world ocean were calculated. The ensemble averages across maximum catch potential projections from the three Earth system models are presented here.

4.3.2 Dynamic size-based food web model

The size-based model is based on the approach described by Blanchard *et al.* (2012) and uses the same parameterization unless stated otherwise below. It distinguishes fish by their size, but does not consider individual species. The model is driven by the output of two Earth system models: the Geophysical Fluid Dynamic Laboratory Earth System Model 2M (GFDL ESM 2M) and three different configurations of the Institut Pierre-Simon Laplace Climate Model (IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR). These were chosen from the full range of model systems available

[3] http://www.seaaroundus.org/

in the CMIP5 archive for their ability to represent the plankton size spectrum. The performance of these model systems has been evaluated previously (Laufkötter *et al.*, 2015, Kwiatkowski *et al.*, 2017 and references therein). The ESM outputs that drive the size spectrum model are monthly sea surface temperatures and surface concentrations of different plankton functional types (PFTs). In addition, the annual mean vertical distribution of total plankton biomass is used to infer the depth distribution of fish. All inputs were spatially averaged over each EEZ; the fish model was subsequently run per EEZ. For the historical simulation (1850 to 2005), the model was spun up for 50 years from low fish biomass using the 1850 to 2005 average of temperatures and plankton concentrations. For the projections (2006 to 2100) the model was initialized with the final state of the historical simulation.

The size spectrum model consists of the following components:

1. The pelagic fish community is represented by 100 log-spaced weight classes spanning 1 mg to 100 kg.
2. Trophic interactions are represented explicitly: fish feed according to size-based rules, preferring prey one hundred times smaller in weight. Accordingly, the smallest fish feed on large plankton (e.g. diatoms, mesozooplankton), while larger fish feed on small fish. In the latter case, predation moves biomass from smaller weight classes (the prey) to larger weight classes (the predator). Prey discovery is mediated by search rates that depend on predator size (Acuña, López-Urrutia and Colin, 2011).
3. Ingestion and assimilation of food leads to growth of individual fish, which is represented by moving part of the fish in a size class to the next class.
4. Mortality is a result of predation and intrinsic size-dependent mortality, as well as fishing represented by a mortality of 0.2/yr for all fish above 1.25 g.
5. Recruitment is not modelled explicitly. Instead, the abundance of the first size class of fish (1 mg) is derived by extending the plankton size spectrum; this assumes a continuous size spectrum from plankton to fish.
6. Physiological rates increase with temperature according to an Arrhenius relationship with activation energy of 0.63 eV. This also affects trophic interactions.
7. The plankton community is represented with ten size classes per tenfold increase in weight, which requires a total of 70 (IPSL) to 120 (GFDL) size classes. For each plankton functional type in the ESM, we distribute their biomass over their specific weight range such that each interval of the same width (in log space) contains equal biomass. Weight ranges per plankton type were provided by the authors of the ESMs (IPSL) or based on the nominal size ranges employed in other models for the same PFT (GFDL). The final plankton size spectrum is constructed by combining the size spectrum contributions of all PFTs.
8. The fish model is driven with monthly mean surface concentrations of each plankton functional type, which are converted to concentrations of each plankton size class. The fish model subsequently simulates size spectra of the fish community in the surface ocean. The predicted fish concentrations at the surface are converted to depth-integrated biomass by taking the vertical distribution of fish proportional to the annual mean vertical distribution of plankton.

4.4 FUTURE PROJECTIONS OF FISHERIES CATCHES UNDER CLIMATE CHANGE

Overall, total maximum catch potential in the world's EEZs (excluding those bordering semi-enclosed seas) was projected to decrease under climate change with both DBEM and the size-based model (Figures 4.3 to 4.6). Specifically, maximum catch potential was projected to decrease by 2.8 percent to 5.3 percent and 2.8 percent to 4.3 percent under RCP2.6 by 2050 and 2095 relative to 2000 respectively. In contrast, the decrease was larger, 7.0 percent to 12.1 percent and 16.2 percent to 25.2 percent by 2050 and 2095 relative to 2000, respectively, under RCP8.5. Overall, the projections of changes in future global catch potential are consistent between the two climate-LMR models, although projections by DBEM are more sensitive to the climate scenarios than those by the size-based model.

The projected changes in maximum catch potential varied substantially across EEZs in different regions (Tables 4.1 and 4.2 of the Appendix). Averaged across the two climate-LMR models, EEZs that show the largest decrease (less than -40 percent) by the end of the century are in tropical countries, mostly in the South Pacific regions. These tropical countries include Nauru, Kiribati, Tuvalu, Ecuador, Palau, Micronesia (Federated States of) and Tokelau. However, in the mid-century timescale, in addition to tropical EEZs, potential catches in EEZs in the temperate Northeast Atlantic were also projected to decrease substantially (about -30 percent). In contrast, high latitude regions are often projected to increase in catch potential, or at least experience much less of a decrease. Increases in catch potential are seen in both models near the Southern Ocean, and particularly in the DBEM in the waters around Norway, the Russian Federation and Greenland, and Canada. However, projections from DBEM and the size-based models vary considerably at regional scales in the Arctic region, with DBEM projecting a substantial increase in potential catch while size-based models project decreases or slight increases in potential catch in many polar regions.

FIGURE 4.3

Projected changes in maximum catch potential (%) under RCP2.6 by 2050 (A: 2046 to 2055) and 2095 (B: 2091 to 2100) for the DBEM projections

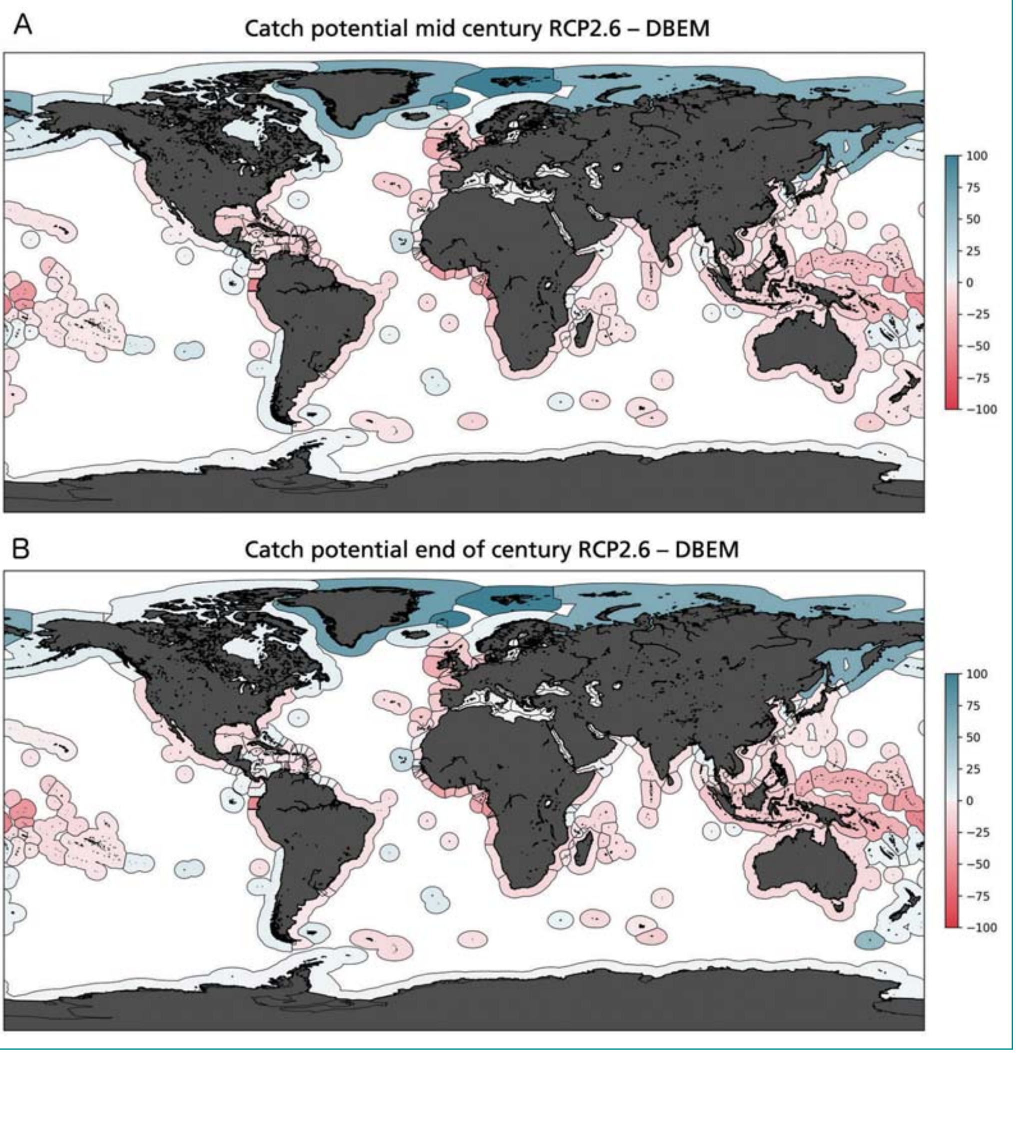


FIGURE 4.4

Projected changes in maximum catch potential (%) under RCP8.5 by 2050 (A: 2046 to 2055) and 2095 (B: 2091 to 2100) for the DBEM projections

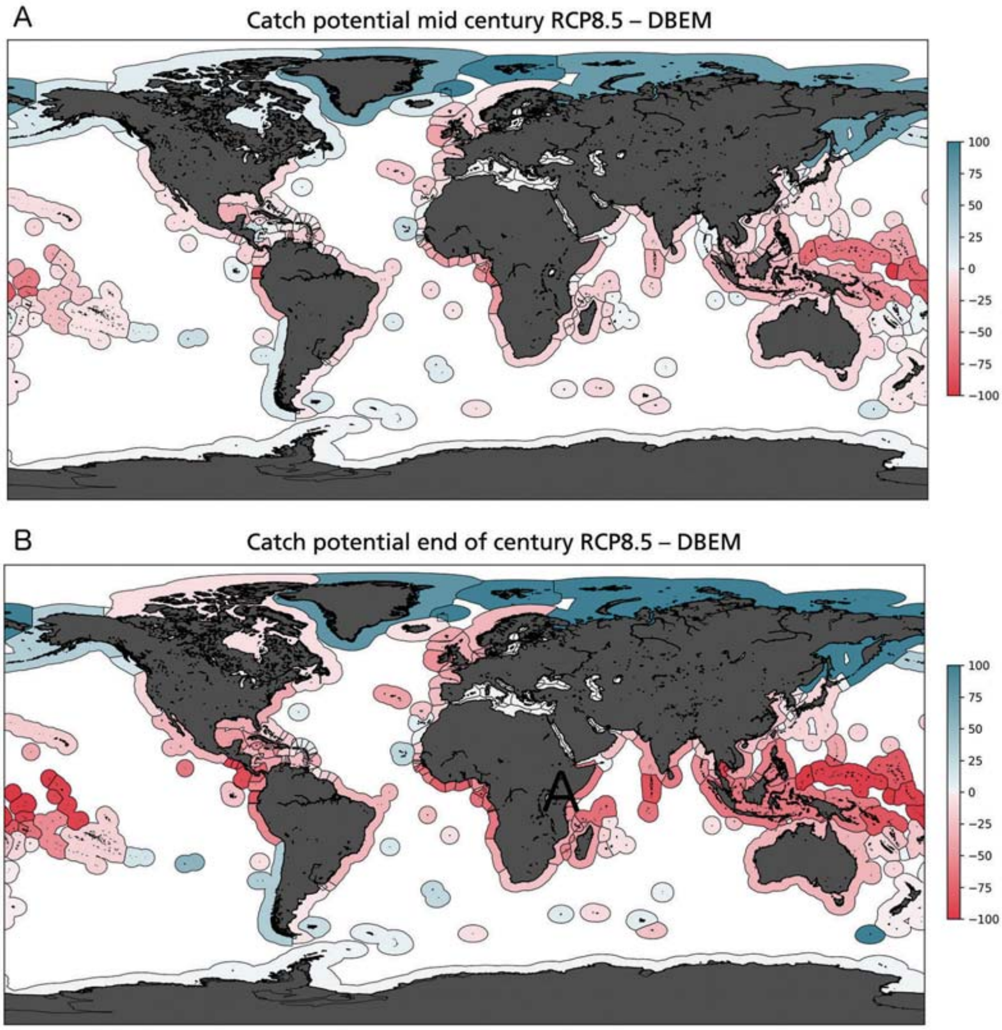
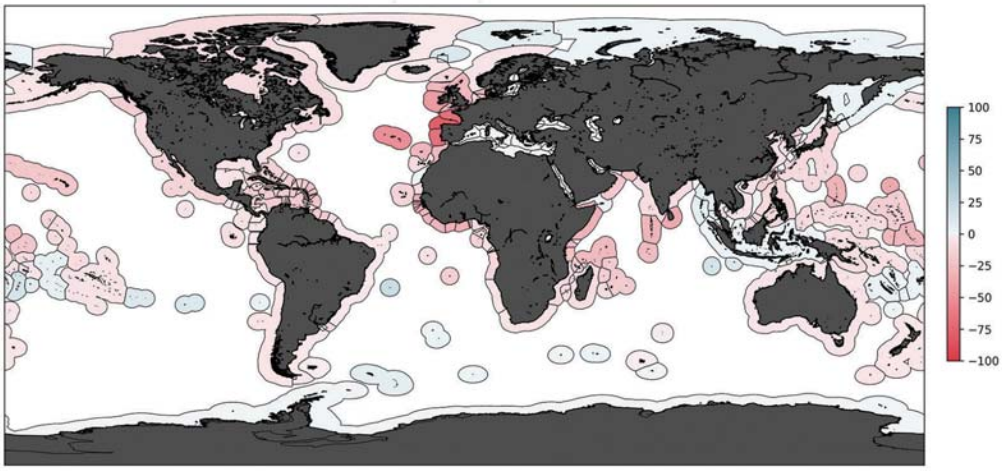


FIGURE 4.5

Projected changes in maximum catch potential (%) under RCP2.6 by 2050 (A, 2046 to 2055) and 2095 (B, 2091 to 2100) for the size-based model

A Catch potential mid century RCP2.6 – dynamic size-based food web model



B Catch potential end of century RCP2.6 – dynamic size-based food web model

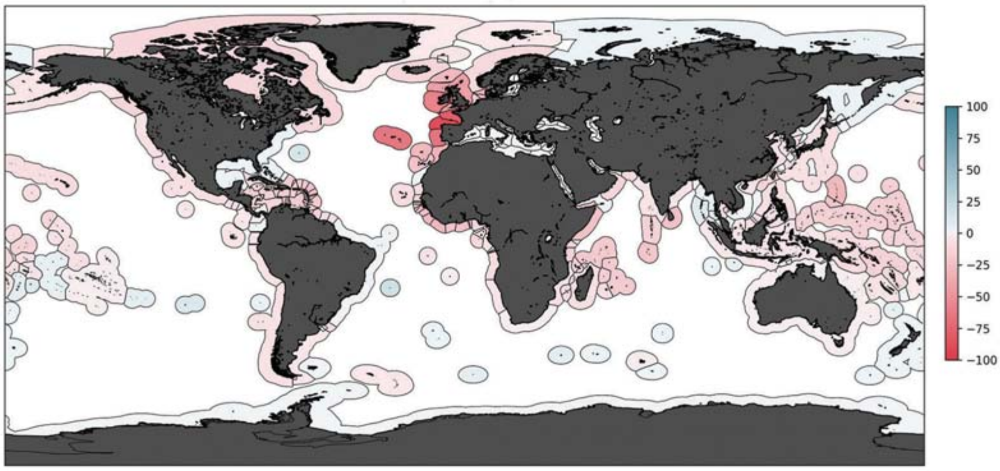
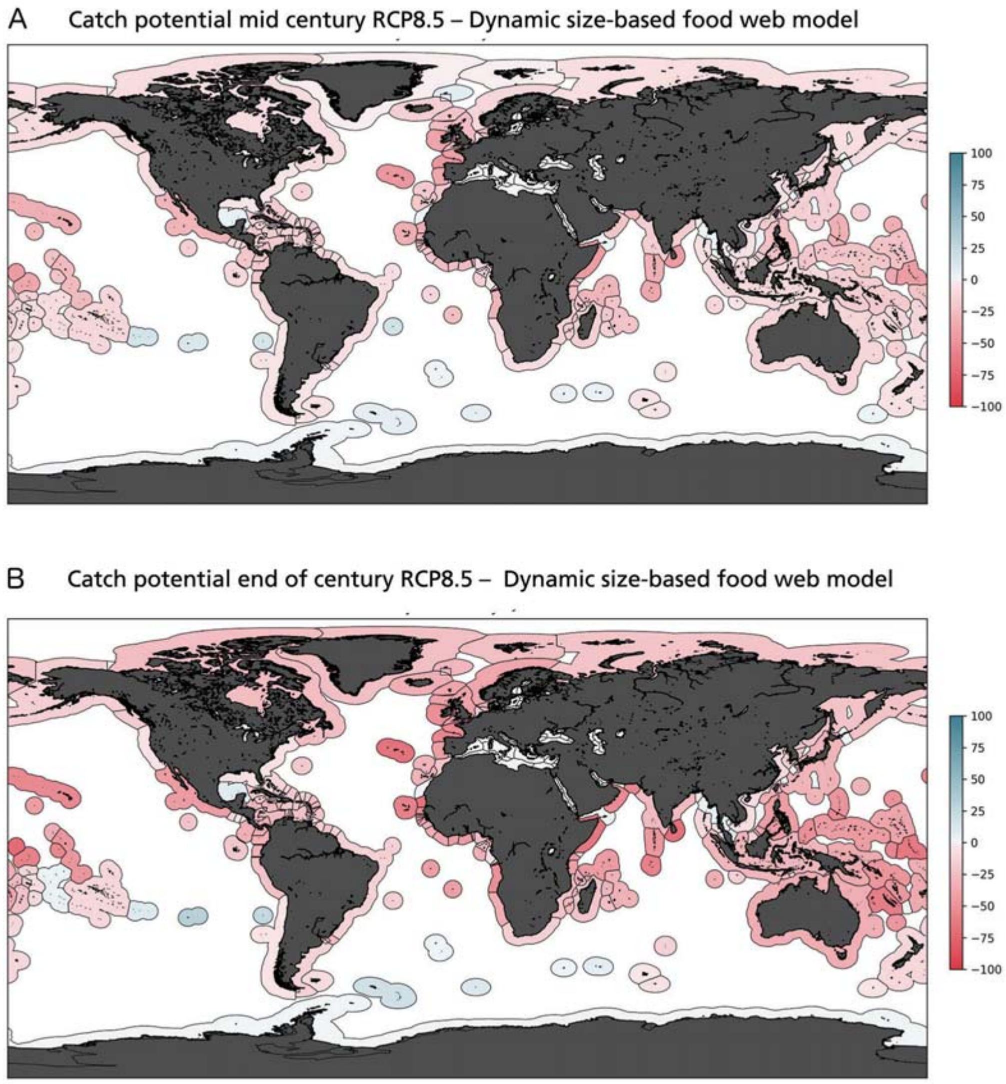


FIGURE 4.6
Projected changes in maximum catch potential (%) under RCP8.5 by 2050 (A: 2046 to 2055) and 2095 (B: 2091 to 2100) for the size-based model



4.5 DISCUSSION

The projected decrease in maximum catch potential may be driven by the direct effect of warming on fish physiology, by a decrease in their food (phytoplankton and zooplankton), and/or loss of habitat. Despite the fact that the two LMR models differ considerably in their representation of these drivers, they largely agree on the direction and magnitude of change in catch potential (Figures 4.3 to 4.6). A main reason for the high level of agreement between the two climate-LMR models is that changes in potential catches in both models are strongly driven by changes in plankton productivity. While both models are also affected by temperature, they differ in implementation: in the DBEM temperature affects fish distribution, growth, body size and mortality, while in the size-spectrum model it universally affects physiological rates. For the size-spectrum model in particular, this implies that a temperature increase does not have a uniquely positive or negative impact on stocks or catches. Accordingly, it seems likely that the main cause of the decrease in global catch potential projected by both models is the decrease in plankton productivity.

Changes in temperature and oxygen may dampen or enhance the effect of changes in plankton productivity. For instance, while consistently large decreases in catch potential in tropical regions, particularly the South Pacific, may primarily be as a result of a decrease in plankton productivity, simultaneous loss of habitat can exacerbate this. Particularly, in DBEM, the combination of changes in ocean conditions in the tropical oceans are outside the scope of the preferred environment predicted by the model, causing a decrease in habitat suitability and thus abundance of exploited species. In some cases, species were projected to become locally extinct in these tropical areas, and the rate of local extinction increases with atmospheric carbon dioxide concentration (Cheung, Reygondeau and Frölicher, 2016). Other species that can tolerate or adapt to the future environmental conditions in the tropical regions may increase in abundance, but these species are not currently important to fisheries and thus not included in the model.

The projected changes in catch potential in the high latitude regions are much more variable between models, time periods and EEZs. In some areas, warming and increased net primary productivity in high latitude regions by the 2050s were projected to increase ecosystem productivity and open up new habitats for species to grow and expand into, leading to an increase in potential catches. However, towards the end of the twenty-first century, some Earth system models project an increase in nutrient limitation in the Arctic, leading to a decrease in net primary production. As a result, catch potential is projected to decrease. The differences in relative sensitivity of projected changes in catch potential to changes in temperature and plankton productivity between DBEM and the size-based model contribute to the variability of their projections.

These projected changes in catch potential in the world's EEZ provide an indication of the potential vulnerability and risk of impacts on the marine living resources to climate change; they should be interpreted with caution, taking into consideration a few key areas of uncertainties of the climate-LMR models. The key uncertainties and their potential implications for interpreting the risks and vulnerabilities are summarized in the following:

- Earth system models have substantial biases in coastal regions, particularly in upwelling regions where fisheries productivity is often very high. Therefore, projections for fisheries in EEZs that are predominantly operating in the near-shore and upwelling regions have low confidence; similarly potentially important features like regime shifts and tipping points are not always captured by these models, particularly where these are triggered by regional mesoscale dynamics.
- The range of the projected climate change and the related response of the ecosystem among the different Earth system models is considerable (Bopp *et al.*, 2013), particularly at the regional level, and for individual EEZs it often equals or exceeds the average change itself.
- Neither the DBEM nor the size-based model incorporate mechanisms related to the capacity of fish species to adapt to climate change. Such adaptation would be possible through selection operating on standing genetic diversity in traits associated with temperature sensitivity and changes in food availability, as well as evolutionary or trans-generation adaptation in these traits. These mechanisms have the potential to reduce the sensitivity of marine species and ecosystems to climate change.
- In both models, trophic feedbacks from upper trophic levels to biogeochemical properties of the climate and ocean systems are not considered. Although the effects of such trophic feedbacks on future catch potential are currently not clearly characterized and may have relatively smaller contributions to changes in future

catch compared to the direct effects of climate change, the lack of understanding contributes to the general uncertainty of the projections.

- The scenarios represent hypotheses of greenhouse gas emission pathways at the global level, they do not include hypotheses of specific mitigation or adaptation strategies by individual countries or organizations.
- Changes in catch potential essentially reflect future changes in the productive capacity of the regions considered compared to present capacity. These changes do not necessarily reflect expected changes in realized catches in the future compared to the present. While they constitute an upper boundary of the long-term sustainable catch, translating potential into realized catches depends on past and future exploitation and management practices.

Overall, the two climate-LMR models integrate the current understanding about the main mechanisms linking greenhouse gas emission, changes in ocean conditions, marine ecosystems and fisheries. The models help to provide quantitative assessments on the potential risk of impacts of climate change on marine living resources under alternative emission scenarios. The results highlight that increasing carbon emissions are likely to reduce global fisheries catch potential with regional variations. The projections have higher confidence in suggesting high risk of impacts in tropical regions, as reflected by the agreement between the two climate-LMR models. Regional variations and confidence of the projections are further discussed and reflected in the regional chapters of this report.

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APPENDIX 4.1

TABLE 4.1

Projected changes in catch potential (%) by 2050 and 2100 relative to 2000 under RCP2.6 and RCP8.5 based on outputs from the dynamic bioclimate envelope model. The table shows the average change per EEZ, as well as the variability (range) around the average, representing the different estimates from the array of climate models used to drive the fisheries projections

Scenarios	DBEM model: Mid Century RCP2.6		DBEM model: Mid Century RCP8.5		DBEM model: End of Century RCP2.6		DBEM model: End of Century RCP8.5	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
American Samoa	-1.96	4.34	-9.52	16.81	-4.98	3.07	-66.73	27.57
Angola	-23.70	32.41	-43.65	16.66	-19.97	37.34	-63.95	26.56
Antigua and Barbuda	-5.46	15.26	-0.36	27.58	-1.81	14.16	9.93	64.67
Argentina	-1.23	3.35	-2.94	4.08	-1.28	0.45	-2.41	6.70
Australia	-6.37	9.12	-10.54	17.87	-8.76	13.46	-30.24	42.30
Macquarie Island (Australia)	-15.15	8.74	14.72	71.77	50.51	239.79	595.06	1 665.25
Bangladesh	-1.24	7.84	1.59	21.82	5.10	5.78	-18.69	43.66
Bahamas	-7.53	6.04	-3.73	9.96	1.61	20.42	-13.06	24.78
Barbados	-12.91	27.16	-18.60	28.22	-9.22	22.52	-30.60	38.62
Belgium	-24.94	18.72	-25.81	27.74	-23.60	11.73	-38.68	28.43
Bermuda	2.95	6.65	1.29	14.45	3.31	15.61	6.83	26.59
Bouvet Island	-11.49	11.25	-6.02	12.40	-5.03	8.13	-5.66	10.56
Brazil	-7.27	8.17	-11.01	3.39	-5.44	8.68	-28.91	23.12
Trindade and Martim Vaz Island (Brazil)	1.54	24.38	7.94	33.78	7.98	28.12	11.76	64.78
Belize	9.25	60.95	32.72	105.26	6.83	45.81	-40.04	56.34
Chagos Archipelago	-6.65	7.69	-13.06	15.54	-7.65	8.97	-66.38	42.19
Solomon Islands	-25.61	39.37	-50.79	20.76	-31.73	43.15	-82.98	8.08
British Virgin Island	-5.16	5.06	-0.03	13.24	1.09	11.95	2.38	30.74
Brunei Darussalam	-1.62	18.59	-20.07	36.44	-5.53	20.23	-52.77	19.81
Myanmar	-0.12	12.84	1.37	46.57	1.76	14.71	-16.59	86.66
Cambodia	-9.66	7.67	-26.45	35.40	-11.85	2.26	-97.93	4.98
Cameroon	-18.28	66.23	-34.01	73.48	-19.45	69.44	-55.42	14.30
Cabo Verde	17.52	17.00	24.03	8.60	20.93	17.87	26.92	9.01
Cayman Islands	-9.33	12.57	-12.35	11.57	-5.20	11.97	-52.49	50.94
Sri Lanka	-6.91	11.51	-16.08	24.32	-6.00	7.85	-63.26	31.93
Chile	4.08	8.53	10.19	16.92	4.56	10.48	34.81	47.78
Easter Island (Chile)	12.72	21.12	20.42	24.20	9.96	22.62	55.40	80.55
Desventuradas Islands (Chile)	-1.76	7.66	-2.93	6.03	-4.51	8.32	-5.06	21.29
China	-6.38	9.13	-11.07	4.24	-6.97	7.84	-24.07	2.94
Taiwan Province of China	-11.12	18.80	-18.32	13.10	-10.62	12.55	-32.62	17.86
Christmas Island	3.58	15.49	5.52	16.39	1.37	7.22	-25.40	67.02
Cocos (Keeling) Islands	0.57	8.75	2.95	8.98	0.58	4.40	-4.71	43.41
Comoros	0.51	14.51	-9.82	8.60	-0.82	16.78	-46.51	84.82
Mayotte	3.58	16.32	-10.96	20.62	1.81	15.43	-48.84	92.19
Democratic Republic of the Congo	-46.29	22.53	-53.86	25.22	-48.51	24.77	-63.79	29.31
Congo	-29.09	36.06	-42.65	24.89	-33.82	52.05	-60.57	35.16
Cook Islands	-4.23	4.84	-24.44	29.50	-8.33	4.64	-52.72	2.89
Cuba	-10.82	13.65	-15.25	21.56	-3.57	18.74	-40.06	16.91
Benin	-20.91	63.99	-24.68	73.89	-15.34	70.36	-65.97	33.28
Dominica	-11.79	14.46	-11.87	21.16	-9.38	10.27	-21.72	35.06

Scenarios	**DBEM model: Mid Century RCP2.6**		**DBEM model: Mid Century RCP8.5**		**DBEM model: End of Century RCP2.6**		**DBEM model: End of Century RCP8.5**	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Dominican Republic	-9.48	11.61	-4.44	17.86	-2.67	13.77	-18.72	31.10
Ecuador	-54.67	50.03	-79.45	36.51	-53.45	58.66	-82.36	40.48
Galapagos Islands (Ecuador)	2.73	5.19	2.86	18.75	2.48	4.42	-21.19	84.44
El Salvador	3.32	28.47	-20.06	122.52	-0.71	24.98	-93.05	9.19
Equatorial Guinea	-34.11	41.40	-47.48	51.31	-34.24	41.32	-67.72	19.36
Faroe Islands	-6.75	12.89	-15.95	4.48	-14.84	4.11	-37.05	41.41
Falkland Islands (Malvinas)	2.05	3.85	10.56	9.68	6.36	6.22	21.74	13.59
South Georgia and the South Sandwich Islands	-2.59	6.64	1.83	27.55	-8.01	3.62	4.28	50.58
Fiji	3.53	5.76	1.34	10.55	3.17	13.41	-20.80	21.95
Islands in the Mozambique Channel	-1.56	16.34	-11.01	11.85	-3.70	15.99	-54.22	9.47
Tromelin Island	-7.72	0.84	-10.81	6.25	-13.04	7.65	-13.84	16.58
French Guyana	-12.51	27.61	-0.93	40.83	0.87	11.76	-17.22	100.23
French Polynesia	-1.55	10.52	-3.17	16.86	-2.94	10.97	-14.77	15.63
Gabon	-48.15	44.61	-63.73	26.62	-47.39	46.50	-69.85	28.94
Gambia	4.63	2.87	6.19	5.73	7.76	5.41	-28.31	18.63
Germany (North Sea)	-24.29	45.60	-25.32	35.09	-21.66	28.30	-43.29	55.56
Ghana	-25.76	41.22	-35.02	57.28	-25.19	48.87	-76.15	6.84
Greenland	65.46	162.81	73.21	230.49	73.62	248.28	81.41	268.58
Grenada	-13.93	53.46	-12.57	52.34	0.21	44.23	7.66	143.38
Guadeloupe	-7.81	13.08	-4.83	21.10	-6.35	12.02	-2.43	52.53
Guam	-3.43	6.70	-8.74	6.00	-6.93	3.86	-83.13	27.16
Guinea	-14.29	43.80	-30.32	58.47	-14.62	45.34	-65.00	17.31
Guyana	-4.88	19.34	-4.36	33.92	4.03	2.63	-1.31	96.81
Haiti	-7.93	17.17	-5.93	24.76	-3.83	14.93	-51.05	34.89
Heard and McDonald Islands	-9.00	14.48	-7.16	13.54	-15.51	20.19	-22.91	5.07
Iceland	23.60	75.01	10.92	77.57	10.69	62.65	-5.38	61.88
India (mainland)	-10.30	23.92	-17.03	42.38	-7.18	16.64	-43.67	61.93
Andaman and Nicobar Islands	0.25	5.40	1.50	26.46	-1.79	3.71	-50.09	64.87
Indonesia (eastern)	-12.51	16.37	-31.60	28.27	-17.42	21.19	-64.43	26.00
Ireland	-33.43	74.12	-39.44	69.86	-33.88	68.30	-50.52	70.67
Côte d'Ivoire	-31.14	39.51	-37.73	52.06	-31.82	55.17	-72.25	6.29
Jamaica	-4.82	5.80	3.19	23.56	-1.36	7.37	-39.78	41.36
Japan	-3.85	10.53	-6.20	4.92	-1.61	5.93	-11.85	17.36
Johnston Atoll	0.08	9.41	-11.24	17.10	-2.58	6.66	-37.23	60.77
Kenya	1.88	9.43	2.02	24.14	3.42	9.75	-48.43	74.28
Democratic People's Republic of Korea	0.82	4.96	-3.16	15.71	-2.49	5.63	-8.77	15.40
Republic of Korea	3.74	8.64	4.06	4.48	2.16	9.49	-4.57	4.67
Liberia	-41.32	51.40	-44.32	65.61	-38.81	58.65	-76.26	9.40
Madagascar	-1.84	16.52	-12.20	6.64	-4.59	17.66	-39.90	25.75
Malaysia	-10.00	18.79	-25.17	32.45	-15.22	11.23	-64.94	42.70
Sabah (Malaysia)	-7.08	16.97	-20.80	49.47	-10.54	14.09	-55.24	8.16
Maldives	-11.17	13.85	-30.97	57.40	-9.73	10.85	-84.97	5.54
Sarawak (Malaysia)	-15.35	20.20	-29.01	43.37	-17.45	13.88	-51.93	42.79
Martinique	-12.57	20.54	-14.32	27.31	-9.60	15.67	-27.39	34.41

Scenarios	DBEM model: Mid Century RCP2.6		DBEM model: Mid Century RCP8.5		DBEM model: End of Century RCP2.6		DBEM model: End of Century RCP8.5	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Mauritania	-5.26	5.55	-6.13	5.01	-4.42	9.29	-17.36	23.76
Mauritius	-3.32	11.76	0.23	18.94	-6.54	17.15	-4.34	16.73
Hawaii (United States of America)	-3.01	12.23	-7.35	14.13	-0.43	7.99	-16.83	25.65
Montserrat	-5.73	10.96	-1.86	24.72	-3.76	7.63	5.93	57.69
Mozambique	-8.51	8.95	-14.25	4.74	-13.70	11.71	-34.90	52.50
Oman	-2.94	17.00	-8.92	28.09	-0.75	8.59	-24.82	56.63
Namibia	-12.47	15.43	-16.60	17.10	-6.10	9.31	-34.46	22.58
Nauru	-45.16	78.51	-98.86	1.85	-42.48	29.01	-99.81	0.13
Netherlands	-19.93	27.39	-21.83	23.09	-19.03	17.28	-38.21	41.13
New Caledonia	4.65	19.47	-0.25	2.17	0.64	18.14	-10.68	15.73
Vanuatu	5.69	14.92	1.18	3.74	7.68	30.63	-23.95	21.97
New Zealand	-2.82	2.97	-2.27	5.02	1.04	7.18	-0.43	5.38
Nigeria	-17.12	64.98	-33.82	70.36	-15.38	68.35	-52.75	26.91
Niue	0.07	17.92	-2.21	12.89	-3.47	19.17	-3.36	21.62
Norfolk Island	-1.62	4.45	-0.96	3.26	-2.17	6.09	-10.71	7.81
Norway	3.34	6.41	-2.91	5.00	2.45	13.51	-28.77	45.31
Jan Mayen Island	993.66	2 765.99	573.79	1 673.96	1 148.64	3 402.58	777.46	2 130.39
Northern Mariana Islands	-5.44	3.11	-8.53	4.35	-7.07	4.34	-37.30	56.88
Micronesia (Federated States of)	-23.79	41.93	-65.55	41.18	-32.57	47.73	-96.73	3.26
Marshall Island	-12.04	25.80	-39.47	30.68	-15.56	27.70	-82.13	16.45
Palau	-24.23	48.14	-71.41	52.65	-31.16	53.19	-99.30	1.04
Pakistan	-9.20	47.19	-13.64	52.58	-0.68	27.42	-22.71	88.03
Papua New Guinea	-18.40	19.57	-35.87	3.21	-25.83	15.27	-61.19	13.11
Peru	-8.75	4.73	-30.21	24.30	-9.57	9.23	-55.30	43.93
Philippines	-8.26	19.61	-23.72	35.15	-11.22	15.30	-59.21	25.70
Pitcairn Islands	7.91	22.63	9.52	13.63	4.30	23.71	14.26	22.41
Portugal	-12.28	2.74	-14.75	23.05	-16.43	5.83	-24.54	50.20
Madeira Islands	-14.29	23.32	-19.72	17.15	-17.33	25.83	-22.52	25.75
Azores (Portugal)	-15.28	13.79	-19.24	11.27	-6.83	32.78	-40.11	8.40
Guinea-Bissau	-14.32	45.35	-20.95	47.01	-10.86	40.13	-65.03	29.23
Timor-Leste	-5.16	10.65	-8.87	18.55	-8.18	9.09	-45.65	48.37
Puerto Rico	-6.54	8.55	-2.69	14.47	-2.61	11.23	-4.30	30.89
Réunion	-6.05	9.90	-11.17	15.19	-12.52	16.33	-15.73	19.46
Russian Federation	60.31	73.74	75.38	66.06	62.85	63.48	138.03	191.10
Saint Helena	-4.21	9.95	-3.23	18.60	-1.65	8.33	-5.27	22.92
Saint Kitts and Nevis	-7.09	8.22	-1.59	25.19	-4.34	8.64	6.37	58.53
Anguilla	-6.67	7.21	-2.25	17.74	-0.68	10.69	4.02	45.35
Saint Lucia	-17.74	30.11	-23.55	33.05	-12.28	17.58	-40.28	37.04
Saint Pierre and Miquelon	-7.00	7.73	-13.71	9.52	-8.21	8.39	-21.37	19.55
Saint Vincent and the Grenadines	-19.26	35.16	-26.05	38.42	-11.69	20.47	-32.17	51.86
Sao Tome and Principe	-32.15	34.78	-53.14	48.81	-33.05	32.10	-82.68	12.75
Senegal	1.98	5.00	4.72	10.98	5.17	4.98	-28.38	7.57
Seychelles	-8.39	3.36	-15.58	3.68	-8.66	1.92	-68.45	30.02
Sierra Leone	-17.21	37.02	-35.13	64.66	-22.69	49.63	-57.41	9.93
Singapore	-35.13	61.77	-73.45	61.76	-41.47	34.94	-99.96	0.11
Viet Nam	-6.77	8.85	-11.71	9.76	-7.49	2.30	-40.76	16.39

Scenarios	**DBEM model: Mid Century RCP2.6**		**DBEM model: Mid Century RCP8.5**		**DBEM model: End of Century RCP2.6**		**DBEM model: End of Century RCP8.5**	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Somalia	-10.30	3.22	-22.39	2.35	-9.52	1.71	-60.89	44.32
Prince Edward Island	3.98	27.14	-0.53	23.96	2.36	18.59	9.24	64.97
Canary Islands	-2.58	22.85	-2.51	17.90	-5.17	16.45	6.30	27.03
Suriname	-13.84	69.14	-14.49	63.54	0.88	43.03	-16.09	95.44
Svalbard	386.16	897.82	532.97	1 272.25	486.22	1 097.20	566.33	1 236.33
Togo	-22.60	62.42	-30.63	74.57	-16.78	69.99	-71.47	18.66
Tokelau	-41.69	61.81	-70.36	60.84	-41.10	61.28	-96.04	2.68
Tonga	0.76	16.29	-0.81	11.50	-1.99	18.11	-11.59	18.31
Trinidad and Tobago	-10.95	42.24	-12.00	36.51	2.80	29.75	-5.39	97.16
Turks and Caicos Islands	-3.68	9.91	5.87	26.83	9.54	35.23	-16.54	51.83
Tuvalu	-52.53	78.08	-79.69	29.69	-54.68	69.31	-99.65	0.91
United Kingdom	-15.11	29.89	-17.88	43.37	-17.73	25.52	-34.52	49.29
Channel Islands	-26.63	35.27	-28.83	37.06	-25.42	35.38	-43.14	33.39
United Republic of Tanzania	0.80	5.94	-1.60	21.17	2.14	8.90	-52.40	79.76
Palmyra Atoll and Kingman Reef	-18.97	53.02	-35.80	85.07	-15.49	38.79	-98.68	1.57
Jarvis Island	-2.37	2.99	-8.99	10.04	-7.49	4.76	-90.58	16.79
Howland Island and Baker Island	-13.16	19.82	-30.31	29.58	-22.02	20.26	-100.00	0.00
United States of America (West Coast)	-3.57	12.48	-6.02	12.46	-9.28	22.69	-12.31	27.59
United States Virgin Islands	-5.01	8.01	-0.58	16.17	-3.48	4.67	3.66	46.62
United States of America (East Coast and Gulf of Mexico)	-8.30	9.05	-11.40	12.93	-8.98	11.50	-36.29	7.83
Ascension Island	-6.57	9.98	-8.70	7.34	-3.10	3.53	-25.47	42.43
Tristan da Cunha Island	5.31	13.27	9.04	12.75	8.70	12.70	25.42	29.63
Uruguay	-8.79	20.69	-10.43	46.02	-5.91	21.68	-17.65	53.24
Venezuela (Bolivarian Republic of)	-15.77	37.97	-16.24	42.13	-5.07	13.74	-23.97	57.42
Wake Island	-3.69	5.39	-11.12	1.31	-5.39	12.12	-19.84	19.62
Wallis and Futuna Island	-4.58	8.29	-13.44	33.00	-7.05	9.28	-81.75	6.06
Samoa	-2.86	2.40	-6.65	28.10	-5.49	1.81	-77.82	2.41
St Paul and Amsterdam Islands (French Southern and Antarctic Territories)	-2.71	13.03	0.02	10.29	-1.83	16.89	3.30	18.98
Crozet Islands (French Southern and Antarctic Territories)	-6.38	13.48	-9.01	5.60	-9.36	25.14	-7.81	34.22
Kerguelen Islands (French Southern and Antarctic Territories)	-5.57	7.22	-3.40	15.81	-1.06	30.57	6.16	55.21
Clipperton Island	0.05	0.33	-1.00	7.34	-2.46	5.25	-64.30	97.98
Saint Barthélemy	-8.30	6.73	-2.06	26.47	-5.38	8.33	8.70	69.63
Saint-Martin (French Part)	-8.67	1.49	-3.62	19.25	-6.78	7.14	4.61	56.62
Curaçao	-18.33	49.71	-22.46	56.08	-11.97	28.39	-14.29	102.91
Bonaire	-19.70	51.38	-22.59	58.39	-11.50	17.84	-6.90	124.97
Sint Eustatius and Saba	-7.81	5.34	-2.37	24.94	-5.48	5.67	4.42	57.17
Sint Maarten (partie néerlandaise)	-9.35	3.58	-4.50	20.32	-7.15	6.03	3.82	59.60
France (Atlantic Coast)	-22.65	37.56	-26.12	32.54	-24.53	39.63	-37.96	22.16
Honduras (Pacific)	-0.25	23.49	-17.93	99.27	-2.46	20.50	-92.54	8.93

Scenarios	DBEM model: Mid Century RCP2.6		DBEM model: Mid Century RCP8.5		DBEM model: End of Century RCP2.6		DBEM model: End of Century RCP8.5	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Honduras (Caribbean)	-0.82	27.54	20.58	78.94	1.76	22.03	-26.04	55.05
Canada (Pacific)	1.22	12.11	3.37	16.32	0.34	12.84	14.06	15.60
Canada (East Coast and Arctic)	6.32	15.72	8.57	19.79	4.49	23.59	-6.51	38.82
Colombia (Caribbean)	-2.65	46.92	-0.64	60.06	1.07	41.77	-37.74	12.77
Colombia (Pacific)	-4.57	43.68	-14.66	66.30	0.51	39.24	-52.65	89.00
Costa Rica (Caribbean)	4.58	48.70	31.39	152.89	3.54	39.37	-54.33	21.36
Costa Rica (Pacific)	1.16	20.17	-14.48	80.55	0.12	22.59	-89.04	16.44
Denmark (North Sea)	-23.88	51.71	-26.64	38.84	-21.82	34.18	-44.04	56.27
Guatemala (Pacific)	6.06	13.70	-13.30	96.89	0.67	15.59	-94.28	6.58
Indonesia	-12.70	30.76	-28.63	49.59	-18.35	29.62	-62.70	32.52
Kiribati (Gilbert Islands)	-34.16	56.96	-72.61	35.43	-41.82	37.07	-94.04	3.56
Kiribati (Line Islands)	-1.92	4.08	-18.78	24.18	-7.98	0.93	-93.76	9.92
Kiribati (Phoenix Islands)	-43.85	67.23	-59.76	56.04	-46.94	56.87	-99.66	0.49
Mexico (Atlantic)	-15.76	30.56	-32.19	2.28	-3.28	40.49	-43.05	16.57
Mexico (Pacific)	-0.25	11.49	-6.55	21.55	-4.92	18.46	-28.61	30.74
Morocco (South)	-2.38	1.72	-6.59	13.43	-7.32	14.64	-14.46	19.68
Nicaragua (Caribbean)	-3.19	27.61	17.30	73.22	1.40	25.30	-35.09	46.19
Nicaragua (Pacific)	4.05	26.96	0.97	80.03	1.96	25.39	-92.15	9.77
Panama	-5.38	28.92	-20.00	58.50	-3.66	30.22	-73.42	27.41
South Africa	-8.25	12.96	-15.26	16.26	-9.54	15.38	-21.19	25.22
Thailand (Andaman Sea)	0.66	15.48	-8.82	51.55	-1.62	17.93	-34.38	58.20
Thailand (Gulf of Thailand)	-9.87	8.88	-26.08	16.81	-12.21	3.92	-95.03	7.65
United States of America (Alaska)	10.31	36.77	13.14	55.27	8.00	20.63	33.74	125.58
Spain (Northwest)	-16.13	30.01	-19.43	20.12	-19.37	34.22	-27.54	2.53
Aruba	-16.98	46.43	-22.78	50.27	-11.66	23.74	-23.03	73.53
Îles Glorieuses	1.45	13.32	2.17	23.58	-0.53	15.81	-37.29	79.95

TABLE 4.2

Projected changes in catch potential (%) by 2050 and 2100 relative to 2000 under RCP2.6 and RCP8.5 based on outputs from the dynamic size-based food web model. The table shows the average change per EEZ as well as the variability (range) around the average, representing the different estimates from the array of climate models used to drive the projections

Scenarios	Dynamic size-based food web model: Mid Century RCP2.6		Dynamic size-based food web model: Mid Century RCP8.5		Dynamic size-based food web model: End of Century RCP2.6		Dynamic size-based food web model: End of Century RCP8.5	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
American Samoa	-2.22	15.34	-7.61	48.31	-2.96	21.61	-6.55	90.51
Angola	-10.90	28.37	-30.10	33.31	-7.43	2.25	-51.51	62.34
Antigua and Barbuda	-21.46	46.02	-18.74	51.96	-21.46	45.07	-24.14	53.12
Argentina	-1.46	5.20	-3.67	3.53	-1.95	2.13	-13.82	18.28
Australia	-3.00	4.25	-12.24	12.80	-0.45	4.11	-34.05	30.66
Macquarie Island (Australia)	-3.47	10.21	1.67	11.53	1.54	7.57	-3.85	14.26
Bangladesh	0.65	2.77	-1.70	7.22	0.74	3.00	-3.51	12.57
Bahamas	-13.71	26.12	-17.31	13.85	1.75	9.24	-10.99	55.95
Barbados	-21.03	40.97	-16.60	41.08	-17.83	28.59	-22.32	41.18
Belgium	-7.95		-5.96		-8.61		-19.21	
Bermuda	-2.37	2.10	-13.52	14.59	13.27	23.00	-17.99	38.63
Bouvet Island	1.70	11.65	4.84	25.05	5.30	16.64	10.62	43.45
Brazil	-0.84	1.87	-6.57	10.39	0.00	1.85	-14.70	22.36
Trindade and Martim Vaz Island (Brazil)	20.58	25.77	15.74	44.68	16.97	5.27	-16.13	35.69
Belize	-14.65	16.04	-17.49	25.69	-14.14	18.12	-27.16	20.72
Chagos Archipelago	-25.71	27.52	-37.08	35.07	-20.52	37.51	-58.04	47.60
Solomon Islands	-4.01	13.11	-18.74	31.97	-12.71	17.03	-47.10	24.30
British Virgin Island	-14.29	20.82	-11.88	22.51	-16.75	46.14	-14.83	16.24
Brunei Darussalam	-10.94	43.04	-13.41	26.96	-8.85	33.61	-28.42	22.59
Myanmar	6.32	1.87	2.04	15.84	4.15	4.86	4.19	24.76
Cambodia	-3.55	16.13	-0.71	21.13	-4.26	10.58	2.12	31.32
Cameroon	-6.77	19.89	-3.94	11.68	-3.76	5.20	-10.79	20.45
Cabo Verde	-12.31	27.42	-33.31	33.02	-7.39	41.66	-58.31	44.76
Cayman Islands	-14.63	16.10	-14.37	17.05	-12.20	18.31	-20.53	13.23
Sri Lanka	-35.67	36.64	-43.66	55.18	-22.93	18.35	-68.48	68.78
Chile	-3.58	6.85	-3.60	17.88	-4.29	9.32	-3.38	46.33
Easter Island (Chile)	10.63	31.93	10.64	52.63	11.36	17.13	31.01	142.96
Desventuradas Islands (Chile)	3.05	5.16	12.92	13.93	2.54	16.14	24.97	29.81
China	-4.20	6.09	-4.74	9.40	-4.20	5.72	-9.20	11.44
Taiwan Province of China	-13.06	19.88	-17.95	12.58	-10.72	15.90	-30.68	25.52
Christmas Island	10.81	11.79	-2.70	33.53	3.68	8.41	-15.02	54.64
Cocos (Keeling) Islands	14.29	21.08	-10.43	40.42	1.90	0.91	-33.95	57.87
Comoros	-16.88	23.12	-20.10	27.68	-14.02	14.22	-32.27	41.14
Mayotte	-12.32	15.07	-15.83	17.67	-10.14	9.98	-24.73	31.19
Democratic Republic of the Congo	-10.82	10.59	-10.76	14.87	-9.62	8.23	-23.63	17.53
Congo	-3.16	9.80	-1.98	9.95	-3.16	9.59	-2.33	19.04
Cook Islands	3.96	14.02	-7.67	40.89	3.96	18.14	2.39	86.39
Cuba	-13.48	22.87	-12.61	20.31	-10.11	19.96	-17.82	10.87
Benin	-21.86	37.98	-18.41	52.59	-18.97	40.06	-36.65	64.39
Dominica	-25.16	46.35	-22.85	49.23	-22.55	39.24	-27.82	45.18
Dominican Republic	-16.98	26.79	-13.63	29.61	-16.04	36.55	-19.31	14.94

Scenarios	Dynamic size-based food web model: Mid Century RCP2.6		Dynamic size-based food web model: Mid Century RCP8.5		Dynamic size-based food web model: End of Century RCP2.6		Dynamic size-based food web model: End of Century RCP8.5	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Ecuador	-2.27	13.35	-20.53	39.15	-3.65	6.01	-31.24	38.15
Galapagos Islands (Ecuador)	-4.04	6.22	-9.56	31.37	-2.91	7.46	-19.27	47.01
El Salvador	-2.79	10.80	-7.57	49.74	-2.79	4.42	-0.82	77.34
Equatorial Guinea	-13.78	9.42	-15.06	31.71	-9.76	11.06	-31.45	42.03
Faroe Islands	-10.62	26.58	-21.83	80.79	-26.34	28.64	-37.79	119.16
Falkland Islands (Malvinas)	-0.42	2.61	-4.31	6.17	0.14	4.12	-7.99	16.06
South Georgia and the South Sandwich Islands	5.88	16.96	5.17	24.26	-1.31	14.42	17.81	47.16
Fiji	1.78	21.62	-11.22	35.14	-0.85	29.09	-35.49	30.81
Islands in the Mozambique Channel	-7.05	4.77	-16.99	9.87	-7.45	11.08	-27.52	21.56
Tromelin Island	-15.50	17.17	-19.13	24.95	-16.00	18.02	-29.47	38.79
French Guyana	-7.14	5.45	-8.19	12.97	-4.15	7.25	-13.84	16.77
French Polynesia	-2.75	2.59	-10.60	22.88	-0.40	8.31	-10.44	57.02
Gabon	-4.63	7.15	-2.25	5.98	-4.37	4.23	-4.34	15.41
Gambia	-26.19	29.86	-22.77	26.62	-12.52	30.02	-44.37	43.94
Germany (North Sea)	-19.47	20.50	-18.87	28.15	-24.09	20.52	-24.14	23.37
Ghana	-32.17	30.42	-26.26	50.37	-21.72	38.24	-45.24	65.30
Greenland	-1.71	38.21	-0.22	51.22	-1.02	21.25	-24.73	43.33
Grenada	-8.49	32.39	-7.52	35.98	-15.44	27.37	-13.15	37.44
Guadeloupe	-25.08	51.50	-23.64	54.79	-24.13	44.49	-28.12	54.42
Guam	-24.71	19.11	-31.96	17.12	-19.17	23.32	-53.58	21.32
Guinea	-26.76	30.90	-18.78	37.79	-22.43	29.11	-30.40	54.33
Guyana	-18.69	36.34	-11.88	42.53	-14.59	17.40	-16.46	38.33
Haiti	-18.09	25.36	-15.30	25.30	-15.08	31.90	-25.33	21.61
Heard and McDonald Islands	0.00	12.52	-1.72	8.52	1.27	7.41	-4.34	14.82
Iceland	-2.31	22.22	-15.55	61.20	-11.08	18.56	-32.12	83.03
India (mainland)	-7.34	17.57	-17.15	34.30	-3.43	2.35	-26.51	58.60
Andaman and Nicobar Islands	5.80	12.71	-5.10	63.30	7.41	13.61	-9.76	79.38
Indonesia (eastern)	0.99	1.71	-9.91	20.58	-1.64	5.21	-28.59	41.25
Ireland	-44.44	60.61	-39.83	98.51	-58.24	82.73	-51.37	83.09
Côte d’Ivoire	-30.50	28.96	-25.42	49.35	-22.58	35.90	-41.68	65.20
Jamaica	-17.07	24.59	-16.75	28.91	-12.80	28.77	-26.73	24.70
Japan	-9.22	12.56	-15.01	10.97	-5.18	6.17	-30.26	28.90
Johnston Atoll	-9.60	9.46	-27.91	55.13	-7.07	27.18	-42.59	42.49
Kenya	-25.79	25.47	-31.84	26.14	-12.43	28.66	-45.68	44.64
Democratic People’s Republic of Korea	-14.18	20.18	-20.20	21.54	-4.34	24.57	-22.04	41.97
Republic of Korea	-5.26	6.72	-9.43	13.05	-5.22	9.94	-15.05	14.27
Liberia	-29.30	33.15	-25.09	54.08	-27.37	38.38	-37.42	71.19
Madagascar	-6.30	8.77	-15.16	7.14	-6.09	8.41	-21.31	14.71
Malaysia	1.90	11.80	-4.28	13.87	4.84	22.55	8.82	33.94
Sabah (Malaysia)	-8.26	38.19	-17.15	23.87	-8.26	24.98	-39.29	28.11
Maldives	-29.10	23.57	-32.45	25.19	-12.96	20.13	-46.50	39.39
Sarawak (Malaysia)	-10.26	33.69	-7.55	19.70	-6.84	25.86	-14.74	16.42
Martinique	-23.12	43.47	-22.71	44.97	-20.70	35.33	-27.83	41.88
Mauritania	-9.26	29.48	-34.01	41.46	-6.27	36.91	-66.00	59.05

Scenarios	**Dynamic size-based food web model: Mid Century RCP2.6**		**Dynamic size-based food web model: Mid Century RCP8.5**		**Dynamic size-based food web model: End of Century RCP2.6**		**Dynamic size-based food web model: End of Century RCP8.5**	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Mauritius	-17.68	13.46	-21.29	23.81	-17.92	13.43	-30.85	35.58
Hawaii (United States of America)	-19.66	24.29	-32.45	30.54	-7.03	6.92	-53.98	41.66
Montserrat	-23.44	48.05	-20.63	55.38	-20.31	41.58	-25.07	49.05
Mozambique	-7.86	3.17	-14.66	11.05	-5.08	11.90	-23.30	21.79
Oman	-19.91	31.15	-20.89	35.54	-10.63	18.52	-53.27	70.96
Namibia	-3.14	9.56	-8.77	37.99	-2.43	1.39	-34.01	40.45
Nauru	-26.44	35.97	-36.53	28.98	-11.63	31.24	-55.32	41.10
Netherlands	-9.86	9.79	-9.44	18.68	-15.99	11.58	-17.39	21.04
New Caledonia	3.33	16.22	-10.83	33.81	-3.76	3.81	-59.86	34.44
Vanuatu	0.91	6.97	-11.41	19.55	-8.94	11.11	-45.34	13.72
New Zealand	-1.58	4.11	-4.49	1.57	1.25	2.65	-10.76	4.42
Nigeria	-9.09	23.65	-11.92	40.53	-11.22	22.31	-24.82	53.47
Niue	6.16	17.54	-10.16	42.78	9.32	26.84	-8.68	65.78
Norfolk Island	0.00	10.78	-14.28	9.99	4.60	8.30	-46.32	45.26
Norway	-2.80	40.05	-11.35	78.18	-8.67	33.59	-38.19	102.44
Jan Mayen Island	11.66	69.19	6.71	51.87	-2.65	52.12	-28.71	185.90
Northern Mariana Islands	-30.03	22.81	-31.82	17.30	-25.87	23.11	-48.40	21.40
Micronesia (Federated States of)	-7.80	9.10	-21.04	18.45	-14.56	13.62	-42.98	25.70
Marshall Island	-16.07	6.44	-23.17	27.54	-15.32	18.00	-38.40	29.75
Palau	-7.14	13.79	-18.92	17.39	-13.69	7.15	-51.42	20.92
Pakistan	-22.96	31.39	-27.54	33.80	-8.30	25.23	-55.04	60.08
Papua New Guinea	-6.67	2.71	-16.56	19.65	-7.39	8.53	-35.39	31.04
Peru	-4.49	4.70	-8.88	19.50	-3.16	6.92	-22.68	48.71
Philippines	-9.25	23.15	-23.33	23.89	-5.04	16.97	-42.19	26.63
Pitcairn Islands	9.38	25.20	14.40	41.69	5.16	11.89	9.35	66.62
Portugal	-67.40	65.79	-36.78	85.48	-65.88	76.90	-42.20	99.75
Madeira Islands	-28.46	29.26	-18.27	28.66	-27.98	34.82	-29.04	65.26
Azores (Portugal)	-50.82	62.26	-47.24	64.02	-63.53	74.30	-66.75	58.07
Guinea-Bissau	-34.14	32.01	-22.68	39.13	-25.67	32.13	-37.49	57.00
Timor-Leste	-0.29	7.23	-14.21	21.39	-3.14	1.23	-36.78	46.16
Puerto Rico	-18.73	37.28	-14.92	38.74	-16.33	39.64	-20.32	33.26
Réunion	-7.39	9.18	-14.20	7.64	-6.82	1.45	-24.07	15.68
Russian Federation	2.97	24.78	-6.64	29.02	2.97	8.25	-22.57	66.34
Saint Helena	-14.94	18.12	-24.45	25.46	-0.62	25.64	-42.81	47.35
Saint Kitts and Nevis	-21.71	48.44	-18.16	55.99	-19.43	43.34	-24.15	50.81
Anguilla	-16.59	31.21	-13.63	37.93	-18.01	47.53	-18.54	34.73
Saint Lucia	-20.25	39.17	-20.05	40.15	-17.09	32.62	-24.61	34.64
Saint Pierre and Miquelon	-15.13	15.47	-15.20	28.46	-16.14	19.36	-35.59	32.21
Saint Vincent and the Grenadines	-16.38	35.18	-14.07	35.90	-14.66	29.03	-19.19	32.04
Sao Tome and Principe	-11.69	7.53	-12.81	30.12	-10.29	9.12	-26.61	35.58
Senegal	-29.95	32.02	-30.82	29.32	-10.05	31.38	-49.67	42.70
Seychelles	-26.09	32.25	-29.40	35.33	-18.52	28.92	-43.44	50.68
Sierra Leone	-29.72	40.08	-22.77	48.25	-26.63	40.41	-33.58	68.06
Singapore	-11.11	9.20	-13.75	8.03	-2.62	6.75	-14.10	20.84
Viet Nam	-2.78	14.83	-4.27	11.12	0.00	11.30	-6.53	18.22
Somalia	-30.71	37.47	-43.37	39.86	-22.78	29.48	-63.81	59.55

Scenarios	Dynamic size-based food web model: Mid Century RCP2.6		Dynamic size-based food web model: Mid Century RCP8.5		Dynamic size-based food web model: End of Century RCP2.6		Dynamic size-based food web model: End of Century RCP8.5	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Prince Edward Island	0.37	4.77	3.33	15.17	6.09	10.33	1.76	12.72
Canary Islands	-8.37	21.13	-19.99	18.03	-21.26	29.46	-30.01	58.92
Suriname	-18.50	21.56	-15.88	21.05	-5.14	9.77	-22.82	23.07
Svalbard	5.56	92.14	-0.63	112.78	-1.11	82.05	-24.51	84.15
Togo	-22.87	36.34	-19.60	53.01	-19.51	40.90	-38.13	64.93
Tokelau	-7.50	23.00	-13.45	36.15	-6.19	11.28	-11.98	65.81
Tonga	13.76	21.50	-6.05	39.75	5.46	24.19	-22.55	48.09
Trinidad and Tobago	-6.72	27.26	-3.58	31.60	-11.15	17.52	-7.45	30.34
Turks and Caicos Islands	-8.09	11.58	-8.86	30.65	3.47	38.49	-9.75	27.95
Tuvalu	-7.87	19.63	-21.31	30.73	-10.07	12.10	-33.56	43.60
United Kingdom	-27.39	33.77	-25.64	57.13	-42.13	48.06	-40.18	69.16
Channel Islands	-45.91	21.83	-30.70	61.88	-50.20	30.01	-38.91	75.69
United Republic of Tanzania	-23.31	27.79	-25.91	28.72	-12.90	27.03	-39.87	46.78
Palmyra Atoll and Kingman Reef	-11.24	19.08	-23.00	13.12	-10.66	16.25	-33.15	31.86
Jarvis Island	-7.89	11.06	-21.80	45.45	-3.86	25.52	-55.40	66.51
Howland Island and Baker Island	-22.62	25.00	-44.43	34.99	-6.59	42.58	-70.24	54.30
United States of America (West Coast)	-6.44	6.55	-7.13	6.07	-4.40	6.13	-4.13	4.15
United States Virgin Islands	-20.57	43.55	-17.31	45.42	-17.22	40.05	-23.69	43.13
United States of America (East Coast and Gulf of Mexico)	-3.97	9.58	-2.43	5.81	1.58	4.96	-4.87	12.55
Ascension Island	-5.08	4.57	-10.91	19.24	-3.31	8.44	-42.22	52.36
Tristan da Cunha Island	1.86	1.45	0.75	7.63	2.26	5.10	1.02	24.75
Uruguay	-7.44	24.44	-14.70	21.14	-7.69	18.51	-26.01	7.02
Venezuela (Bolivarian Republic of)	-19.53	40.86	-14.81	38.71	-17.19	35.17	-22.09	34.81
Wake Island	-35.96	22.64	-33.41	18.98	-15.93	30.71	-49.78	28.07
Wallis and Futuna Island	-5.19	20.24	-10.98	41.52	-4.55	25.96	-27.21	74.15
Samoa	-2.87	20.31	-8.84	47.48	-2.68	23.07	-16.32	87.40
St Paul and Amsterdam Islands (French Southern and Antarctic Territories)	-0.52	3.67	-3.85	4.42	2.10	7.29	-13.52	25.66
Crozet Islands (French Southern and Antarctic Territories)	2.12	4.00	3.11	11.27	2.12	10.27	5.53	16.29
Kerguelen Islands (French Southern and Antarctic Territories)	-0.21	6.98	-2.65	6.97	-0.63	4.94	-2.09	13.51
Clipperton Island	-2.69	19.43	-15.49	41.58	-1.80	22.94	-21.50	52.30
Saint Barthélemy	-20.59	48.01	-16.94	57.01	-20.59	44.92	-22.85	54.46
Saint-Martin (French Part)	-19.48	46.17	-17.41	52.70	-18.18	43.33	-23.73	51.03
Curaçao	-22.84	43.74	-18.40	43.61	-15.74	39.78	-27.22	38.53
Bonaire	-21.08	45.01	-18.14	47.04	-15.68	41.12	-26.98	42.71
Sint Eustatius and Saba	-19.88	44.96	-17.62	50.26	-17.06	40.76	-24.08	46.73
Sint Maarten (partie néerlandaise)	-19.38	45.09	-17.36	50.75	-16.88	41.85	-23.85	48.58
France (Atlantic Coast)	-67.50	61.97	-40.74	81.61	-77.20	84.93	-53.00	89.94
Honduras (Pacific)	-0.93	8.50	-1.53	55.95	4.64	10.87	8.65	99.10

Scenarios	**Dynamic size-based food web model: Mid Century RCP2.6**		**Dynamic size-based food web model: Mid Century RCP8.5**		**Dynamic size-based food web model: End of Century RCP2.6**		**Dynamic size-based food web model: End of Century RCP8.5**	
Metric	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Honduras (Caribbean)	-14.97	18.83	-17.32	26.63	-12.93	19.62	-25.87	22.86
Canada (Pacific)	-16.53	16.87	-7.66	30.04	-12.40	14.14	-17.55	34.57
Canada (East Coast and Arctic)	-7.95	15.71	-8.12	26.71	-10.60	15.46	-25.53	37.61
Colombia (Caribbean)	-17.15	39.29	-17.50	47.49	-10.46	38.75	-25.01	44.02
Colombia (Pacific)	-1.67	17.72	-18.67	46.14	0.30	6.39	-31.33	46.55
Costa Rica (Caribbean)	-11.30	9.93	-11.33	15.54	-7.81	13.80	-20.56	13.86
Costa Rica (Pacific)	-4.05	18.17	-20.92	44.19	-1.03	5.41	-32.19	46.55
Denmark (North Sea)	-25.13	25.41	-27.04	33.86	-29.27	24.46	-34.01	30.64
Guatemala (Pacific)	-2.52	18.27	-9.32	41.49	-3.77	8.98	-8.95	64.06
Indonesia	0.99	1.71	-9.91	20.58	-1.64	5.21	-28.59	41.25
Kiribati (Gilbert Islands)	-28.24	32.11	-42.27	30.94	-11.54	40.86	-62.80	42.49
Kiribati (Line Islands)	-7.44	15.00	-26.11	21.89	-4.46	21.73	-47.55	51.78
Kiribati (Phoenix Islands)	-19.21	16.40	-37.34	22.83	-12.50	31.68	-57.66	40.15
Mexico (Atlantic)	-2.98	7.37	3.80	21.29	2.47	18.07	7.41	33.31
Mexico (Pacific)	-11.73	25.46	-29.32	36.38	-5.56	17.32	-43.71	43.42
Morocco (South)	-26.14	33.47	-18.07	60.89	-30.59	48.24	-20.55	160.47
Nicaragua (Caribbean)	-14.29	26.38	-16.56	34.78	-11.59	27.04	-25.79	30.80
Nicaragua (Pacific)	-3.03	12.07	-7.47	47.26	0.98	4.87	-0.93	73.28
Panama	-2.93	24.11	-21.71	42.40	-0.54	9.01	-33.87	46.77
South Africa	-3.72	13.84	-7.20	14.34	-0.57	6.31	-15.12	28.39
Thailand (Andaman Sea)	6.22	13.52	1.14	31.54	3.95	24.29	-3.73	35.34
Thailand (Gulf of Thailand)	-6.67	18.66	-1.42	24.19	-6.91	12.54	3.48	37.77
United States of America (Alaska)	-3.59	9.95	-9.13	10.14	-3.52	2.09	-15.96	24.62
Spain (Northwest)	-78.53	87.93	-47.26	91.91	-88.14	95.10	-55.59	103.56
Aruba	-23.62	44.32	-18.18	43.57	-15.58	40.04	-26.98	37.59
Îles Glorieuses	-14.86	21.83	-18.56	27.49	-12.89	10.76	-29.85	39.80

Chapter 5: Climate change impacts, vulnerabilities and adaptations: North Atlantic and Atlantic Arctic marine fisheries

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KEY MESSAGES

- For many countries bordering the North Atlantic, fisheries contribute very little to national gross domestic product (GDP) and per capita seafood consumption is low, hence, fisheries are not primarily concerned with maintaining food security. In Greenland, Iceland and the Faroe Islands however, fishing remains a nationally important activity.
- Throughout the North Atlantic there are specific communities, towns or regions that rely heavily on fisheries for employment and income-security. Indigenous peoples of the Atlantic Arctic such as the Inuit in Canada, Kalaallit in Greenland, the Saami in Norway and the Russian Federation are heavily reliant on fisheries to maintain cultural heritage and food security and are especially vulnerable to climate change.
- Large-scale changes in the distribution and productivity of commercial fish species have been observed on both sides of the North Atlantic and shifts in some key fisheries targets have created major challenges for resource allocation between different countries and fleets.
- For some species such as Atlantic cod, climate change can have opposite impacts on recruitment and productivity, depending on where the stock is located. Warmer temperatures are associated with poor recruitment of cod in the Celtic Sea, Irish Sea and North Sea, but good recruitment in the Barents Sea and Labrador coast of Canada.
- Dramatic, long-term decreases in ocean pH have been observed throughout the North Atlantic over multiple decades. Continued declines in pH are anticipated and the consequences for commercial shellfish or early life stages of important finfish remain unclear.
- Major biogeographical shifts in zooplankton have been documented in response to warming. Warm-temperate, pseudo-oceanic species experienced a poleward shift of about 10° of latitude or 23 km/yr for the period 1958 to 2005. Continued shifts in these prey species may pose threats to the productivity of some fish stocks.
- Large-scale redistribution of maximum fisheries catch potential is projected by 2055 under a business as usual scenario, including a 30 percent to 70 percent increase in yield of high-latitude regions, particularly the exclusive economic zone (EEZ)

regions of Norway and Greenland and the Grand Banks of Canada, and decreases at latitudes lower than around 50 °N.

- A wide diversity of climate change adaptation measures has been tested, applied and advocated in the North Atlantic region. These have tended to focus on capacity building within the sector, policy measures, building resilience through a reduction in other stressors, developing alternative markets or livelihoods and protecting critical infrastructure used by the fishing industry. Institutional, legal, financial and logistical barriers to successful adaptation have been encountered on both sides of the Atlantic.

5.1 REGIONS AND FISHERIES OF THE NORTH ATLANTIC

The North Atlantic (FAO major fishing areas 21 and 27) is a huge, ecologically, socially and economically diverse region spanning from the Azores in the south (37 °N) with average sea temperatures around 24 °C to Spitzbergen and north Greenland in the high Arctic (78 °N) with temperatures well below freezing (see Figure 5.1). It is bounded by two continents (North America and Europe).

The Northwest Atlantic (FAO major fishing area 21) has large, industrial fisheries active on the continental shelf such as the Grand Banks of Newfoundland, the Scotian Shelf and Georges Bank. Historically, fisheries mainly targeted demersal groundfish, primarily gadoids and flounders via otter trawling and fixed gears (e.g. gillnet, bottom longline). The main targets of pelagic trawlers (purse seiners) are Atlantic herring (*Clupea harengus*) and mackerel (*Scomber scombrus*). Other fisheries have increased in recent decades such as those on squids (shortfin [*Illex illecebrosus*] and longfin [*Doryteuthis pealeii*]). International waters support important fisheries for redfish (*Sebastes* spp.), flatfishes (yellowtail flounder [*Limanda ferruginea*] and American plaice [*Hippoglossoides platessoides*], Greenland halibut [*Reinhardtius hippoglossoides*]), cod (*Gadus morhua*) and capelin (*Mallotus villosus*). The size of groundfish fishing fleets has decreased in the most recent decades. The fleet in the United States of America decreased from 1 000 vessels in the mid-1990s to 400 vessels in 2012 (Thunberg and Correia, 2015). The largest decrease was a 69 percent decline in the number of limited access vessels, with an 80 percent decline in the Gulf of Maine. The share of small (less than 10 metre) and large (greater than or equal to 23 metres) vessels declined and increased, respectively. The diversity and size of gear (trawl, gillnet, hook) used by vessels fishing groundfish in the United States of America has remained relatively stable (Thunberg and Correia, 2015). In Atlantic waters off Canada, landings of groundfish decreased from 50 percent to 13 percent of the total national catch from 1991 to 2011 while the economic value of total fisheries catches increased as a result of a large upsurge in the landings of valuable shellfish (lobster [*Homarus americanus*], snow crab [*Chionoecetes opilio*] and shrimps) captured off Nova Scotia, Newfoundland and Labrador. More than 90 percent of the approximately 15 000 registered fishing vessels operating in Atlantic waters off Canada are small (less than 14 metres) and two-thirds of all landings in this region were from pots and traps (Department of Fisheries and Oceans Canada (DFO), Canadian Fisheries Statistics, 2011 to 2012[1]).

Most of the fisheries in the Northwest Atlantic are managed within the exclusive economic zones (EEZ) of the United States of America or Canada by National Oceanographic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) and DFO, respectively, as well as Greenland. Fishing rights on the Flemish Cap and all other deeper waters are governed by treaties maintained by the Northwest Atlantic Fisheries Organization (NAFO). Arctic fisheries take place mostly within the ice-free EEZs of the subarctic/boreal seas (see Blomeyer *et al.*, 2015). The most important fisheries in the Atlantic Arctic are in the Barents Sea (FAO

[1] http://www.dfo-mpo.gc.ca/stats/commercial/cfs/2012/cfs12-eng.htm

fishing area 27.1), the Norwegian Sea (FAO fishing area 27.2), and around Greenland and Iceland (FAO fishing areas 27.5 and 27.14), for cod, haddock (*Melanogrammus aeglefinus*), Atlantic herring, but also exclusively Arctic species including capelin, Greenland halibut, northern shrimp (*Pandalus borealis*) and polar cod (*Boreogadus saida*). In subarctic waters, the Norwegian and Barents seas have the greatest numbers of exploited species (more than 20 species each) including krill (*Thysanoessa inermis* and *T. longicaudata*) and copepods (*Calanus finmarchicus*). In the 1970s, polar cod was intensively fished by former Union of Soviet Socialist Republics, Norwegian, Danish and German Democratic Republic fleets in the Barents Sea, White Sea and in Soviet waters. Landings have declined from 348 000 tonnes in 1971 to less than 70 000 tonnes today with most of the current catches by the Russian Federation fleet (Blomeyer *et al.*, 2015). In the Barents Sea, capelin is targeted using pelagic trawls and purse seines and the species is also bycatch in fish and shrimp trawls. Strong fluctuations in the catches of capelin coincide with cycles of the Arctic Oscillation or Northern Annular Mode.

Atlantic cod is caught mainly with bottom otter trawls and pelagic trawls. The major fishing grounds for Atlantic cod are around Iceland, in the Barents Sea, off Newfoundland and West Greenland, with Iceland and Norway accounting for the biggest share of landings in recent years. Greenland halibut is caught on the deep shelf, mainly with bottom longlines and gillnets. Almost all of the Northeast Greenland halibut caught are by the Norwegian and Russian Federation fleets (Blomeyer *et al.*, 2015).

Fishing is of high economic importance for a few Northeast Atlantic (Northwest European) countries, notably Iceland, Greenland and the Faroe Islands. Fisheries products contribute 20 percent of national GDP for the Faroe Islands and Greenland and over 90 percent of their exports. Although, fishing accounts for less than one percent of Europe's total GDP, income and employment from fishing and related activities can be very important to certain fishery-dependent towns and coastal villages (see Section 5.6.1, below). Fisheries in the Northeast Atlantic are regulated through a combination of arrangements. These include national policies and regulations, the European Union (EU) Common Fisheries Policy, bilateral and multilateral agreements between countries with shared stocks, and measures adopted by the three regional fisheries management organizations: the North East Atlantic Fisheries Commission (NEAFC), the International Commission for Conservation of Atlantic Tunas (ICCAT), and the North Atlantic Salmon Conservation Organization (NASCO).

The main fishing nations dependent on the North Sea subregion (FAO fishing area 27.4) are the United Kingdom of Great Britain and Northern Ireland, Denmark, the Netherlands, Belgium, Germany and Sweden (STECF, 2017). The most valuable species include Atlantic mackerel, Atlantic cod, Atlantic herring, common sole (*Solea solea*), European plaice (*Pleuronectes platessa*) and brown shrimp (*Crangon crangon*). In 2015, the EU member state fleet had 4 955 vessels operating in the North Sea region with 47 percent from the United Kingdom of Great Britain and Northern Ireland. In 2015 Denmark, France and United Kingdom of Great Britain and Northern Ireland together accounted for around 73 percent of the total days at sea. Around 41 percent of the days at sea were undertaken by small-scale coastal vessels using passive gears. In 2015, the weight and value of landings generated by the North Sea fleet amounted to approximately 1.66 million tonnes and EUR 1.8 billion (equivalent to approximately USD 2.2 billion), respectively (STECF, 2017). In 2015, Atlantic herring (386 000 tonnes) was the most important species in terms of weight. Landings of European sprat (*Sprattus sprattus*), Atlantic mackerel, sandeels (*Ammodytes* spp.) and European plaice were the next most important species in terms of weight. In terms of value, the most important species were Atlantic mackerel followed by Atlantic cod, Atlantic herring, common sole, European plaice, common shrimp and Norway lobster (*Nephrops norvegicus*) (STECF, 2017).

The major players in the Northeast Atlantic margin subregion (FAO fishing areas 27.6–9) are the Spanish, French, United Kingdom of Great Britain and Northern Ireland, Portuguese and Irish fleets, with the latter two having the highest dependency on the region for production. The most important species include Atlantic mackerel, horse mackerel (*Trachurus trachurus*), hake (*Merluccius merluccius*) and Norway lobster (STECF, 2017). The ten EU member state fleets operating in the region collectively numbered over 14 600 active vessels in 2015 with the Spanish fleet comprising 37 percent of the total. The weight and value of landings generated by the Northeast Atlantic fleet amounted to approximately 1.4 million tonnes and EUR 2.4 billion (equivalent to approximately USD 2.9 billion), respectively (STECF, 2017). The main species landed in terms of weight were small pelagic species, including Atlantic mackerel, blue whiting (*Micromesistius poutassou*), followed by European hake and horse mackerel. The most valuable species were European hake followed by Atlantic mackerel, Norway lobster as well as monkfish (*Lophius piscatorius*) (STECF, 2017).

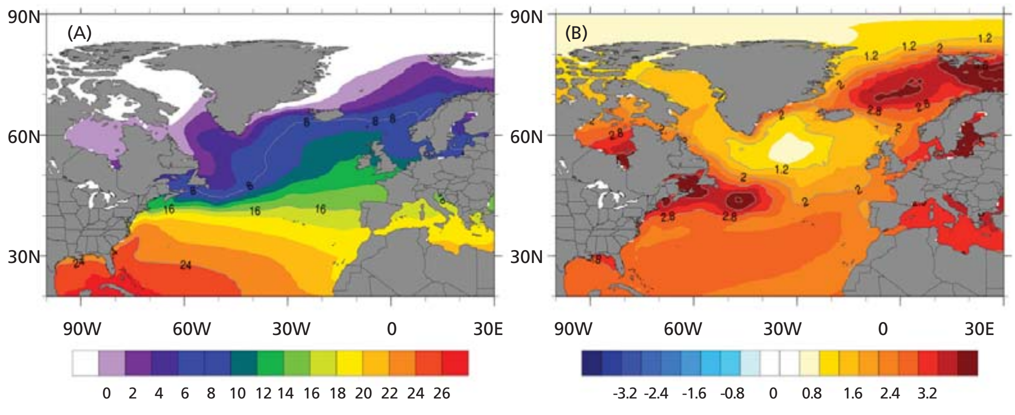
In 2015, the fleet of the Azores (FAO fishing area 27.10) consisted of 761 vessels, 85.5 percent of which had an overall length of 12 metres or less. The most representative species were various tuna species (41.2 percent) which, together with blue jack mackerel (*Trachurus picturatus*), blackspot seabream (*Pagellus bogaraveo*), conger eel (*Conger conger*) and silver scabbard fish (*Lepidopus caudatus*), represented around 66 percent of the total of landings (STECF, 2017).

5.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT

5.2.1 Temperature and salinity

FIGURE 5.1

Sea surface temperature (Climate Model Intercomparison Project version 5 [CMIP5] ensemble average, °C) interpolated on a 1×1 grid for the entire year



(A) mean climate from the historical experiment for the period (1956 to 2005); (B) difference in the mean climate in the future time period (RCP8.5: 2050 to 2099) compared to the historical reference period (1956 to 2005).

Sea surface temperatures (SST) in the North Atlantic have generally increased by 0.1 °C to 0.5 °C/decade over the past century, and the rate of warming has been particularly rapid since the 1980s. Warming is expected to continue, as suggested by global models (see Figure 5.1) into the future. From 1982 to 2010, spatial differences were observed in the SST trend across the North Atlantic with the highest rates of warming (well above 0.5 °C per decade) observed for the Gulf Stream front, the subpolar gyre and Labrador Sea on the western margin, and the European continental shelf above 50 °N in the east (Taboada and Anadón, 2012). On the other hand, the mean SST off Eastern Greenland decreased. Isotherms of annual mean SST have generally shifted to higher latitudes at a rate less than 50 km per decade (Taboada and Anadón, 2012). In the future, warming is expected everywhere (Figure 5.1) but particularly in the Atlantic-Arctic, including the Barents Sea and Greenland Sea, as well to the east of the Grand Banks, where SST is anticipated to rise by more than 3 °C over the next 50 to 100 years. By contrast, only moderate warming (less than 1 °C) is anticipated off SW Greenland (Figure 5.1).

In the Northwest Atlantic, the cold Labrador Current meets the warm Gulf Stream off the Grand Banks, southeast of Newfoundland and results in extremely rich fishing grounds. These currents interact with topographical discontinuities such as Cape Cod along the continental shelf to create large differences in the physical and chemical environment of the southern (mid-Atlantic shelf) and northern (Gulf of Maine and Scotian Shelf) components of the region. Within the last 35 years, summertime water temperatures in both southern and northern regions have warmed at approximately 1 °C per decade (Thomas *et al.*, 2017). Some areas such as the Gulf of Maine have changed more markedly and have witnessed changes in the seasonality of "summer" temperatures (earlier onset and increased duration).

Across the Northwest Atlantic, average SST is projected to increase an additional 2.0 °C to 4.0 °C by 2100 under the business as usual (RCP8.5) scenario with a high amount of spatial variability in warming (Figure 5.1). The frequency of storminess is expected to increase and sea level rise is expected to continue, which would negatively impact fishing activities.

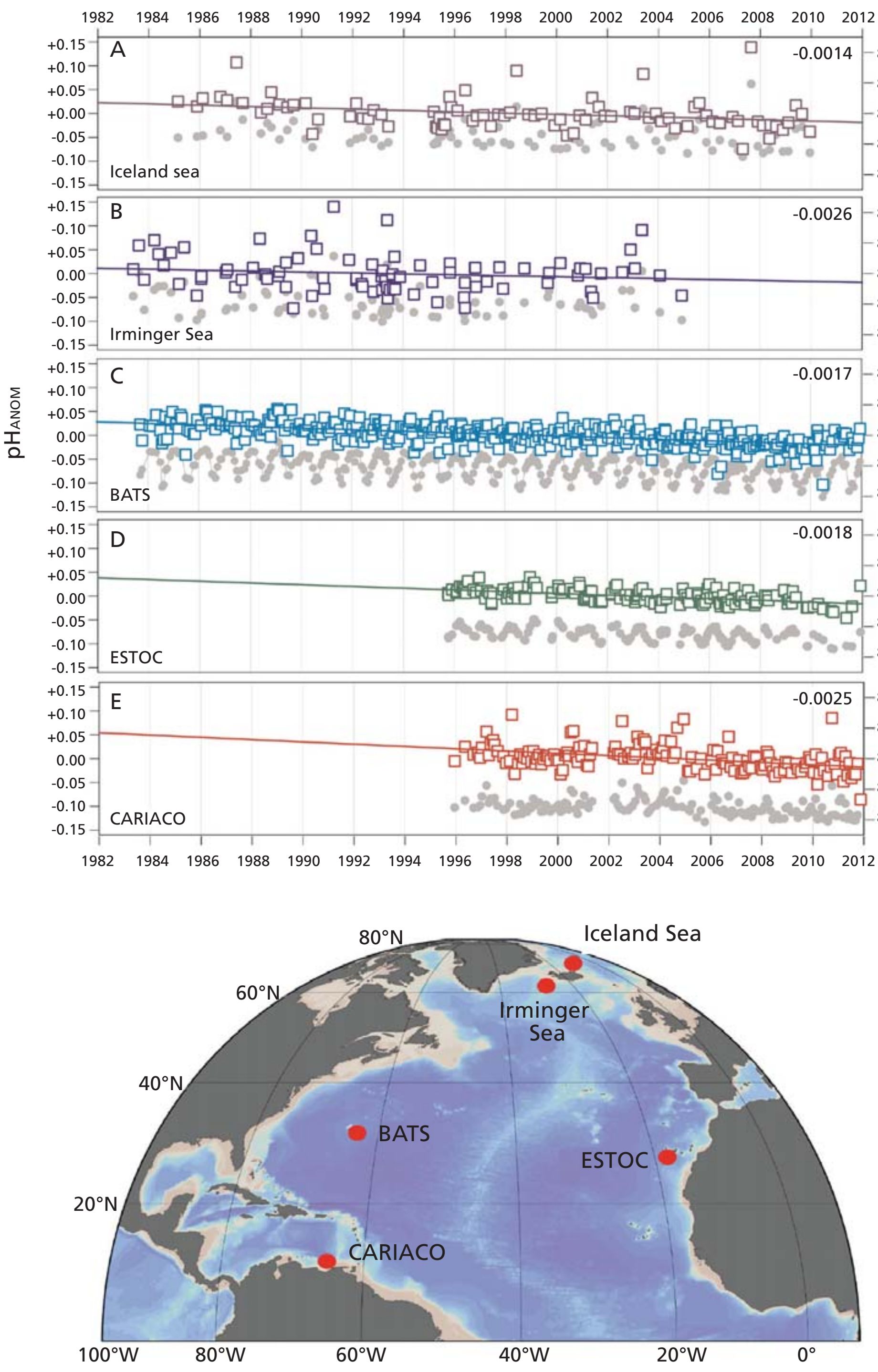
Assessment of trends in water temperature, salinity and acidification in the Atlantic-Arctic region is difficult because of multi-decadal variability and a general lack of historical measurements prior to the 1950s. Seawater temperatures have risen dramatically since the 1970s, and subsurface pulses of relatively warm water of Atlantic origin have been detected all around the Eurasian basin (Rhein *et al.*, 2013). Extreme warming has occurred in the Kara and Barents seas during the winters of 2000 to 2016 (Kohnemann *et al.*, 2017). Singh *et al.* (2013) reported particularly large increases in SST by as much as 4 °C in areas such as the Labrador Sea, the Iceland Sea (along the Greenland coast and near Iceland), the Greenland Sea, and in Hudson Bay between 1982 and 2010. With the observed decline in sea ice and release of freshwater from multi-year sea ice (or the Greenland Ice sheet), water salinity has decreased. In the period from 1992 to 1999, freshening of all regions throughout the Arctic as well as increased freshwater transport out of the Arctic was detected (Dickson *et al.*, 2002).

5.2.2 Carbonate chemistry and ocean acidification

Five, relatively long-term data sets in the North Atlantic show a consistent pattern of decrease in surface-ocean pH (Figure 5.2) albeit with strongly variable site-specific values (e.g. -0.0014 pH units/year in the Iceland Sea; -0.0026 pH units/year in the Irminger Sea) (Bates *et al.*, 2014). These measurements are usually made at 5 m to 20 m water depth and pH and saturation state decrease (and pCO_2 increases) with increasing water depth. Moreover, considerable spatial variability in pCO_2 in shelf waters is caused by the influence of rivers. In the European shelf seas, both observations and modelling show that CO_2 levels in near-surface can vary between 200 ppm and 450 ppm, contributing to a pH variability of as much as 1.0 pH unit over an annual cycle (Provoost *et al.*, 2010). Collated pH measurements from waters around the United Kingdom of Great Britain and Northern Ireland suggest a long-term decline over the past 30 years, and North Sea pH has decreased at a rate of around 0.0035 pH units per year (Ostle *et al.*, 2016).

FIGURE 5.2

North Atlantic time series showing long-term decrease in surface pH at five sites: Iceland Sea, Irminger Sea, Bermuda Atlantic Time-series Study (BATS), European Station for Time series in the Ocean Canary Islands (ESTOC) and Cariaco Basin, Venezuela (CARIACO Ocean Time Series)



Top: site location map; Bottom: data for each site shown as pH anomalies (coloured symbols, left hand scale) and observed pH (grey symbols, right hand scale), the latter calculated from dissolved inorganic carbon and total alkalinity from Bates *et al*. (2014), omitting data from Pacific time series.

Areas of the Northwest Atlantic have witnessed decreases in pH consistent with ocean acidification (OA) but changes in large-scale circulation patterns and runoff from large estuaries have caused larger changes in the saturation state (Ωar) of aragonite, a measure of the degree of OA. Coastal areas near large estuaries and cold-water currents display greater acidification (a lower saturation state of aragonite) compared to deeper, offshore waters of warmer origin (Wanninkhof *et al.*, 2015). The pH of bottom waters of estuaries such as the Gulf of St. Lawrence has decreased 0.2 pH to 0.3 pH units over the last 70 years with expected negative impacts on shellfish (molluscs) and potentially on fish early life stages.

In the Arctic, OA is particularly important because solubility of CO_2 is greater at cold temperatures and, consequently, the onset of under-saturation (Ωar less than 1) will occur first in polar waters. There are very few long-term time series measurements of pH in the Atlantic high Arctic, however, decreases in pH and calcium carbonate concentrations have been observed in the surface waters on the continental shelves along the Arctic coasts, although it is thought that this is mainly a result of freshwater influx from melting ice-caps and rivers emptying into the Arctic Ocean (Steinacher *et al.*, 2009).

5.2.3 Natural climate variability in the North Atlantic

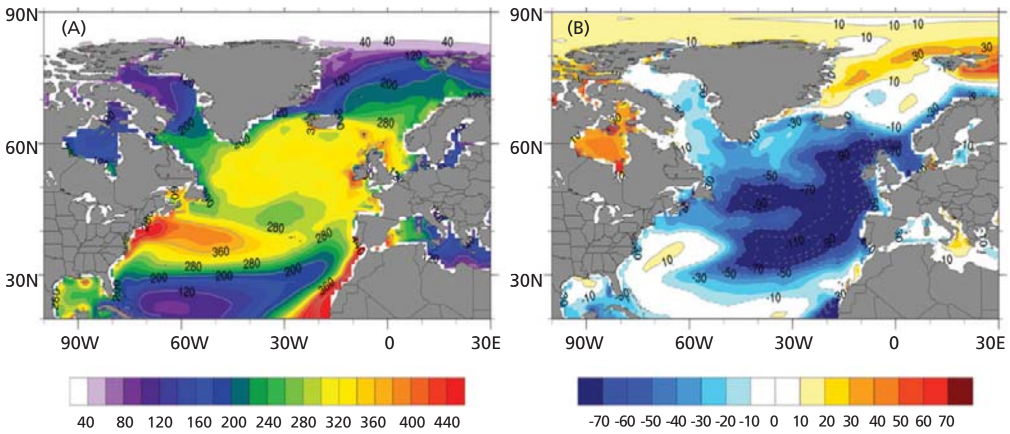
The North Atlantic experiences decadal to annual oscillations in weather patterns that impact the productivity of its marine ecosystems and fish stocks. The Atlantic Multi-decadal Oscillation (AMO) is a quasi-cycle of roughly 70 years of a little more than 1 °C change in SST. The North Atlantic Oscillation (NAO), by contrast, is the difference in atmospheric pressure between the Azores high and the Icelandic low and year-to-year changes in the NAO cause changes in wind speed, precipitation, evaporation, and the exchange of heat between ocean and atmosphere with strong impacts on oceanic conditions. During winters with a strong NAO index, the ocean responds quickly and the effects can continue throughout the following year. Long-term, climate-driven warming is superimposed on natural climate variability such as the AMO and NAO and the ecological consequences of these combined processes are challenging to understand. Although the NAO is one of the climate indices for which it is most difficult to provide accurate future projections (IPCC, 2013), the combined estimates from different climate models suggest that the NAO may become slightly more positive (on average) in the future (Karpechko, 2010).

5.2.4 Phytoplankton productivity

A major uncertainty with regard to future projections for fisheries yield (Chapter 4) is the lack of clear consensus as to whether primary production (phytoplankton) will increase or decrease at different localities and, therefore, which countries' fisheries will be "winners" or "losers" in the long-term. At a local scale, recent studies for the Northeast Atlantic (e.g. Fernandes *et al.*, 2017) have tended to use outputs from downscaled regional models that anticipate a decline in net primary production. Consequently, these studies also suggest an overall decline in the net present value of fisheries in most subregions. Global climate models also suggest an overall decline in primary productivity for much of the Northeast Atlantic (see Figure 5.3), but a moderate increase for the Northwest Atlantic (eastern United States of America) and especially the Atlantic-Arctic and in Hudson Bay.

While spring phytoplankton blooms occur in the Arctic Ocean, they are currently constrained by the sea ice and strong vertical stratification. Although the dynamic processes influencing phytoplankton growth such as the extent of cracks (leads) in pack ice are still being resolved, for this Atlantic-Arctic subregion, sea ice is declining and ice-free summers may occur by the mid-twenty-first century. Such change may cause Arctic phytoplankton production to increase and mimic conditions currently experienced in the Northeast Atlantic (Yool, Popova and Coward, 2015). This could, in turn, result in additional fisheries benefits for the Atlantic-Arctic subregion.

FIGURE 5.3
Average, annual primary productivity (CMIP5 ensemble average, 1×10^{-9} mol/m²/s) interpolated on a 1×1 grid



(A): mean primary organic carbon production by all types of phytoplankton for the period (1956 to 2005). (B): difference in the primary productivity in the future time period (RCP8.5: 2050 to 2099) compared to the historical reference period (1956 to 2005).

5.2.5 Dissolved oxygen

There is evidence that areas of low dissolved oxygen have started to proliferate around the world (Diaz and Rosenberg, 2008). Stendardo and Gruber (2012) examined oxygen trends over five decades in the North Atlantic and identified declines in almost all regions during the period from 1960 to 2009. Whether or not these changes in dissolved oxygen are a result of long-term climate change remains unclear, and it is also unknown whether such changes will impact on commercial fish and their fisheries (Townhill *et al.*, 2017).

5.2.6 Marine ecosystems

Similar to other ocean areas, a mixture of pressures including climate change, overfishing, habitat modification and eutrophication have changed the composition and distribution of marine flora and fauna in the northern Atlantic. Climate change may have important consequences for the base of the food web such as the seasonal timing and magnitude of blooms of phytoplankton and/or zooplankton at high latitudes (e.g. Henson *et al.*, 2017). Global-scale climate modelling of phytoplankton has projected large shifts in the seasonal timing of blooms throughout subpolar waters of the North Atlantic and polar waters of the Arctic (Henson *et al.*, 2017). Zooplankton resources, important to the diets of early life stages of fish, may also drastically shift in the future. For example, *Calanus finmarchicus* is a key species of zooplankton in the diets of early life stages of many commercially important fish on shelf areas throughout much of the North Atlantic. Projected warming of bottom waters of the Northeast shelf of the United States of America under a "business as usual" scenario of greenhouse gas emissions is expected to decrease the average abundance of *C. finmarchicus* in this region by as much as 50 percent by the end of this century (Grieve, Hare and Saba, 2017).

In the Northeast Atlantic, major biogeographical shifts in zooplankton have been identified in response to warming including poleward increases in warm-water species and a reduction in the number of cold-water species in the same areas (Beaugrand, Luczak and Edwards, 2009). All zooplankton assemblages exhibited coherent, long-term shifts but the speed of these biogeographic shifts was surprisingly rapid. Warm-temperate, pseudo-oceanic species experienced a poleward shift of about 10° of latitude (52 to 62 °N, 10 °W) or 23 km per year for the period 1958 to 2005 (Beaugrand, Luczak and Edwards, 2009). The magnitude of the species shifts was, however, similar to the poleward shift of some isotherms. These shifts have caused an increase in the diversity of calanoid copepods in the Northeast Atlantic and its adjacent seas (such as the North Sea).

5.3 CLIMATE CHANGE EFFECTS ON STOCKS SUSTAINING THE MAIN FISHERIES

5.3.1 Distribution and abundance

In the Northwest Atlantic, thorough monitoring of fish stocks within trawl surveys has occurred annually for at least four decades by the US NOAA NMFS and DFO. Additional, broad-scale ecosystem surveys have been conducted within specific decades making the mid-Atlantic Bight, Gulf of Maine and Scotian Shelf a data-rich region. Within US waters, Nye *et al.* (2009) investigated shifts in 36 commercial fish stocks over a 40 year time period from 1968 to 2007. There were clear poleward shifts consistent with warming in many fish stocks, most notably for alewife (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*), silver hake (*Merluccius bilinearis*), red hake (*Urophycis chuss*), and yellowtail flounder. Changes were observed in the minimum and maximum latitude of occurrence of fish stocks and 17 stocks significantly increased their mean depth of occurrence. Shifts in distribution were most closely associated with changes in the AMO that was consistently positive in the late 1990s and 2000s. When data on the distribution of both adult fish and their eggs and larvae were compared between 1977 to 1987 and 1999 to 2008, most taxa (23 of 27) displayed shifts and, in half of those taxa, larvae and adults shifted in the same direction, either poleward and/or deeper (Walsh *et al.*, 2015). In this and other regions, fish are expected to move poleward, if possible, to track the same water temperatures. Across Atlantic waters of the United States of America and Canada (33 °N to 48 °N latitude), projected warming until 2060 is expected to modify the habitats in terms of suitable water temperatures of 76 percent of the fishery target species in Canada (55 percent contract, 21 percent expand) and 85 percent of those in the United States of America (65 percent contract, 20 percent gain) (Shackell, Ricard and Stortini, 2014).

In an analysis of 50 fish species common in the Northeast Atlantic, 70 percent responded to warming by changing distribution and abundance (Simpson *et al.*, 2011). Specifically, warm-water species with smaller maximum body size generally increased in abundance while cold-water, large-bodied species decreased. Fishery-independent survey data indicate that the centres of distribution for a broad range of North Sea fish species have shifted by distances ranging from 48 km to 403 km between the 1970s and early 2000s (Dulvy *et al.*, 2008; Perry *et al.*, 2005). The North Sea demersal fish assemblage has shifted to deeper waters at an average rate of 3.6 m per decade over the last 30 years (Dulvy *et al.*, 2008).

In the North Sea, the locations where peak commercial catches of target species such as cod, haddock, plaice and sole were obtained have all shifted over the past 100 years (Engelhard *et al.*, 2011; Engelhard, Righton and Pinnegar, 2014). However, distributions have shifted in various directions, and shifts cannot simply be described as poleward. Annual groundfish surveys between 1999 and 2007 indicate that warm-water “Lusitanian” fishes (including sole, john dory (*Zeus faber*), sardine (*Sardina pilchardus*) and boarfish (*Capros aper*) have increased on the shelf to the north and west of Ireland, while the “boreal” community (including cod, haddock, plaice and herring) has declined to the south (Lynam, Cusack and Stokes, 2010). Pelagic fish surveys between 1965 and 2012 suggest a strong “subtropicalization” of species in the North Sea and Baltic Sea (Montero-Serra *et al.*, 2015). Pelagic fish communities throughout the Northeast Atlantic have shifted away from cold-water assemblages typically characterized by herring and sprat from the 1960s to 1980s, to warmer-water assemblages typified by mackerel, horse mackerel, sardine and anchovy (*Engraulis encrasicolus*) from the 1990s onwards. In all cases, SST was identified as the primary driver of change (Montero-Serra *et al.*, 2015). A similar shift from a colder to warmer fish community occurred between 2004 and 2012 in the Barents Sea where an Arctic community characterized by bigeye sculpin (*Triglops nybelini*), Greenland halibut, and snailfish (*Liparis* spp.) shifted poleward and was replaced largely by a boreal (Atlantic shallow-water) community dominated by American plaice, Atlantic cod and haddock (Fossheim *et al.*, 2015).

Species may migrate across political or management boundaries, which can create conflict in the allocation of quotas (portions of the overall total allowable catch or TAC) to the different nations sharing the common stock. A recent, notable example arose with regard to quota allocations for mackerel between Norway and the EU, and between Iceland, the Faroe Islands and the EU in the Northeast Atlantic. Starting in 2007, North Sea mackerel began to shift to the north and the west, away from Norway, eventually resulting in disagreements in 2009 over the effective quota, and hence permissible catches, for Norwegian vessels in EU waters. During the same period, with the sudden high abundance of mackerel in their territorial waters, Iceland and the Faroe Islands unilaterally claimed nearly 10-fold increases in their quota for this stock (representing 46 percent of the internationally agreed TAC). Whether the apparent changes in mackerel distribution, northwards and westwards, were a result of long-term climate change remains unclear. Hughes *et al.* (2014) suggested that SST had a significant positive association with the observed shift of mackerel and historical movements of mackerel to the western North Sea and off the coast of Iceland also coincided with positive (warm) phases of the AMO (Beare *et al.*, 2004).

MacKenzie *et al.* (2014) reported that commercial boats targeting mackerel in waters east of Greenland have now started catching bluefin tuna (*Thunnus thunnus*). The presence of bluefin tuna in this area of the North Atlantic is likely as a result of a combination of warmer temperatures and immigration of an important prey species (mackerel). Since 2008, ICCAT has granted a small but increasing share of bluefin tuna quota to Norway and Iceland. ICCAT has also amended its criteria for allocating quota shares to recognize shifts in species distribution, such that they are not only based on a "track record" of fishing but also the rights of coastal states to make use of resources present within their EEZ (TemaNord, 2011).

Models such as those described in Chapter 4 project that the distributions of exploited species will continue to shift in the next five decades both globally and in the Northeast Atlantic specifically (Cheung *et al.*, 2010; Lindegren *et al.*, 2010). Uncertainty in projected warming among different global climate models notwithstanding, the combined estimates from three species distribution models for 14 commercial fish in the Northeast Atlantic suggested poleward shifts at an average rate of 27 km per decade (Jones *et al.*, 2013), which is slightly faster than that (20 km per decade) currently observed for common fish in the North Sea (Dulvy *et al.*, 2008). Applying a similar model to predict the distribution of eight Northeast Atlantic fish species, Lenoir, Beaugrand and Lecuyer (2011) projected an increased probability of occurrence of horse mackerel and anchovy in northern waters in the 2090s compared with the 1960s, a decrease in pollack (*Pollachius pollachius*), haddock and saithe (*Pollachius virens*), and no overall change in the distribution of turbot (*Scophthalmus maximus*) and European sprat.

5.3.2 Changes in fisheries productivity - environmental influences on recruitment

Fishers and scientists in the North Atlantic have known for over 100 years that the status of fish stocks can be greatly influenced by climatic conditions (Hjort, 1914). The amount of young fish entering the fishery each year (recruitment) is critically dependent on the match or mismatch between the occurrence of the larvae and availability of their zooplankton food (Cushing, 1982) as well as a number of other processes such as predation that affect early life-history stages (see Kjesbu *et al.*, 2014; Petitgas *et al.*, 2012). Based on empirical data, there are often strong relationships between recruitment success, fisheries catches and climatic variables as demonstrated, for example, for cod (Planque and Frédou, 1999) and mackerel (Jansen and Gislason, 2011). In widely-distributed species, climate change is expected to have either positive or negative impacts on productivity depending on the geographical location of specific stocks. For example, relationships between recruitment and water temperature of cod stocks across the North Atlantic (Planque and Frédou, 1999) suggest that stocks at the high latitudinal limit (e.g. in the Barents Sea) or the western Atlantic (e.g. Labrador) will benefit from warming, whereas increased water temperature may lead to a collapse of warmer-water cod stocks in the North, Celtic and Irish Seas (Drinkwater, 2005). During recent decades of reduced fishing mortality on cod stocks in the Northeast Atlantic, the stock in the Barents Sea has increased to record levels (spawning stock biomass 2.7 million tonnes in 2013) whereas stocks have been very slow to recover elsewhere.

A clear seasonal shift to earlier appearance of fish larvae has been described for several species in the southern North Sea (Greve *et al.*, 2005), and this has been linked to marked changes in zooplankton composition and sea surface temperature of this region. The loss of a key prey item for cod larvae (the copepod *Calanus finmarchicus*) has been correlated with recent failures in cod recruitment in the North Sea and an apparent increase in flatfish recruitment (Beaugrand *et al.*, 2003). Using market sampling data, Fincham, Rijnsdorp and Engelhard (2013) reported that four out of seven sole stocks had exhibited a significant, long-term trend towards earlier spawning at a rate of 1.5 weeks per decade since 1970. Similarly, the timing of peak roe landings for Atlantic cod in the northern North Sea, central North Sea and Irish Sea occurred 0.9 to 2.4 weeks earlier per decade across three decades. The peak timing was negatively correlated with temperatures experienced by cod during early vitellogenesis, suggesting that rising sea temperatures have contributed to a shift in spawning phenology (McQueen and Marshall, 2017).

5.3.3 Ocean acidification

The impacts of OA are suggested to be most apparent for animals with calcium carbonate shells and skeletons such as molluscs and some crustaceans (Hendriks, Duarte and Álvarez, 2010; Kroeker *et al.*, 2013), but responses are highly variable among and within taxonomic groups. Several major programmes of research are underway in Europe and North America to determine the possible consequences of future OA. In laboratory studies, significant effects have been noted for several important commercial shellfish species, notably mussels, oysters, lobster and Nephrops (e.g. Agnalt *et al.*; Styf, Nisson Sköld and Eriksson, 2013).

Narita and Rehdanz (2017) performed a Europe-wide assessment of the economic impact of OA on mollusc production using two scenarios of biological sensitivity based on a quantitative comparison of findings from previous OA laboratory experiments (Kroeker *et al.*, 2013). Their approach suggested that the highest overall impact was expected in countries with the largest current production such as France, Italy and Spain. For Europe as a whole, the annual impact was estimated to be over 1 billion USD by 2100 although subject to considerable uncertainty.

The impacts of OA on North Atlantic commercial finfish populations is particularly poorly understood. Although several studies have noted that early life stages (eggs and young larvae) may be sensitive to the direct effect of OA (e.g. Franke and Clemmesen, 2011; Frommel *et al.*, 2012), the results appear to depend on the species and habitat of the stock (e.g. Pimentel *et al.*, 2016). Negative impacts of OA on larval growth, development, metabolism and survival have been documented, as have positive, indirect food web impacts of OA on survival and growth (Sswat *et al.*, 2017).

5.4 OTHER NON-CLIMATE STRESSORS (E.G. OVERFISHING, POLLUTION, HABITAT MODIFICATION)

In the 1980s and 1990s many stocks in the Northwest and Northeast Atlantic were overfished. Since 2001, fisheries management in the United States of America, Canada and northern Europe has seen successes in rebuilding stocks. For example, the United States of America currently lists 23 stocks in Atlantic waters as rebuilt including several gadoids, flounders, elasmobranchs, scallop (*Placopecten megallanticus*), monkfish and several highly migratory species. Notably, although once supporting the largest fishery in the Northwest Atlantic, cod stocks collapsed in the 1990s as a result of a combination of both overfishing and warming-driven declines in productivity (Fogarty *et al.*, 2008) and have still not recovered to within safe biological limits despite drastic reductions in fishing effort including complete moratoriums. The collapse of the cod stocks off eastern Canada was followed by historically unprecedented increases in catches of American lobster as well as increases in snow crab and shrimp (*Pandalus borealis*). Large increases and subsequent decreases were also observed in stocks of forage fish. These shifts highlight how whole ecosystems can be restructured by the combined effects of fishing and climate variability and the decades of time required for them to potentially return to previous conditions (Frank *et al.*, 2011).

It is important to note that extensive fishing can cause fish populations to become more vulnerable to short-term natural climate variability (e.g. Ottersen, Hjermann and Stenseth, 2006) by making such populations less able to "buffer" against the effects of the occasional poor year classes. Conversely, long-term climate change may make stocks more vulnerable to fishing, by reducing the overall "carrying capacity" of the stock, such that it might not be sustained at, or expected to recover to, levels observed in the past (Jennings and Blanchard, 2004). In the case of cod in the North Sea, climate-driven warming has been estimated to have been eroding the maximum sustainable yield at a rate of 32 000 tonnes per decade since 1980. Calculations show that the North Sea cod stock could still support a sustainable fishery under a warmer climate but only at very much lower levels of fishing mortality (Cook and Heath 2005).

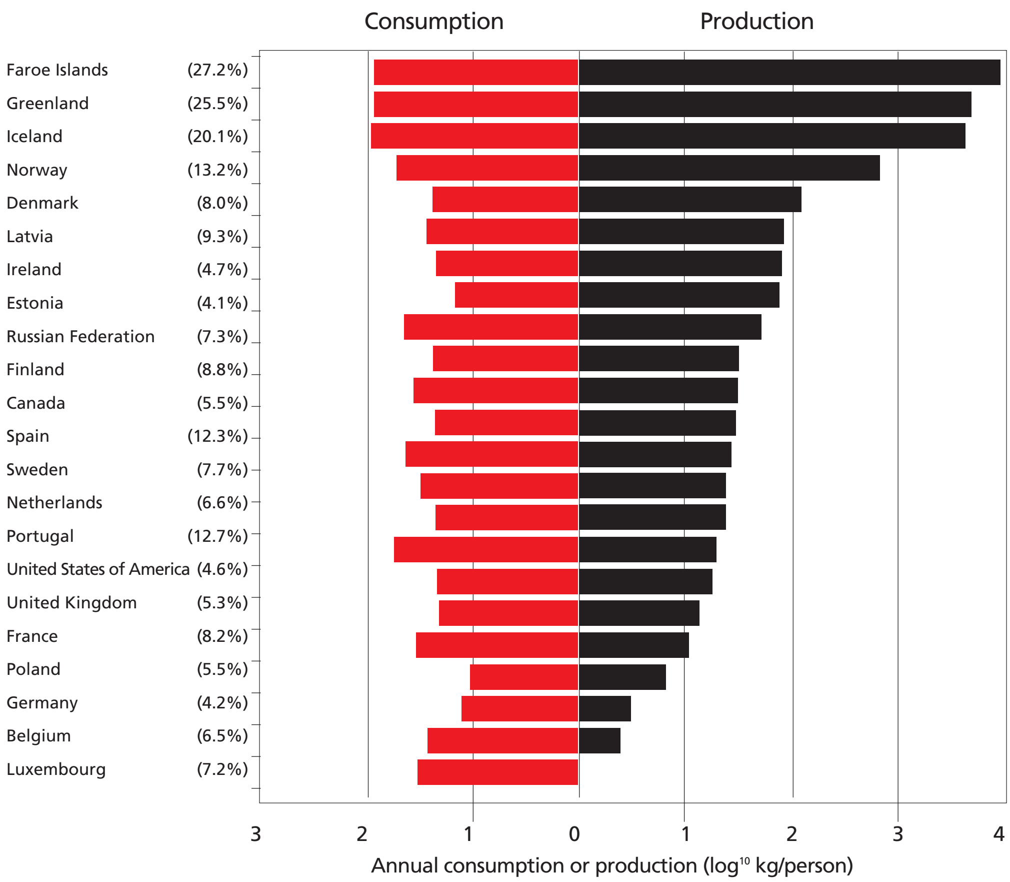
Engelhard *et al.* (2011) suggest that, apart from climate and fishing, other factors may also have had an important influence on flatfish distributions in the North Sea throughout the twentieth century. These may have included habitat modification, changes in prey availability, and changes in precipitation and run-off patterns. The Dutch and Belgian coasts were previously very good nursery grounds for juvenile plaice, but the closure of the Zuiderzee in the early 1930s and modification of the Rhine, Meuse, and Scheldt estuaries in the 1960s and 1970s have likely reduced the recruitment from these nursery grounds and hence may have affected the abundance and distribution of older age groups in the North Sea.

5.5 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

5.5.1 Dependency on fisheries

For most countries bordering the North Atlantic, fisheries contribute very little to national GDP and fish protein constitutes a small proportion of protein intake (see Figure 5.4), hence, fisheries are not primarily concerned with maintaining food or income-security. Some exceptions to this include Greenland, Iceland and the Faroe Islands where fishing remains vital to the national economy and annual per capita consumption of fish and seafood exceeds 80 kg/person. Figure 5.4 shows per capita seafood consumption and production based on FAO data for 2013. Notably, in many northern countries production greatly exceeds consumption, whereas in countries further south, often with large human populations (e.g. Portugal, France, Germany, Belgium, United Kingdom of Great Britain and Northern Ireland), as well as land-locked countries of Europe (e.g. Luxembourg), consumption exceeds production and the deficit is made up via imports from elsewhere.

FIGURE 5.4
Per capita seafood production and consumption in North Atlantic countries based on FAO data for 2013



Number on the Y-axis is the percentage that fish and seafood contributes to total protein consumption in each country.

In specific communities, towns and regions throughout Europe and North America, fishing provides the mainstay of employment. For example, 82 percent of regional activity has been attributed to the fisheries sector in Killybegs (County Donegal) in Ireland (Macfadyen *et al.*, 2010). In the United States of America, communities such as Lubec in Northern Maine or New Bedford in Massachusetts, have few other types of employment available and, hence, are highly dependent on fishing (see Colburn *et al.*, 2016). Natale *et al.* (2013) set out to identify the most fisheries-dependent communities in EU coastal areas. These authors identified 388 fisheries-dependent communities that together play host to 54 percent of total fishery employment in Europe. These included Castlebay and Ullapool in the United Kingdom of Great Britain and Northern Ireland, Hvide Sande and Østerby in Denmark, Puerto de Cillero in Spain, Grundsund in Sweden and Kihnu, Lehtma and Manija in Estonia with a fisheries employment dependency ratio higher than five percent.

Arnason (2007) used an economic model to understand potential economic impacts of climate change on fisheries and on the national economies in Iceland and Greenland. In Iceland, future dramatic increases assumed in fisheries yields resulted in only a minor increase in national GDP (four percent by 2054) even though fishing accounts for approximately ten percent of GDP and 40 percent of export earnings. Given the uncertainty in this analysis, this small increase is close to the margin of error. Benefits for the national economy of Greenland, in which fishing represents 90 percent of the exports, were greater (a 40 percent increase in GDP by 2054) but this assumed an enormous increase in fish production (by 200 percent over 50 years). For other North Atlantic countries with less economic reliance on fisheries, it seems highly unlikely that climate change, as manifested through impacts on fisheries, will have a significant impact on national economic development.

The traditional harvesting techniques of several groups of indigenous peoples in the North Atlantic and Atlantic-Arctic such as the Inuit in Greenland and Canada, Evenk and Nenets in the Russian Federation, and the Saami in Norway and the Russian Federation, are expected to be impacted by climate change. These impacts will result from changes in the composition and productivity of fish stocks as well as changes in sea ice conditions and severe weather (Koivurova *et al.*, 2008). Coastal indigenous peoples are commonly highly vulnerable to ecosystem and economic change. Cisneros-Montemayor *et al.* (2016) attempted to quantify seafood consumption among 1 900 coastal indigenous communities around the world and this included several in the Atlantic-Arctic. Indigenous peoples inhabiting Arctic coasts have the highest mean per capita fish consumption by climate region, at 74 kg per year and these include the Saami, Inuit in Canada (e.g. Inuvialuit around Hudson Bay) and Kalaallit in Greenland.

5.5.2 Maximum catch potential and economic development

Cheung *et al.* (2010) estimated future changes in maximum potential catch (a proxy for maximum sustainable yield) given projected shifts in the distribution of 1 066 species of exploited marine fish and invertebrates from 2005 to 2055 as a result of climate change and changes in marine primary productivity. That study suggested that climate change may lead to large-scale redistribution of global maximum catch potential, with an average of 30 percent to 70 percent increase in yield of high-latitude regions (north of 50 °N in the northern hemisphere), but a drop of up to 40 percent in the tropics. EEZ regions with the highest forecast increases in catch potential by 2055 included Norway and Greenland (and also the Grand Banks of Canada). Areas south of around 50° latitude in the North Atlantic were projected to generally lose out (Cheung *et al.*, 2010). In Chapter 4, similar projections of maximum catch potential are provided based on outputs from a slightly modified version of the same bioclimate envelope model (DBEM) but identical climate forcing data, and also a size-structured ecosystem model (Blanchard *et al.*, 2012). Notably, catches in EEZs of most temperate Northeast Atlantic countries were projected to decline substantially (by approximately 30 percent), in contrast to high latitude regions in the North Atlantic where catch potentials are projected to increase substantially. Shackell, Ricard and Stortini (2014) suggest that stocks are expected to decline in United States of America Atlantic waters and increase in Canadian waters, a trend primarily driven by increases in lobster in Canadian waters.

In the Arctic, total fisheries catch and revenue (or value of fish landed) are projected to increase by about 39 percent (14 percent to 59 percent) by 2050 relative to 2000 according to a study conducted by Lam *et al.* (2014). In that study, catches by European countries (Faroe Islands, Greenland, Iceland, Norway, the Russian Federation and

Sweden) were projected to increase by 20 percent. Projections of increases in revenue, fishers' income, fishing cost, household incomes and economy-wide impacts followed a very similar pattern to catch projections.

Much of the existing literature on the impact of climate change on fisheries economics has been focused on regional and local studies. Eide and Heen (2002) explored the effects of global warming on Barents Sea fisheries and therefore implications for the north Norwegian economy, within which the fisheries sector contributes eight percent to both regional products and employment. A range of possible environmental scenarios was examined including eight different management regimes and four environmental scenarios. The management regimes included open access (or no management), limited entry, quota regulation and combinations of the last two. An increase in average sea temperature of 2 °C resulted in enhanced growth and recruitment of cod and herring, increased annual catches, increased local employment and profitability in these Barents Sea fisheries. Annual catches were however, overwhelmingly determined by the various management regimes tested rather than the different climatic scenarios (Eide and Heen, 2002).

Fernandes *et al.* (2017) used observational and experimental data, theoretical, and modelling approaches to quantify potential effects of ocean warming and acidification on the fisheries catches, resulting revenues and employment in the United Kingdom of Great Britain and Northern Ireland under different greenhouse gas emission scenarios. Standing stock biomasses were projected to decrease significantly by 2050 and the main driver of this decrease was sea surface temperature rise. Overall, losses in revenue were estimated to range between one percent and 21 percent in the short-term (2020 to 2050). Losses in total employment (fisheries and associated industries) may reach approximately three to 20 percent during 2020 to 2050 with the small vessel (less than 10 m) fleet and associated industries bearing most of the losses. Climate change impacts on fisheries profits have been examined in the sardine fishery of the Iberian Atlantic (Garza-Gil, Torralba-Cano and Varela-Lafuente, 2010) and ranged from to non-significant for the Bay of Biscay to positive on the Portuguese coast, where most of the "immigrant" fish species examined are considered marketable (Vinagre *et al.*, 2011).

5.6 VULNERABILITY OF THE MAIN FISHERIES AND THE DEPENDENT COMMUNITIES/ECONOMIES

A number of fishery vulnerability assessments have been conducted for the North Atlantic and many more are currently underway. Some of these studies only focus on the perceived vulnerability of species, whereas others focus on "downstream" vulnerability of fishing fleets and dependent communities.

Hare *et al.* (2016) conducted a climate vulnerability assessment on 82 fish and invertebrate species in the northeast shelf of the United States of America. The authors defined climate vulnerability as the extent to which abundance or productivity of the species could be impacted by climate change and/or decadal variability using life history traits and habitat preferences to rank species in terms of "sensitivity". That study found that overall climate vulnerability is high to very high for approximately half the species assessed; diadromous and benthic invertebrate species (most notably Atlantic salmon *Salmo salar* and Bay scallop *Argopecten irradians*) exhibit the greatest vulnerability. In addition, most species included in the assessment had a high potential for a change in distribution in response to projected changes in climate. Negative effects of climate change were expected for approximately half of the species assessed, but some species were expected to be positively affected (e.g. to increase in productivity and abundance).

Colburn *et al.* (2016) used the ranking of species' vulnerability developed by Hare *et al.* (2016) to determine the most vulnerable fishing communities along the Eastern and Gulf coasts of the United States of America, based not only on catch composition but also on social indicators including employment in the sector, labour force structure and rates of unemployment. Community social vulnerability indices (CVIs) were calculated for 2 659 communities in 19 states from Maine to Texas, of which 1 130 communities showed evidence of commercial and/or recreational fishing activity (Jepson and Colburn, 2013). CVIs were based around “fishing dependence” (a combination of commercial engagement and reliance) and “social vulnerability” (poverty, labour force disruption, personal disruption, housing characteristics). Communities in Massachusetts (e.g. New Bedford) were identified as being particularly vulnerable to climate change because they are highly reliant upon commercial fishing, they exhibit limited catch diversity, they scored poorly on two of the four social vulnerability indicators and highly on two of the three climate change exposure indicators. Several communities in New Jersey (e.g. Barnegat Light) were identified as being particularly vulnerable for similar reasons.

As part of the analyses by Colburn *et al.* (2016), coastal fishing communities vulnerable to sea level rise were also identified. Mid-Atlantic communities in the low lying coastal plain, especially those clustered around the Chesapeake Bay area and the New Jersey shore ranked highly with regard to expected vulnerability to sea level rise. New England communities in the Gulf of Maine and southern parts of the region were not projected to be as vulnerable. South Atlantic communities (North Carolina to Florida’s east coast) had pockets of high vulnerability and those in southeastern Florida had the highest concentration of vulnerable communities, including those located in the Florida Keys.

Ekstrom *et al.* (2015) examined US communities most vulnerable to losses in shellfish (mollusc) production as a result of ongoing OA. Their study suggested that 16 out of 23 bioregions around the United States of America are exposed to rapid OA. The marine ecosystems and shelled molluscs around the Pacific Northwest are expected to be exposed soonest to rising global OA, followed by those on the Gulf of Maine and Atlantic coast of the United States of America. Communities highly reliant on shelled molluscs in these bioregions are at risk from OA either now or in the coming decades. Pockets of marine ecosystems along the East and Gulf coasts will experience acidification earlier than global projections indicate, because of the presence of local amplifiers such as coastal eutrophication and river discharge of water with low saturation state (Ωar). The areas that will be exposed to OA (including local amplifiers) and where high and medium–high social vulnerability is present include southern Massachusetts, Rhode Island, Connecticut, New Jersey, portions around the Chesapeake Bay, and the Carolinas.

5.7 RESPONSES (ADAPTATION)

Climate change is affecting marine and coastal ecosystems throughout the North Atlantic, including commercial, recreational and subsistence fisheries. Traditional fisheries management tools, such as restrictions on allowable catch, landing size, seasonal closures, gear restrictions, marine protected areas, essential fish habitat protection, and protection of spawning aggregations, are and will remain necessary (see Grafton, 2010) but may not be sufficient on their own to sustain fisheries in the face of the combined onslaught of climatic and non-climatic stressors in the future.

A wide diversity of adaptation measures has been tested, applied and advocated in the North Atlantic and these are reviewed in two reports from the United States of America (Gregg *et al.*, 2016) and the United Kingdom of Great Britain and Northern Ireland (Defra, 2013). Climate adaptation actions are taken to either avoid (or minimize) or take advantage of climate change impacts, either by decreasing vulnerability or increasing resilience. In the United States of America, the EcoAdapt program aims to promote adaptation action in the fisheries sector by: 1) providing real-life, practical adaptation case studies to catalyse creative thinking, and 2) synthesize information collected through interviews and surveys to further develop the field of study. Gregg *et al.* (2016) provides a summary of adaptation actions in the United States of America (both Atlantic and Pacific), based on interviews with federal, tribal, state and other practitioners. Commonly used adaptation approaches and examples are presented in four broad categories:

1. **Capacity building:** strategies include conducting research and assessments, investing in training and outreach efforts, developing new tools and resources, and monitoring climate change impacts and adaptation effectiveness.
2. **Policy:** strategies include developing adaptation plans, creating new or enhancing existing policies, and developing adaptive management strategies.
3. **Natural resource management and conservation:** strategies include incorporating climate change into restoration efforts, enhancing connectivity, reducing local change, and reducing non-climate stressors that may exacerbate the effects of climate change.
4. **Infrastructure, planning, and development:** strategies include protecting critical coastal infrastructure used by the fishing industry, and creating or modifying coastal development measures (e.g. removing shoreline hardening, encouraging low-impact development) to increase habitat resilience.

The majority of fishery adaptation efforts in the United States of America to date have been focused on capacity building, including conducting research and assessments, creating resources and tools, and monitoring how climatic changes are affecting species, habitats, and fishing communities (Gregg *et al.*, 2016). However, EcoAdapt recommends the following "best bets" for advancing climate-informed fisheries management over the long term (see Gregg *et al.*, 2016):

1. **Advance monitoring efforts of climate-driven impacts on species, habitat, and fishing communities.** Documenting environmental and climatic change is key to natural resources management.
2. **Enhance habitat connectivity and areas under protection.**
3. **Reduce non-climate stressors.** The cumulative effects of non-climate stressors reduce the overall resilience of species, habitats and communities to climate change.
4. **Create flexible multi-species permitting, licensing and management plans.** Enabling flexibility in terms of when, where, what and how much is harvested will become increasingly important to sustain fishing livelihoods.
5. **Adjust quotas to help sustain stocks** (e.g. reduce fishing pressure on vulnerable stocks).
6. **Temporarily close fisheries if necessary.** Given the uncertainty of climate change and the risks associated with extreme events, managers should adjust status quo policies by supporting rapid response measures to reduce stress on vulnerable stocks, including temporary closures.
7. **Evaluate potential and establish procedures for new commercial and recreational fisheries** (e.g. establishment of catch limits, new permitting procedures).
8. **Create international cooperative fisheries agreements.** Climate change will not be confined by political or social boundaries.
9. **Diversify fisheries and/or livelihoods.** In some areas, climate-induced effects on fisheries may threaten entire communities' livelihoods.

In 2013 the United Kingdom of Great Britain and Northern Ireland Department for Environment Food and Rural Affairs (Defra) commissioned its *Economics of Climate Resilience* (ECR) report on "sea fisheries" (Defra, 2013), which included a detailed assessment of whether or not the United Kingdom of Great Britain and Northern Ireland fishing sector will be able to adapt to the opportunities and threats associated with future climate change. Against the background of current policy, the adaptive capacity of the United Kingdom of Great Britain and Northern Ireland fishing industry as a whole was judged to be relatively high. This is because it has strong commercial incentives to make the most of profitable opportunities, and fishing vessel operators are used to dealing with constantly changing weather and fish stock sizes. However, the ability of some segments within the sector (e.g. small vessel operators) to adapt is likely to be more constrained than others. Such operators face constraints on their ability to travel distances to reach their favoured fish stock, the time they are able to be at sea and their access to the rights to catch particular species. The key adaptation actions highlighted for the United Kingdom of Great Britain and Northern Ireland fishing industry as a whole included:

1. Travelling further to fish for current species, if stocks move away from United Kingdom of Great Britain and Northern Ireland ports, particularly for large pelagic fishing vessels, such as those targeting mackerel and herring.
2. Diversifying the livelihoods of port communities, this may include recreational fishing where popular angling species become locally more abundant (e.g. sea bass).
3. Enhancing vessel capacity if stocks of currently fished species increase and sufficient quota allows.
4. Changing gear to fish for different species, if new or more profitable opportunities to fish different species are available, especially if these are not yet covered by EU quota restrictions (e.g. squid).
5. Developing routes to export markets to match the changes in catch supplied. These routes may be to locations (such as southern Europe) that currently eat the fish stocks that may move into the United Kingdom of Great Britain and Northern Ireland EEZ.
6. Stimulating domestic demand for a broader range of species, through joint retailer and media campaigns.

Kopke and O'Mahony (2011) provided an overview of adaptive capacity, barriers to adaptation, and information needs in the Irish fisheries sector, which echoed many of the "barriers to adaptation" cited in the ECR report (Defra, 2013). Barriers included "market failures" stemming from uncertainty around new or emerging species in the United Kingdom of Great Britain and Northern Ireland EEZ. "Information barriers" include that not all vessel operators may be aware of best practice techniques used by foreign fleets that can allow them to maximize opportunities offered by shifts in stock distribution. "Policy barriers" exist because the process of collecting and considering scientific evidence required to change regulations for setting sustainable catch quotas is likely slower than the pace of changes in stocks. There is a risk that quota allocations significantly restrict fishing activity where stocks are increasing and in some circumstances incentivize maladaptation. "Behavioural constraints" stem from the relatively limited number of fish species favoured by United Kingdom of Great Britain and Northern Ireland consumers. Although emerging species can be sold to niche markets and restaurants, for the most part, such species are exported.

The ECR report identified that fisheries management and quota arrangements can severely constrain the ability of fishers to adapt to climate change and this is true on both sides of the Atlantic. For example, under the EU Common Fisheries Policy, TACs are shared between EU member nations through pre-agreed "relative stability" arrangements. These arrangements are based on member state catches during a historical reference period, 1973 to 1978 (Morin, 2000) and give each member state a fixed percentage share of the total stock in perpetuity. Climate change has since shifted the geographical distribution of commercial species so that the national shares no longer coincide with geographic proximity. Small amounts of quota can be swapped each year between member states which could theoretically be used if distributions of managed stocks shift into new areas, or retreat from traditional ones. Some sharing arrangements ("fisheries agreements") are also in place between the EU and non-EU countries (such as Norway, Iceland, Greenland and the Faroe Islands) for stocks that are shared (e.g. mackerel and cod). Climate change greatly complicates the situation, as demonstrated during the recent North Atlantic "mackerel wars" (see Section 4.1 above).

Governments have implemented various measures to manage fisheries, both to conserve fish stocks and to help communities that depend on fishery resources to adapt to changes caused by overfishing and other factors. Measures include buybacks, introduction of transferable quotas, and investments in alternative sources of employment and income. Successful adaptation to climate change is likely to involve an extension of such policies, and in Europe the annual cost of adaptation has been estimated to range between USD 0.03 billion and USD 0.15 billion (World Bank, 2010). As countries surrounding the North Atlantic are some of the most affluent on the planet, it is assumed that, for the most part, "adaptive capacity" is high and that this will reduce long-term, overall vulnerability compared to other FAO regions.

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Chapter 6: Climate change impacts, vulnerabilities and adaptations: North Pacific and Pacific Arctic marine fisheries

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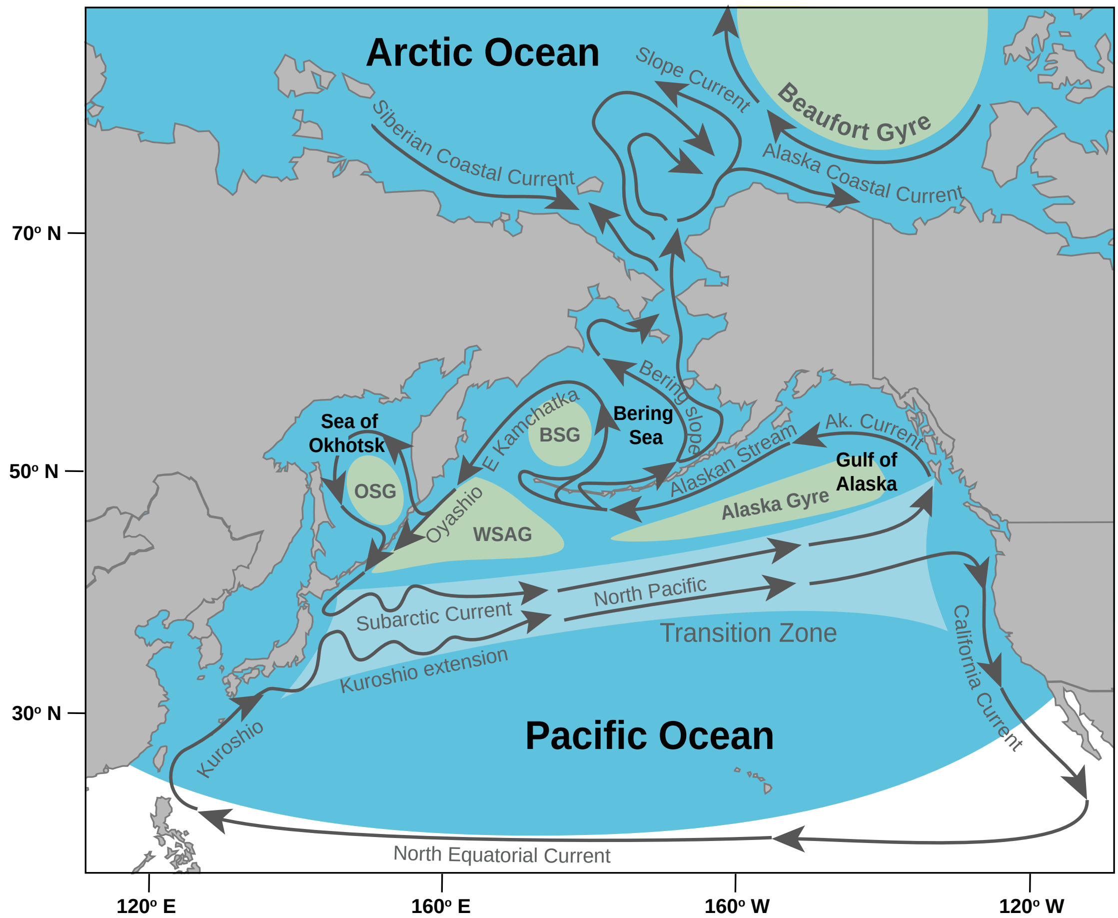
KEY MESSAGES

- The North Pacific has experienced disturbances in recent years that are very likely driven in part by anthropogenic climate change, including the persistent anomalously warm conditions in the Northeast Pacific from 2014 to 2016.
- Extreme events are expected to become more frequent and longer in duration across the North Pacific under unmitigated CO_2 scenarios (medium confidence).
- There is high confidence that extreme events will directly or indirectly induce disturbances to some existing fisheries, while others may be unaffected.
- Some demersal fish and crab stocks in multiple regions, as well as Chinook salmon in the Northeast Pacific, may decline as a result of ocean acidification, warming waters, and phenological mismatch and shifts in prey resources (medium confidence).
- There is high confidence that centroids of biomass for some fish and crab species in the Bering Sea will shift northward into northern Bering Sea waters, where commercial fishing is limited.
- There is high confidence that small boat fisheries (catcher vessels in Alaska, saury fishing vessels) as well as shore-based subsistence and recreational fishers are the most vulnerable to future climate change.
- Realized impacts of climate-driven changes on fisheries will depend on constraints to, or opportunities for, adaptation from non-climate pressures such as fishery dependency and diversity, global socio-economic drivers, pollution, non-climate-driven habitat loss, sea level rise, evolving scientific understanding, and technological advancements.

FIGURE 6.1
The North Pacific region



Map of the North Pacific and Pacific Arctic region and key oceanographic features, including major currents (arrows) and major gyres (green polygons); Okhotsk Sea Gyre (OSG), Western Sub-arctic Gyre (WSAG), and Bering Sea Gyre (BSG).

6.1 REGIONS AND FISHERIES OF THE NORTH PACIFIC

Roughly half of all fish captured globally each year come from the North Pacific (FAO, 2016) which is comprised of diverse marine ecosystems (Figure 6.1) that include the following:

6.1.1 The Northwest Pacific

The Northwest Pacific is one of the most productive areas in the world and with an annual catch of more than 21 million tonnes harvested in the region, represents 25 percent of worldwide capture fisheries production annually (FAO, 2016). Key fisheries include walleye pollock (*Gadus chalcogrammus*, formerly *Theragra chalcogramma*), Japanese anchovy (*Engraulis japonicus*), Pacific chub mackerel (*Scomber japonicus*), largehead hairtail (*Trichiurus lepturus*), forage fish species, scads (family *Carangidae*), crab, shrimp and molluscs. Oceanographic features of the western North Pacific are largely characterized by two western boundary currents (WBCs): Kuroshio (subtropical WBC), which transports warm and oligotrophic water, and the Oyashio (subarctic WBC), which transports cold and nutrient-rich subarctic water (Figure 6.1). Where these currents meet, mixing promotes biological production and sustains high fishery production in the western North Pacific. In addition, strong temperature gradients between the Oyashio and Kuroshio delineate a variety of species habitats.

6.1.2 The Northeast Pacific

The Northeast Pacific is characterized by productive boundary currents and upwelling zones that support large fisheries for migratory bluefin (*Thunnus orientalis*) and albacore tuna (*T. alalunga*), small pelagics, Pacific halibut (*Hippoglossus stenolepis*) and other groundfish, and a number of Pacific salmon (*Oncorhynchus* spp.) stocks, as well as valuable crab, shrimp and squid fisheries with a collective average annual value to Canada's Pacific economy of about USD 230 million (DFO, 2013). Important non-migrant fish stocks include rockfish species, characterized by slow growth rates, high longevity, and low recruitment rates, potentially making them more vulnerable to climate change (Bograd *et al.*, 2016). Marine recreational fisheries are also very important and contribute over USD 90 million annually to Canada's Pacific economy (DFO, 2013).

6.1.3 The Pacific Arctic

The Eastern Bering Sea (EBS), Beaufort, and Chukchi seas that comprise the Pacific Arctic are dynamic, shallow, ice-driven ecosystems (Sigler *et al.*, 2016b) that support some of the most productive fisheries in the world and are critical to regional and national economies and food security. With more than 2.5 million tonnes landed in 2015, and a total landings revenue of about USD 1.7 billion (2015 values), more than half of all domestic landings in the United States of America came from Alaska fisheries in the EBS for groundfish (including walleye pollock, Pacific cod, Pacific halibut, rockfish, and flatfish), crab and Pacific salmon, including the largest wild salmon fishery in the world for Bristol Bay sockeye salmon. Subsistence harvest of fish and marine mammals is a significant feature of Arctic fisheries and is critical to long-term sustainability of local communities. Climate drives regional productivity and fisheries; in particular, ice extent and persistence in the Arctic influences the distribution of fish and marine mammals and the subsistence harvest of fish and marine mammals by local communities (Huntington *et al.*, 2013; Moore and Stabeno, 2015). In the EBS, winter sea ice structures the formation of the summer "cold pool", a body of dense, cold bottom water (less than 2 °C) that influences food web interactions on the shelf through divergent tolerance of predators and prey of cold pool conditions, determines the relative strength of top-down versus bottom-up controls, and promotes lipid-rich trophic pathways that enhance recruitment of multiple groundfish and crab species during cold years (Sigler *et al.*, 2016b).

6.1.4 The Central Pacific

The Central Pacific region transitions from warm-water oligotrophic coral ecosystems to cool-water pelagic ecosystems and supports a diversity of fish species and fisheries. More than 14.5 million tonnes were landed by fisheries in the central Pacific in 2014, most of which were harvested in the western central region (12.8 million tonnes; FAO, 2016). In the Hawaiian Islands, the marine ecosystem supports a strong subsistence harvest, a recreational fishery for reef and open-water fish, and a commercial longline fleet for tuna and swordfish (Pooley, 1993). In 2015, USA commercial fishery landings revenue totalled about USD 111 million with bigeye tuna accounting for at least 50 percent of Hawaii's landings revenue each year from 2006 to 2015 (NMFS, 2017a). As of 2012, 80 percent of fisheries revenue came from large-scale commercial longlines compared to smaller-scale fisheries (Lowther and Liddel, 2014). A roughly 1 500 000 km^2 fishery closure area surrounding the northwest Hawaiian Islands is one of the largest marine protected areas in the ocean. Many commercial fisheries target the highly productive North Pacific Transition Zone (NPTZ, approximately between 32°N and 42°N; Figure 6.1), where both commercially fished species and marine predators take advantage of the mesoscale oceanographic features that aggregate prey at the transition from the subarctic to subtropical frontal zones. As such, potential bycatch of protected species remains a concern for these open-ocean fisheries (Howell *et al.*, 2015).

6.2 OBSERVED AND PROJECTED IMPACTS ON THE MARINE ENVIRONMENT

Over the next century, significant environmental change is anticipated for the North Pacific under unmitigated as well as moderate CO_2 future scenarios (IPCC, 2013, 2014). Changes in water temperature, circulation, oxygen conditions, and ocean pH may alter species distributions and interactions in ways that yield novel system dynamics and whole ecosystem reorganization (Poloczanska *et al.*, 2016). Within the North Pacific, the largest potential climate impacts on fisheries include changes in temperature and ice conditions, which can alter the flow of energy to upper trophic levels; changes in the location, timing and magnitude of coastal upwelling, which can impact lower trophic productivity and predator-prey interactions; changes in ocean circulation, which can impact the characteristics of source waters to the region and alter advective pathways; and changes in ocean biogeochemistry, including the supply and stoichiometry of nutrients, alterations in the depth and strength of stratification, reduced oxygen content at mid-ocean levels, and increasing acidification (IPCC, 2013, 2014).

6.2.1 Physical and chemical changes

Warming ocean temperatures

Across the North Pacific, temperatures increased by 0.1 °C/yr to 0.3 °C/yr from 1950 to 2009[1], although the California Current System (CCS) and Northwest Pacific have shown greater rates of increase (0.6 °C to 1.0 °C and 0.3 °C to 0.6 °C, respectively; Poloczanska *et al.*, 2013). Continued sea surface warming is anticipated for the entire North Pacific over the next century (Figure 6.2). Relative to 1956 to 2000 average conditions, projected increases for the 2050 to 2099 period range from a total of 1.4 °C to 2.2 °C (moderate CO_2 scenarios; hereafter RCP4.5) to 3.0 °C to 3.2 °C (unmitigated CO_2 scenarios; hereafter RCP8.5) for the EBS and Western Bering Sea, Sea of Okhotsk, and Gulf of Alaska (GOA; Figure 6.2). Projected total increases in sea surface temperatures (SST) for the Arctic range from 0.6 °C to 1.4 °C and 0.8 °C to 2.4 °C (RCP4.5 and RCP8.5, respectively; 2050 to 2099 relative to 1956 to 2005), but represent an eight-fold increase in variability over 1956 to 2005 levels. In the EBS and Arctic, increased temperatures represent a relatively larger change than in warmer central Pacific regions. Average summer bottom temperatures in the EBS historically averaged between 2 °C to 4 °C but under unmitigated scenarios are projected to increase by about 3 °C (2 °C to 4 °C) by 2099; summer SST across the region, which has historically ranged between 2 °C and 10 °C may increase by as much as 4 °C to 8 °C by 2099 (Figure 6.3). Multi-year periods of cooler than average conditions, typical over the last two decades in the EBS and associated with high productivity in the system (Sigler *et al.*, 2016b), are expected to decline in frequency, duration, and magnitude (Hermann *et al.*, 2016), and are absent in multiple unmitigated scenarios after 2050.

Decreasing and more variable ice cover

Sea ice extent and thickness has shown consistent declining trends in multiple regions of the North Pacific. In the high Arctic, sea ice extent declined between 1979 and 2017 at a rate of between 2.5 percent and 13.2 percent per decade (April and September, respectively; approximately 86 100 km^2 per year for September; Ding *et al.*, 2017). Decline is especially apparent for the oldest, thickest sea ice (4+ years) which constituted approximately 150 000 km^2 in 2017 compared to over 2 million km^2 in the mid-1980s[2]. September 2017 Arctic sea ice volume calculated using the Pan-Arctic Ice

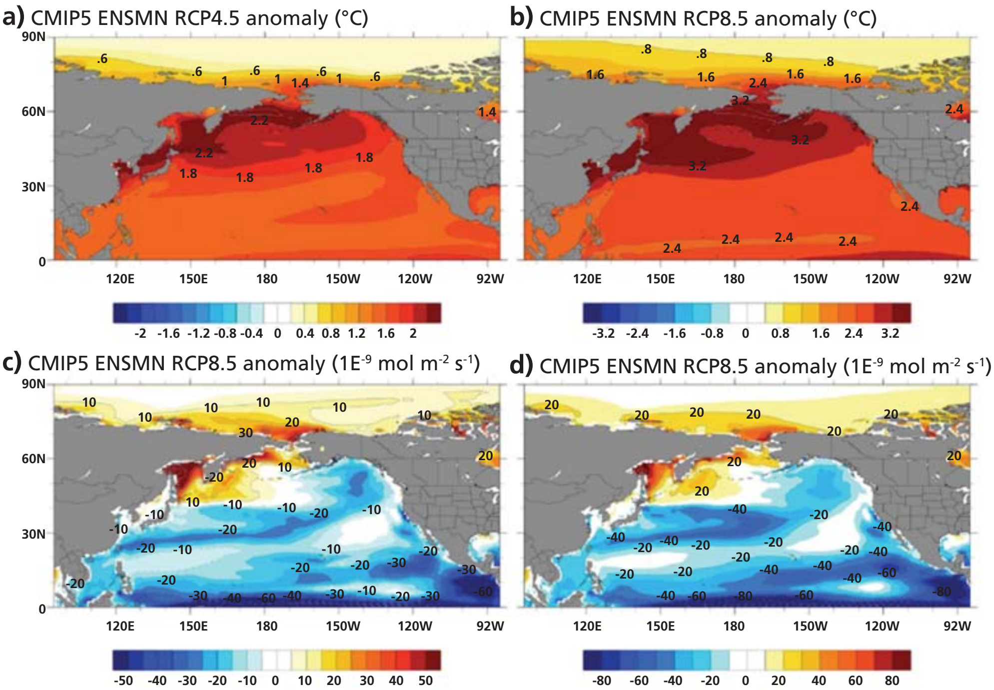
[1] For this report historical, present, and projection reporting periods may vary by study.

[2] National Snow and Ice Data Center http://nsidc.org/arcticseaicenews based on Tschudi, M., Fowler, C., Maslanik, J., Stewart, J.S. & Meier, W. 2016. *EASE-Grid Sea Ice Age, Version 3.* Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/PFSVFZA9Y85G [Cited 15 October 2017].

Ocean Modeling and Assimilation System at the University of Washington (PIOMAS[3]) was 72 percent lower than the August 1979 maximum. Sea ice cover also showed decreasing trends in the Sea of Okhotsk: reconstructed sea ice production decreased by 11.4 percent from 1974 to 2008 (Kashiwase, Ohshima and Nihashi, 2014) mainly as a result of warmer autumn air temperatures.

FIGURE 6.2

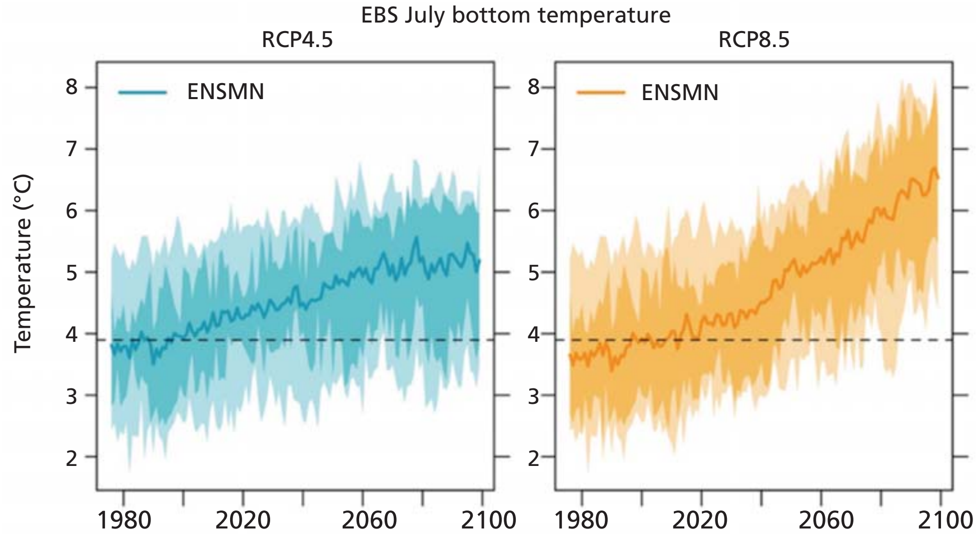
Climate Model Intercomparison Project version 5 (CMIP5) ensemble average (ENSMN) end of century projections of change in SST and phytoplankton production



Changes in (2050 to 2099) annual mean SST (a, b) and annual mean primary organic carbon production (c,d) under moderate CO_2 scenarios (RCP4.5; a, c) and unmitigated CO_2 scenarios (RCP8.5; b, d) relative to 1956 to 2005. Image courtesy of the United States Department of Commerce, NOAA Earth System Research Laboratory Climate Change Portal www.esrl.noaa.gov/psd/ipcc/ocn/. Projection data from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012).

[3] http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/

FIGURE 6.3
Climate Model Intercomparison Project version 5 (CMIP5) ensemble average (ENSMN) end of century projections of bottom temperature in the EBS

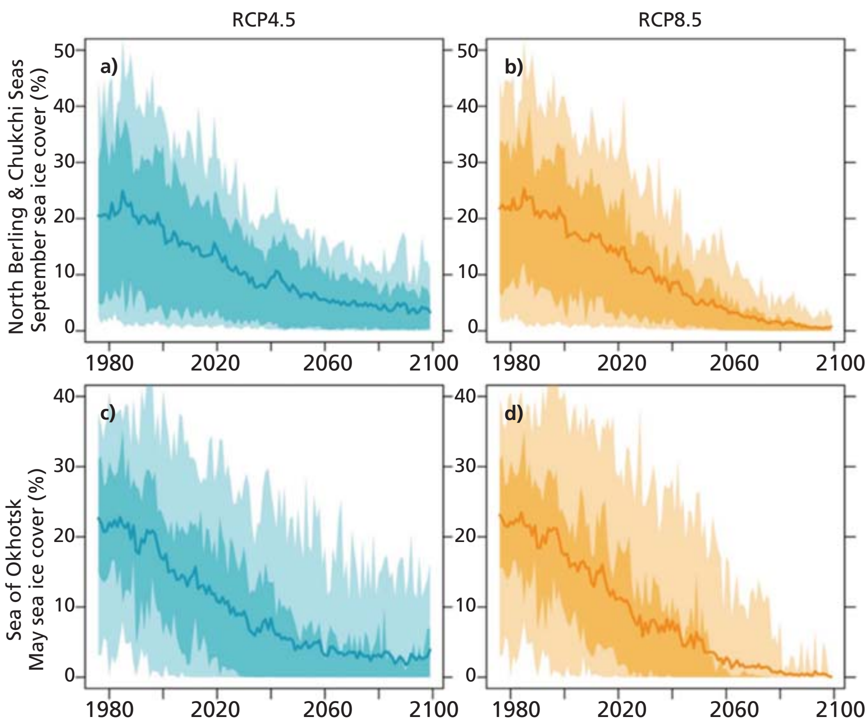


The simulations are forced using historical emission (1976 to 2005) and future projection (2006 to 2099) under moderate (RCP4.5; left) or unmitigated CO_2 (RCP8.5; right) emission scenarios. A one-year running mean is applied. Figures show the ENSMN ensemble mean (solid lines), and in light shading and dark shading, 80 percent and 50 percent of the spread of all the CMIP5 members, respectively. Based on data and images provided by the United States Department of Commerce, NOAA Earth System Research Laboratory Climate Change Portal http://www.esrl.noaa.gov/psd/ipcc/ocn/timeseries.html. Projection data from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor *et al*., 2012).

While the Pacific Arctic will likely continue to experience ice formation during the winter, ensemble projections indicate the Arctic may be ice-free in the summer by mid-century (Figure 6.4). Under both moderate (RCP4.5) and unmitigated CO_2 scenarios (RCP8.5), the extent, thickness, and date of sea ice retreat is projected to decrease. According to ensemble Climate Model Intercomparison Project version 5 (CMIP5) projections, May sea ice percentage cover in 2085 in the Sea of Okhotsk is likely to decline more than 50 percent relative to historical (1986 to 2005) ice conditions, with greater declines projected for unmitigated CO_2 scenarios (Figure 6.4). September sea ice extent over the EBS shelf (Figure 6.4) and the area of the summer cold pool is projected to decline to near zero by 2055 under unmitigated CO_2 scenarios (Figure 6.4; Hermann *et al.*, 2016; Hermann, unpublished data).

FIGURE 6.4

Sea ice area percentage projections (1979 to 2099) for the northern Bering and Chukchi Seas and Sea of Okhotsk based on CMIP5 ensemble projections



Projections of September sea ice cover in the Northern Bering & Chuckchi Seas (a,b), and mean annual sea ice cover in the Sea of Okhotsk (c,d). The simulations are forced using historical emissions (1976 to 2005) and future projection (2006 to 2099) under (a,c) moderate (RCP4.5) or (b,d) unmitigated CO_2 (RCP8.5) emission scenarios. A one-year running mean is applied. Figures show the ENSMN ensemble mean (solid lines), and in light shading and dark shading, 80 percent and 50 percent of the spread of all the CMIP5 members, respectively. Based on data and images provided by the United States Department of Commerce, NOAA Earth System Research Laboratory Climate Change Portal http://www.esrl.noaa.gov/psd/ipcc/ocn/timeseries.html. Projection data from the fifth phase of the Climate Model Intercomparison Project (CMIP5; Taylor *et al*., 2012).

Upwelling and ocean circulation

There is evidence of upwelling intensification in some eastern boundary currents, including the CCS, although coastal wind observations are too short to definitively attribute trends to climate change (Sydeman *et al.*, 2014; Wang *et al.*, 2015). Global climate models project an increase in coastal upwelling in the northern portion of the CCS (only) and a general lengthening of the upwelling season (Rykaczewski *et al.*, 2015) while enhanced stratification may limit upwelling-driven nutrient delivery to the euphotic zone (Bakun *et al.*, 2015). The net ecosystem effects are uncertain, and likely to be highly variable in space and time (Jacox *et al.*, 2015).

Recently, subtropical western boundary currents have undergone rapid warming at a rate three times faster than the global mean surface ocean warming rate (Wu *et al.*, 2012). The accelerated warming is associated with a synchronous poleward shift and/or intensification of global subtropical western boundary currents in conjunction with a systematic change in winds over both hemispheres. The Kuroshio also showed intensification, while the Oyashio responded to the multi-decadal shift in the wind stress field by contracting northwestward (Kuroda *et al.*, 2015). This shift was observed by repeated hydrographic observations over 19 years but is likely part of multi-decadal oscillations and not indicative of a long-term trend.

Sea level rise

During the period 1993 to 2016, sea level in the mid-North Pacific and Western Tropical Pacific had risen 3.0 mm/yr to 7.0 mm/yr (Lyu *et al.*, 2017), while the Northeast Pacific showed slower or negative sea level rise of -1.0 mm/yr to 3.0 mm/yr (Lyu *et al.*, 2017; Thompson *et al.*, 2017). The east–west pattern in sea level change can be explained by decadal and quasi-decadal variability that resulted in the strengthening of trade winds and a predominantly negative phase of the Pacific Decadal Oscillation (PDO) during much of the altimetry period, and which reversed during the 2012 to 2016 El Niño-Southern Oscillation (ENSO) leading to rapid sea level rise in the Northeast Pacific of 20 mm/yr to 40 mm/yr and concomitant decreases in the Western Pacific. In 2016, sea level across the North Pacific was 5 cm to 15 cm above the 1993 average and the number of days where stations reported extreme high water increased by one to over five days for multiple stations in the Northeast Pacific, Hawaii, and Arctic, but decreased by one to two days in the Western Pacific (Thompson *et al.*, 2017). Thermal expansion of oceans, increased sea ice melt, and changes in sea surface pressure are projected to further contribute to continued sea level rise across the North Pacific at rates exceeding historical observations (Nerem *et al.*, 2018), but with differing regional estimates in magnitude over time because of the effect of ENSO events, which can impact sea level.

Continued sea level rise may particularly impact nearshore habitats along North Pacific coasts and ecosystems at the freshwater-marine interface. Qiu and Zhu (2015) found that the intensity of saltwater intrusion and degree of stratification may increase with sea level rise, and estimated 48 percent and 28 percent changes in freshwater volume in spring- and neap-tides respectively in the Yangtze River estuary by 2100. Evaluations of coastal vulnerability to sea level rise indicate that 37 percent of mangroves in the Guangxi Province (China; mostly along the coasts of Dandouhai and Beihai where sea level rise exceeds low sedimentation rates) and 5.8 percent of coastal wetlands in the Yangtze Estuary may be low to moderately vulnerable to sea level rise under unmitigated CO_2 scenarios (A1F1 rise of 0.59 cm per year; Cui *et al.*, 2015; Li *et al.*, 2014); additionally, 6.9 percent of coastal wetlands in the Yangtze Estuary might be highly vulnerable to sea level rise by 2100 (Cui *et al.*, 2015).

Changes in ocean chemistry, oxygen, and pH

In the Northwest Pacific, freshening in the subtropical gyre at a rate of about -0.001 practical salinity units (psu)/year over the last 50 years has accelerated to -0.008 psu/year in the last two decades (Oka *et al.*, 2017). Water exchanges between subarctic and subtropical areas appear to cause freshening through subduction processes and differential freshening trends in subarctic subsurface and surface layers have been observed (Kuroda *et al.*, 2015). While freshening trends can be mostly explained by displacement of isopycnals (vertical distribution of water density) in the Oyashio accompanied by a multi-decadal shift of the wind stress field, subsurface salinity has an additional freshening trend that may be caused by increasing precipitation in the subarctic region and decreasing sea ice formation in the Sea of Okhotsk (Ohshima *et al.*, 2014).

It is estimated that the ocean is 30 percent more acidic today than it was 300 years ago and global oceans have absorbed roughly 26 percent of the 10.2 (+/-0.7) Pg C/yr released globally during the 2006 to 2015 period. Net carbon uptake in 2016 was greatest in the North Pacific, central Pacific and Arctic, and lowest in the Northwest Pacific. The oceans are expected to continue to absorb atmospheric carbon and surface ocean pH across most of the North Pacific is expected to continue to decline by 0.12 (pH units) over the next century, well beyond the natural variability observed to date (i.e. 0.002 to 0.01 pH units for the North Pacific). Acidification is expected to occur faster and to be more severe in the cold waters of the Pacific Arctic compared to lower latitudes. The response of marine species to lower pH is highly variable and difficult to disentangle from temperature (Poloczanska *et al.*, 2013), making it challenging to identify ocean acidification impacts to date or predict the full range of potential future ecosystem impacts.

Along the eastern boundary of the North Pacific, seasonal hypoxic events (low oxygen, less than 1.4 mL/litre) are becoming increasingly common on the outer continental shelf and slope off the west coast of the United States of America (Connolly *et al.*, 2010). Since 1980 there has been an observed decline in total dissolved oxygen (DO) content in mid-waters throughout much of the eastern North Pacific (Booth *et al.*, 2014), although recent declines followed increasing trends in DO from 1950 to 1980, thus recent declines cannot yet be definitively attributed to anthropogenic climate change (Crawford and Peña, 2016).

6.2.2 Biological and ecological changes

Primary production is projected to increase five percent to eight percent in the historically productive Sea of Okhotsk and Bering Sea, while ten percent to 20 percent declines in primary production are projected for the Northeast and Central Pacific relative to 1956 to 2005 levels (Figure 6.2). In addition, the location of the North Pacific Transition Zone (NPTZ; Figure 6.1) has been recorded as moving northwards resulting in an expansion of oligotrophic tropical waters (Polovina, Howell and Abecassis, 2008). Climate simulations under anthropogenic warming predict the trend will continue, potentially affecting the connectivity of the Western and Eastern Pacific (under RCP8.5; Hazen *et al.*, 2012).

Extreme events

In the boreal winter of 2013/2014, a marine heatwave of strongly positive SST developed in the Northeast Pacific Ocean (Bond *et al.*, 2015) and persisted through a large El Niño in the winter of 2015 (Jacox *et al.*, 2016), yet the persistent warming resulted in a different extratropical expression of El Niño compared to similar magnitude El Niños during 1997/1998 (Jacox *et al.*, 2016). The El Niño conditions, along with preconditioning of waters during 2014/15, and anomalous atmospheric circulation in early 2016 resulted in warm ocean anomalies in the Bering Sea in 2016 that cannot be explained without anthropogenic climate warming (Walsh *et al.*, 2018). Similarly, for the period 2006 to 2020, Oliver *et al.* (2018) found that the intensity and duration of extreme heatwaves in the Bering Sea and GOA were respectively 7.3 and 7.4 times more likely under climate change as compared to the natural world (i.e. under RCP8.5 versus historicalNat[4]). They also found that the return time of such events increased from one in greater than 120 years to one in five years under climate change (RCP8.5 versus historicalNat). Based on this they concluded that it was unlikely that natural variability alone led to the observed extreme marine heatwave in the EBS and GOA in 2016.

Climate change may also increase the intensity and size of storms in the North Pacific. Increases in tropical cyclone intensity with global warming have been confirmed from both historical data studies and theory. Future projections indicate fewer but intensified typhoons in the North Pacific with maximum wind speeds higher than 80 m/s (Tsuboki *et al.*, 2015).

A large harmful algal bloom (HAB) event in the Northeast Pacific during the 2015/2016 period may have contributed to coast-wide mortality of fish, bird, and marine mammal species and caused a prolonged closure of the Dungeness crab (*Metacarcinus magister*) fishery along the entire west coast of the United States of America. Projection of HABs in the Northeast Pacific is an active area of research but

[4] HistoricalNat - representing historical conditions without anthropogenic influence (Oliver *et al.*, 2018).

studies indicate HAB outbreaks may be linked to climate-scale warm ocean conditions (McKibben *et al.*, 2017).

6.3 CLIMATE CHANGE EFFECTS ON STOCKS SUSTAINING THE MAIN FISHERIES

6.3.1 Changes in biomass and condition

Changes in ocean temperature can have direct impacts on fish metabolic demands, distribution, and growth. Following the anomalously warm conditions in the GOA and EBS during 2014 to 2016, below average fish condition (i.e. lighter fish for a given size) were observed for multiple groundfish species including pollock and Pacific cod (Zador and Siddon, 2016) as well as Chinook salmon (Daly, Brodeur and Auth, 2017). Increased metabolic demand can also intensify predation and lead to high mortality rates of adult and juvenile fish. Increased predation during warm years may partially explain low recruitment and increased juvenile mortality of pollock in the EBS (Mueter *et al.*, 2011; Spencer *et al.*, 2016) and reduced marine survival for Chinook salmon in the Northeast Pacific (Holsman *et al.*, 2012). Thermal stress associated with a recent marine heatwave in the central and western Pacific may have contributed to mortality and starvation of adult Pacific cod in the GOA and a subsequent large reduction in the GOA Pacific cod biomass and recommended harvest (approximately 80 percent decline from 2015 to 2017; Barbeaux *et al.*, 2017). While Pacific cod declined in the GOA, the biomass of Pacific Ocean perch (*Sebastes alutus*) and sablefish (*Anoplopoma fimbria*) remained stable or increased (NPFMC, 2017). During the same period, the EBS also experienced the warmest conditions on record. Yet, while warm conditions in Southern EBS may have contributed to reduced biomass and low recruitment of EBS populations of Pacific cod (NPFMC, 2017), cold water in the Northern EBS may have provided a bioenergetic and foraging refuge that mitigated impacts on juvenile pollock (Duffy-Anderson *et al.*, 2017). These disparate patterns indicate that species responses to sudden and persistent warm conditions may be species-specific and mediated by changes in food web dynamics and access to thermal refugia.

In the Central and Western Pacific, the impact of warming ocean temperatures on coral reefs may be widespread and significant. Thermal stress contributed to coral bleaching events in 2016 that impacted a large proportion of reefs and dependent fish communities in the Central and Western Pacific, and may be indicative of expected change and biological response over the next century (van Hooidonk *et al.*, 2016; Kayanne, 2017).

Warming conditions may also present novel opportunities, especially in northern regions. Anomalously warm summer SSTs in the Chukchi Sea in 2007 were associated with high abundances of juvenile pink and chum salmon in the area (Eisner *et al.*, 2013). These salmon returned as adults to coastal regions in relatively high numbers during 2008 (pink salmon) and 2009/2010 (chum salmon) as reported by subsistence users in coastal communities. The loss of ice and a longer ice free season may bring opportunities for new development and increased shipping activity in the Arctic, but also imply increased risks to fish populations, to the broader ecosystem, and to subsistence users and commercial fisheries from disturbance to species, interruption of hunting and fishing access, accidental oil spills, contaminants, and other impacts (IPCC, 2014).

6.3.2 Shifting fish and shellfish distributions

In response to warming conditions, fish may move to reduce thermal stress, escape increased predation, or follow shifting prey resources. Shifting distributions may be more apparent in the Northeast Pacific than the Northwest Pacific because latitudinal SST gradients are steeper in the Northwest Pacific at the convergence of the subtropical and subarctic WBCs. Therefore, while warming may manifest in the WBCs, latitudinal shifts of marine biota in the Northwest Pacific may be difficult to detect (Masuda, 2008).

In contrast, the stretch of continuous coastline in the Northeast Pacific from the cold waters of the EBS and GOA to the warm waters of the Baja Peninsula represents a migration corridor where some of the earliest evidence of climate-induced range-shifts in the region may emerge. Northward shifts are anticipated for many southern species. Indeed, temperature-correlated shifts in distribution are evident in the EBS (Pinsky *et al.*, 2013; Poloczanska *et al.*, 2013), but are often confounded by changes in size composition and abundance (Barbeaux and Hollowed, 2018; Thorson, Ianelli and Kotwicki, 2017). Anomalously warm conditions across the Northeast Pacific in recent years (2014 to 2017) were associated with shifts in fish and shellfish distributions, including large declines in Pacific cod in the GOA and southern EBS and concomitant increases in survey catch per unit effort of Pacific cod, blue king crab (*Paralithodes platypus*) and walleye pollock in the Northern Bering Sea (Siddon and Zador, 2017). Further south, the 2014 to 2016 warming had strong negative effects on anadromous species such as Pacific salmon, yet had positive effects on the southern California sportfish community by bringing new predatory fish into the region. While shifting distributions are apparent and increasingly documented, the degree to which shifts are the direct result of climate-driven changes versus cumulative outcomes of fishing pressure, changes in prey resources, autocorrelated demographic patterns, or other unmeasured habitat features remains an active area of research (Thorson, Ianelli and Kotwicki, 2017).

Significant changes in fish and shellfish distributions are projected for the entire North Pacific region, with regional differences expected (Pinsky *et al.*, 2013). In the Northeast Pacific, pelagic marine communities are projected to shift poleward at a rate of approximately 30 km/decade (Cheung *et al.*, 2015), which would result in range expansions into the northern EBS, and range contractions in the Aleutian Islands and California Current ecosystems. It is important to note however that these projections do not account for demographic effects that influence realized distributions (see Barbeaux and Hollowed, 2018; Thorson, Ianelli and Kotwicki, 2017). Climate change may also impact the distributional ranges of fish species in the Yangtze River and Yellow River estuaries (Shan *et al.*, 2016). Bioclimatic envelope model projections based on the Geophysical Fluid Dynamics Laboratory projections of global water temperatures under low, moderate, and high CO_2 scenarios (RCP2.6, RCP6.0 and RCP8.5, respectively) suggested increases in fish abundance and distribution (particularly for demersal fish) under high CO_2 scenarios (but without considering fishing and other human activities). Projections include a shift in abundance from the northern Yangtze River estuary in 2030 to southern waters by 2050, and a more uniform offshore distribution with the centre of abundance mainly around Chongming Island coastal waters. For the Yellow River estuary, projected abundance was highest outside of the estuary, and lower in Laizhou Bay and coastal waters of the Yellow River estuary (Shan *et al.*, 2016).

In addition to latitudinal shifts in distribution, many species are projected to move into deeper cooler water as conditions warm. Indeed species moved deeper and northward in response to the marine heatwave of 2015/2016, although depth and age-specific metabolic constraints may limit realized patterns of groundfish redistribution within each region (Deutsch *et al.*, 2015; Rutterford *et al.*, 2015). The realized extent of depth redistributions will likely be shaped by oxygen conditions, which are projected to decline at depth for many areas in the North Pacific and may limit species to shallower habitats (Deutsch *et al.*, 2015). Current envelope models that do not include ontogeny or other constraints such as oxygen and pH may underestimate the impact of climate-driven changes as the scope for behavioural adaptation may be less than expected because of age-specific physiological limitations.

6.3.3 Changes in phenology and mismatch

Changes in ocean circulation in combination with changes in food availability and predator distributions may increase the probability of spatial mismatch of species with habitats and prey resources and reduce juvenile recruitment and survival. This may be the case for crab species such as the Bristol Bay red king crab (*Paralithodes camtschaticus*), which are expected to decrease under climate change based on observations of low recruitment in warmer conditions, transport of larvae beyond their prime habitats in warmer years with more on-shelf transport, and poor feeding conditions for crab larvae during early ice melt years (Zheng and Kruse, 2006). Spatial mismatch during warm years has also been observed for juvenile walleye pollock and their key prey in the Bering Sea (Siddon *et al.*, 2013). Changes to upwelling dynamics in marine nearshore environments as well as alteration of freshwater flow and differential rates of warming between natal streams and marine environments could result in changes to outmigration timing of juvenile Northeast Pacific salmon and potential phenological mismatch with marine prey and predator refuge during a critical early-marine population bottleneck (Bakun *et al.*, 2015; Holsman *et al.*, 2012).

Mismatch under climate change may particularly impact species with narrow bioclimatic envelopes (e.g. width of the timing interval in which individuals must enter the breeding habitat), those where the relative rate of change within a bioclimatic envelope exceeds the inherent phenological plasticity of the species, and migratory species whose timing is cued by photoperiods or other non-temperature cues (Anderson *et al.*, 2013). In these cases, population size might not be a reliable indicator of sensitivity, rather variability in average individual condition across years may be a better indicator of extinction risk under climate change (Anderson *et al.*, 2013).

6.3.4 Ocean acidification impacts

One of the potentially significant, yet uncertain, impacts of climate change on marine ecosystems in the North Pacific is ocean acidification. The Northeast Pacific region naturally has low pH waters near the surface, and may be more vulnerable to acidification than other regions. Shellfish resources are probably most sensitive (Haigh *et al.*, 2015), especially juvenile stages of shell-forming species like red king crab (Long *et al.*, 2013).

Fish-killing algae such as *Heterosigma akashiwo* may gain a competitive advantage under ocean acidification, causing blooms to be more frequent and threatening the commercial British Columbia salmon fishery (Haigh *et al.*, 2015). Ocean acidification also negatively affects some ecologically important components of the food web, in particular shelled planktonic organisms such as pteropods (Bednaršek *et al.*, 2012), which can serve as important prey for fish (Armstrong *et al.*, 2008). However, pteropods may be more resilient than previously believed (Peck *et al.*, 2018) and the food web effects of such impacts are highly uncertain. Although ocean acidification has been shown to affect the growth, survival, sensory abilities and behaviour of some fish species, studies of walleye pollock and Pacific cod did not find direct effects on growth or survival (e.g. Hurst, Fernandez and Mathis, 2013).

6.3.5 Cumulative climate-driven impacts

Projected changes in ocean circulation and upwelling in the Northeast Pacific CCS may have significant ecosystem impacts, as evidenced by the pan-trophic ecosystem disruption observed in the CCS in 2005 as a result of delayed upwelling (Barth *et al.*, 2007). Along the eastern boundary of the North Pacific, a warming of the upper ocean could lead to an increase in water column stratification and increased probability of low oxygen conditions in the CCS. Ecosystem impacts of deoxygenation may include more frequent mortality events, particularly for benthic organisms, habitat compression, distributional shifts, and reduced species diversity (Keller *et al.*, 2015). Impacts from declining oxygen levels will be exacerbated by ocean acidification, especially in the Northeast Pacific, where upwelling of "corrosive", low pH waters frequently occurs (Ekstrom *et al.*, 2015; Feely *et al.*, 2008). A modelling study by Kaplan *et al.* (2010) estimated a 20 percent to 80 percent decline in the abundance of some commercially valuable West Coast groundfish as a result of ocean acidification, primarily because of the loss of shellfish prey.

The ability for species to adapt and respond to changing conditions will be governed by the compound constraints posed by multiple pressures and stressors as well as the physiological tolerance and genetic plasticity of individuals. Small populations that have been bottlenecked or genetically homogenized are more susceptible to stressors. Hatchery raised Pacific salmon lack genetic diversity, and spawning with wild populations can reduce a population's genetic fitness and ability to cope with stressors such as increased temperature. Genomic scans have been used to identify the genetic architecture of disease resistance, particularly in Pacific salmon (Miller *et al.*, 2014) and have illustrated a genetic basis for species' intolerance to disease.

Ecosystem health and productivity may also be impacted by climate change. Shan, Chen, and Jin (2017) evaluated future fishery ecosystem health (based on environmental conditions, fishery community structure, and ecosystem function and service) of the Yangtze River and Yellow River estuaries and found that ecosystem health indices gradually decreased with increasing greenhouse gas emission levels. By 2050, ecosystem health indices were roughly three times higher in highly mitigated CO_2 scenarios (RCP2.6) than unmitigated CO_2 scenarios (RCP8.5).

6.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

6.4.1 Fishing and post-harvesting operations

Changes in the location of fish resources could impact fishery access and cost, especially for small vessel and shore-based fisheries that may not be able to track climate-driven changes in species distributions and centroids of biomass. In Canada's Pacific waters, biological impacts from climate change, such as ecosystem and fisheries degradation and damage, changes in biological resources, and species reorganization and displacement, have been proposed as the greatest risks to the region (DFO, 2013). Shifting distributions of some important fish species may especially pose a challenge to shore-based fisheries where harvest allocations are tied to central ports and fisheries are limited in their capacity to follow fish redistributions (Pinsky and Fogarty, 2012). For example, in Alaska some commercial fish and crab species may expand summer feeding migrations into the northern Bering Sea and Chukchi Seas. However, the shallow shelves of the Arctic will continue to cool to near-freezing for extended periods each winter, potentially excluding most boreal species from the region and limiting the establishment of new spawning areas for southern species (Hollowed *et al.*, 2013). Moreover, northward expansion of the commercial fishery, and the establishment of new fisheries, are limited in the northern Bering Sea and are prohibited in the United States of America portions of the Chukchi Sea and Beaufort Sea by existing national laws and in the central Arctic Ocean under an international agreement. Fishing in these areas is presently composed of limited non-trawl commercial fisheries and subsistence harvest of salmon and other fish species in addition to hunting activities, which have been disrupted by changes in ice extent and thickness (Fall *et al.*, 2013; Huntington *et al.*, 2013). Northward movement of fish populations in combination with loss of sea ice may increase trip time and fuel cost for shore-based commercial vessels (which are presently based in the southern EBS) and reduce access to commercial fishery resources (as fish move into fishery closure areas).

In addition to temperature, changes in ocean circulation and primary production may alter fish distributions. For example, projected expansion of the North Pacific Transition Zone may result in further distance travelled for fisheries from the Hawaiian islands, and redistribution of species richness and carrying capacity for marine taxa (Hazen *et al.*, 2012; Woodworth-Jefcoats, Polovina and Drazen, 2017). Similarly, in the Northwest Pacific the path of the subarctic Oyashio recently shifted northeastward (Kuroda and Yokouchi, 2017) shifting fishing grounds of Pacific saury to the northwest and across transboundary lines, presenting a significant problem for small fisheries which do not have rights to cross the international border and are limited in their ability to travel to distant fishing grounds.

Ocean acidification may directly impact shellfish fisheries. Projections that account for the effects of anticipated changes in ocean pH on red king crab larval survival (and assume no acclimation to acidic waters) suggest substantial declines in the harvestable biomass in coming decades (Punt *et al.*, 2014). The welfare loss of ocean acidification on one major red king crab stock (Bristol Bay) to Alaska households has been estimated at USD 500 million to USD 1 billion over the period from 2010 to the end of this century but may be underestimated because the authors only included effects on juvenile stages (Seung *et al.*, 2015). Ocean acidification also affects the hatching success and larval growth and survival of Tanner crab (*Chionoecetes bairdi*) in Alaska and projections that account for these effects suggest a more than 50 percent reduction in catch potential and profits within 20 years (Punt *et al.*, 2016).

Shifting prey resources and conditions can also impact the quality and value of harvested fish. Low fish condition and quality was reported for EBS pollock in 2016, where water temperature was the highest on record, and may have contributed to adult Pacific cod mortality in the GOA (Barbeaux *et al.*, 2017). Warm conditions in 2014/2015 were also associated with poor Chinook salmon condition and size (Daly, Brodeur and Auth, 2017). Similarly, in the Northwest Pacific, saury size is decreasing and future projections indicate further northward shift in distribution and continued reduction of the size of fish (Ito *et al.*, 2013). Since the price of fish strongly depends on fish size and quality, these impacts are serious concerns for fishers.

6.4.2 Communities and livelihoods, and wider societal and economic implications

Differential changes to species productivity and distribution may have disparate impacts on fisheries sectors and fishing communities. For example, commercial groundfish fleets in Alaska can generally be characterized as either catcher vessels, which deliver harvest to shoreside processors and have a large proportion of Alaska-based boats, or at-sea catcher processors that sell processed product directly to first-wholesale market and whose fleet and crew is largely based more than 2 000 km south in Seattle, Washington (Fissel *et al.*, 2017). In the Bering Sea, on average roughly 59 percent of groundfish landings are retained by catcher processors, while in the GOA 86 percent of landings are retained by smaller shore-based catcher vessels. Because of their dependence on discrete processing sites, reduced trip distances, and smaller vessel size, catcher vessels may be less able to adapt to shifting species distributions or increased variability in catch. Salmon harvest similarly is largely conducted by smaller vessels and local fleets out of numerous coastal Alaskan communities, which support the largest salmon fishery for Pacific salmonids. In contrast, larger catcher processors may be able to follow shifting groundfish distributions, and therefore reduce impacts on the Seattle-based fleet.

In addition to tracking changes in fish distributions, fishers that participate in more than one fishery (commonplace in the Northeast Pacific) can adapt to climate-driven change by redistributing effort between different fisheries (Fuller *et al.*, 2017). Such "fisheries connectivity" can help buffer fishing communities from large-scale changes, so long as central key fisheries remain intact. At the same time, changes to a core fish species (e.g. Dungeness crab in the CCS) can have widespread indirect impacts on connected fisheries. Fuller *et al.* (2017) evaluated fisheries connectivity across ports in the CCS and found that ports such as Santa Barbara (United States of America), which have high diversification across fisheries, are likely most resilient to change despite a high reliance on a central fishery (squid). CCS fisheries are typically generalists and therefore more resilient to sudden change given current fisheries structure. Fishing communities with less diversification may be most vulnerable, as climate-driven loss in individual fisheries could reduce the adaptive capacity of fishers and increase sensitivity to future perturbations (Fuller *et al.*, 2017).

Climate-driven changes in the abundance and distribution of resources impact subsistence harvest success and access and may shape long-term trends for indigenous communities in Alaska. While commercial harvest is currently prohibited in the Northern Bering, Beaufort, and Chukchi seas, subsistence harvest is essential to sustaining indigenous communities in the area (Fall *et al.*, 2013; Haynie and Huntington, 2016; Moerlein and Carothers, 2012). In particular, subsistence harvest in the Northern Bering Sea is influenced by social and ecological conditions that impact the cost of fuel, interactions with and participation in commercial fisheries, the duration and predictability of storms, sea ice extent and thickness, and the location of resources (Fall *et al.*, 2013). Historically, communities have adapted to climate-driven changes, but increasing uncertainty facing local communities in Alaska will shape future adaptation (Fall *et al.*, 2013; Moerlein and Carothers, 2012). Indigenous and First Nations communities throughout the Northeast Pacific and Pacific Arctic are disproportionately at risk to climate-change because of their high reliance on shore-based subsistence and commercial fisheries within traditional territories.

6.4.3 Consequences for fisheries management

Rapid changes in abundance and distribution of fish within a region may impact the ability to assess and manage resources effectively. Fish may move out of survey areas, impacting estimates of abundance and size composition. Climate-driven changes may impact fisheries connectivity and the ability for fishing communities to adjust to rapid change (Fuller *et al.*, 2017). Novel fishery opportunities may emerge that will require rapid development of new fishery management plans. Similarly, new transboundary agreements may need to be developed to help co-manage stocks that shift distributions in response to changing conditions. International coordination on surveys, and joint assessment efforts, like those used presently to manage Pacific halibut and Pacific hake in the Northeast Pacific, may be needed for other mobile fish and crab species. Finally, shifting distributions and changes in abundance may lead to new "choke" fish species (i.e. those with low quotas that are caught as bycatch and limit other fisheries), presenting the need for rapid evaluation of bycatch hotspots, avoidance methods, and technologies to avoid incidental capture. Continued development of ecological forecasting methods, in combination with support for in-season monitoring and regulation (like that used by the groundfish fleets in Alaska to reduce salmon bycatch), is needed to minimize climate impacts on fish species and avoid sudden fishery closures.

Shifting conditions and species phenologies can have direct and indirect effects on fish and fisheries that may be difficult to anticipate but may present novel challenges for fisheries management. For example, entanglements of baleen whales in the CCS reached recorded high numbers in 2015 and 2016 as a result of the combined effects of recovery of humpback whale populations, environmental shifts in distribution of whales, and environmental changes in fishing effort (NMFS, 2017b). The marine heatwave from 2014 to 2016 increased densities of forage fish near-shore, which resulted in a similar shift in foraging humpback whales. At the same time, a large HAB and elevated domoic acid (neurotoxin) levels in invertebrates resulted in a later start date for the Dungeness crab fishery. A higher fishery effort (compensating for the delayed start of the fishery), combined with the distributional shift in foraging whales, resulted in greater overlap and risk of whale entanglement. As anomalous warm-water events are predicted to increase in the future (Di Lorenzo and Mantua, 2016), unforeseen overlap between protected species and fisheries may create new conflicts, requiring proactive and adaptive approaches to fisheries management.

6.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES AND THOSE DEPENDENT ON THEM

Through the highly productive capture fisheries of the region, the North Pacific represents a significant source of provisioning resources for global marine protein. Regional fisheries are also highly integral to the economic and cultural identity of dependent communities and nations in the North Pacific and Pacific Arctic. Multiple climate-driven interacting changes are anticipated for the North Pacific, with outcomes that remain uncertain but may be significant relative to historical conditions. In an updated analysis on the national vulnerability to the impacts of climate change on marine fisheries, which included assessment of aggregate indices for exposure, sensitivity and adaptive capacity, Blasiak *et al.* (2017) ranked China 8th, the Russian Federation 48th, Canada 54th, South Korea 129th, Japan 137th, and the United States of America 142nd out of the 147 countries they examined. As an example of vulnerabilities in Canada, Weatherdon *et al.* (2016) conducted a study of the potential impacts of climate change to the coastal First Nations of western Canada and found that climate change is likely to reduce the availability of marine species that are of nutritional, cultural and economic importance, possibly by up to 49 percent for Pacific herring, with estimates of annual losses between CAD 6 million and CAD 12 million (equal to approximately USD 4.7 million–USD 9.3 million at the time of writing). In addition, the availability of salmon for harvest is predicted to decrease by 17 percent to 29 percent. They concluded that First Nations' territories along the northern and central coasts of British Columbia, Canada, will likely experience less severe declines than communities in southern British Columbia. Similarly, Hunter *et al.* (2014) examined the sensitivity of Canada's Pacific fish stocks to climate change based on assumptions that 1) more productive species will be more resilient; 2) species with higher dispersal ability will be more resilient; and 3) species that do not rely on seasonal environmental cues or multiple habitats for key phases of their life cycle will be more resilient. They concluded that the most sensitive species are elasmobranchs, whereas the least sensitive are flatfishes.

6.6 RESPONSES AND ADAPTATION

Managing resources in a changing environment requires a balance between the trade-offs and benefits of multiple, competing objectives which requires flexible governance and management (King, McFarlane and Punt, 2014). An analysis of the adaption of the Canadian commercial fishing sector to climate change, as governed by institutional processes and practices, notes that even economically important fisheries within a region vary in their adaptive advantages because of differences in governance regimes. For example, the crab trap fishery was assessed as low–moderate in adaptability as a result of current governance attributes (e.g. allocation agreements) that may act as barriers if the cyclical population dynamics change under climate change. Conversely, the Pacific halibut fishery was assessed as highly adaptive since there are advanced governance arrangements and management attributes that enable adaptation to shifts in productivity. Similarly, in the United States of America recent national and regional strategic initiatives have been aimed at supporting climate-ready fisheries management (Busch *et al.*, 2016; Sigler *et al.*, 2016a) and vulnerability assessments have highlighted vulnerable species and fishing communities (Colburn *et al.*, 2016; Hare *et al.*, 2016;

Himes-Cornell *et al.*, 2016). Highly adaptive fisheries often require governance regimes that include fishery-governance cooperation, stakeholder involvement, and resource co-management; high monitoring and enforcement capacity; compliance with effort, area and time restrictions; complex multi-sectoral fisheries allocation processes and international fisheries governance negotiations; sophisticated stock assessments and harvest control rules that increasingly include management advice for environmental effects; adoption of climate-sensitive policies and timely fisheries management review (Busch *et al.*, 2016).

Measures to promote resilience of fisheries under climate change might include:

- **Continued development of climate-informed management tools** that include flexibility for allocations, ability to switch quota between species, new fisheries management plans, increased foresight into population changes and fishery closures, adjustable rebuilding plans, and re-evaluation of closure areas. Such changes also require pre-specified criteria for when to adjust targets in order to reduce the risk of ratcheting targets that amplify declines.
- **Evaluation of climate-informed management tools** through climate-driven management strategy evaluations and ecosystem risk assessments should be used to help ensure climate-ready fisheries management (Holsman *et al.*, 2017).
- **Increased innovation to help reduce bycatch**, for example through predictive ecological forecasts of conditions and species distributions, flexibility in bycatch allocation measures, and novel incentive structures for reducing bycatch.
- **Continued evaluation and conservation of existing and emergent critical habitats, migration corridors, and spawning areas**, including considerations of dynamic and adaptive closures.
- **Incorporation of projections into business models** and enhanced infrastructure to scope new shore-based processors in the Northern Bering Sea.
- **Increased ability for local communities to adapt** through co-management and updating subsistence permits to include species that are resilient to and favoured by changing conditions. Increased communication with local communities to improve observations of change and predictions of impacts (through local ecological knowledge) and facilitation of local adaptive policies identified by tribal councils and co-managers and regional governing bodies.
- **Continued reduction of cumulative impacts on ecosystems and fishing communities** through policies aimed at increasing ecosystem productivity, fisheries connectivity and diversity, improved community resilience, and increased efficiency to reduce economic burden and cost of fishery harvest.
- **Distribution of carbon taxing** to improve local and individual adaptation policies.

Negative changes in fish production and extreme events are likely to impact coastal communities with high dependence on individual fishery resources, but such impacts are strongly shaped by the flexibility of fishers and hunters to adjust to changing conditions (Fuller *et al.*, 2017; Haynie and Huntington, 2016) and their ability to utilize novel or expanding species. Marine and fisheries management should therefore include policies that increase flexibility, consider fishery connectivity, and remove roadblocks to adaptation, while incentivizing long-term ecological sustainability. For example, Japanese-type management, "resource management by the resource users themselves" is one approach to increase flexibility (Makino, 2017). While increasing flexibility may seem apparent, it is not always intuitively clear, as unintended outcomes can arise from different polices. For example, rights-based programmes (e.g. quotas) have been advocated as a method to increase sustainability under climate change (Costello *et al.*, 2016), yet can also yield unintended outcomes that may reduce climate change resilience. For example, federal management of Alaska commercial fisheries includes a series of ecosystem-based management approaches, closure areas, and catch share programmes (which represent 75 percent of groundfish landings) aimed at promoting ecological sustainability and economic benefits (NMFS, 2017a; Stram and Evans, 2009). While such programmes increase long-term investment in a given target species, they tend to lead to reduced diversification in fisheries over time through investment, specialization, and management restrictions that reduce switching between target species. This can lead to increased dependency and reduced flexibility for fishers, and potentially increased vulnerability to collapse under future climate change and extreme events (Kasperski and Holland, 2013). The effectiveness of various management approaches also depends on future socio-economic conditions that can influence resources and support for fisheries science and environmental data. Indeed, the optimal mix of fisheries management may include multiple integrated layers of policies that promote diversification and flexibility at multiple scales, enhance management responsiveness, and incentivize stewardship and self-regulation.

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Chapter 7: Climate change impacts, vulnerabilities and adaptations: Mediterranean Sea and the Black Sea marine fisheries

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KEY MESSAGES

- Fisheries in the Mediterranean and Black Sea are multi-specific and multi-fleet, with small pelagic species the most important in terms of landings and small-scale fisheries (SSF) the dominant fleet. Current high rates of overfishing will affect their capacity to cope with climate change impacts.
- Surface warming, increasing heatwaves and a decrease in precipitation are very likely over the Mediterranean, with changes in circulation, sea level rise and winter weather regionally likely. In the Black Sea, surface warming, changes in thermohaline structure, sea level rise and extreme weather events are likely.
- *Meridionalization* (occurrence of warm water species in northern regions) and *tropicalization* (expansion of non-native tropical species) in the Mediterranean, and *Mediterranization* (spreading of Mediterranean species) in the Black Sea, are strengthened by warming and will have positive and negative impacts on fisheries.
- Longitudinal gradients in the rate of warming and changes in primary production are likely and result in an expected increase in fish diversity in the Eastern Mediterranean and decrease in the Western Mediterranean. In the Black Sea, projections show an increase in primary production in the north and a decrease in the south.
- Changes in primary production and runoff will likely have a negative impact on the optimum habitats for small pelagic fish in the Mediterranean. In the Black Sea, changes in anchovy migration, overwintering and schooling behaviour as a result of warming will negatively affect fisheries in several countries.
- Demersal species will suffer regional impacts associated with the expected changes in primary production, thermohaline circulation, and the strength of winter weather. Warming and the expected increase of Atlantic water entering into the Mediterranean will likely affect migrations and spawning behaviour of large pelagic fish.
- Fisheries vulnerability to climate change is likely to be higher in south and southeast developing countries given the higher exposure to warming and arrival

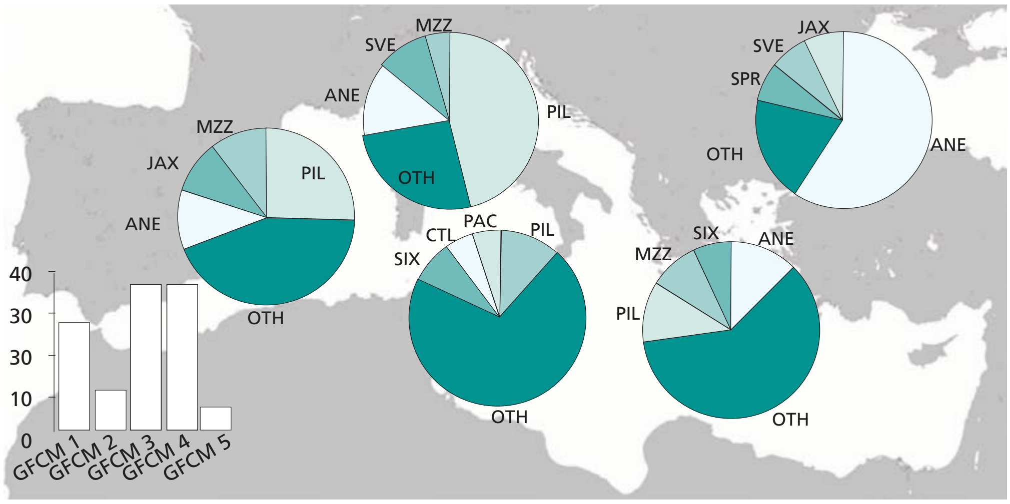
of non-indigenous species, and their overall lower adaptive capacity. Lower vulnerability is expected for the Black Sea, given a lower dependency on fisheries.

- New opportunities will emerge in the SSF and related communities, where new potentially commercial species could increase yields and economic profitability. The arrival of non-indigenous species will also trigger problems in fisheries based on native species.
- Numerous regional initiatives are aimed at embracing short-term measures to reverse the current fisheries and ecosystem challenges with medium- and long-term actions to adapt to climate change impacts. Transboundary research and management strategies are paramount, particularly for developing countries.
- National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) show, in general, limited references to adaptation measures (AMs) for fisheries. Few countries envisioned AMs on: monitoring, commercialization and fish consumption, research on ecological mechanisms and socio-economic impacts, education, and technical actions on species and habitats.

7.1 MAIN FISHERIES OF THE REGION

The Mediterranean and Black Sea fisheries are highly heterogeneous in the number of species harvested, variety of fleets, complex socio-economic elements and diverse governance capacities over the riparian countries, which include developed and developing countries from Europe, Asia and Africa. The dominant fisheries fleet segment in the Mediterranean and Black Sea regions is the small-scale segment, consisting of polyvalent vessels (i.e. using more than one type of gear) up to 12 m length, which makes up 80 percent of the total fleet and employs the highest number of fishers. In contrast, trawlers land the resources with the highest value and purse seiners have the highest landings by mass (FAO, 2016a).

FIGURE 7.1
Percentage of landings per species for the five General Fisheries Commission for the Mediterranean (GFCM) subregions



1) Western Mediterranean; 2) Adriatic Sea; 3) Ionian Sea; 4) Eastern Mediterranean; and 5) Black Sea. ANE - *Engraulis encrasicolus*; PIL - *Sardina pilchardus*; JAX - *Trachurus* spp; SPR - *Sprattus sprattus*; SIX - *Sardinella* spp; SVE - *Chamelea gallina*; MZZ - Unallocated osteichthyes; OTH - Other species. *Source:* FAO (2016).

Thirteen main species contribute to 65 percent of landings in the region. They comprise mainly small and medium pelagic fish, with anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*), horse mackerels (*Trachurus* spp.) and sprat (*Sprattus sprattus*) as the dominant species, accounting for more than 50 percent of the total landings. Small pelagic fish are particularly important in the Black Sea, Adriatic Sea and Western Mediterranean subregions (Figure 7.1; FAO, 2016a). The Ionian and Eastern Mediterranean subregions are, in contrast, dominated by a diverse group of species, mainly demersal, demonstrating the significance of multispecific, SSF in these subregions (Figure 7.1).

The total value of landings across the Mediterranean and the Black Sea is estimated at around USD 3.09 billion and the sector employs a quarter of a million people. The average landing prices in the Western Mediterranean, Ionian and Adriatic Sea subregions are at least double those of the Black Sea and Eastern Mediterranean. On the other hand, fisheries make a more significant economic contribution to the regional economies in the Eastern Mediterranean (FAO, 2016a).

The total Mediterranean and Black Sea catches increased from 1970, with a peak in 1985 to 1988 and since then they have declined by 25 percent and remained almost constant since the late 1990s (FAO, 2016a). The decline in catches is in part a result of overfishing, with 62 percent of stocks considered overexploited (FAO, 2016b). Regional assessments providing scientific advice to the GFCM estimate even higher exploitation rates (FAO, 2016a). European hake (*Merluccius merluccius*) stocks are among the resources under more intense overfishing, with fishing mortality rates up to ten times higher than the optimal target (FAO, 2016a; STECF, 2017).

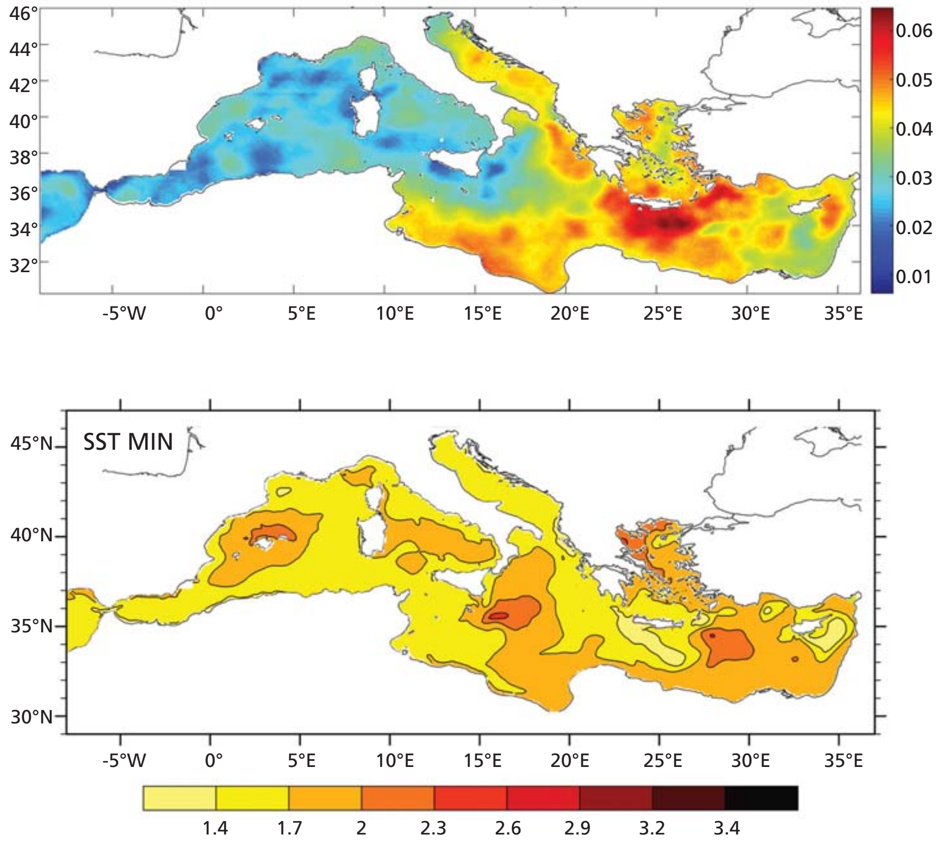
7.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON MARINE ENVIRONMENT

In general, simulations providing climate change projections used in this report are based on Mediterranean and Black Sea regional models. Global models do not properly reproduce temporal and spatial variation of oceanographic variables at the scales of these marginal seas, and therefore their predictions are considered less reliable than the higher resolution regional models.

7.2.1 Physical and chemical

The most frequently reported evidence of climate change impacts of relevance for Mediterranean fisheries are the observed and very likely progressive decrease in precipitation, water warming and salinity increase from surface to the deep water masses, increased intensity and frequency of heat extreme events (heatwaves) and changes in stratification (e.g. Adloff *et al.*, 2015). The climate change impacts on the Black Sea comprise the likely warming of surface waters, changes in vertical thermohaline structure and increased frequency of extreme weather events, especially extreme precipitation events (e.g. Hills, Schoen and Nadcrinicinii, 2013; Miladinova *et al.*, 2017).

FIGURE 7.2
Top - horizontal distribution of satellite-derived SST annual linear trends (°C/yr) over the period 1985 to 2008.
Bottom – minimum values of the anomalies obtained from the composite forecast (out of the six scenario simulations) of sea surface temperature for the 2070 to 2099 period (vs. 1961 to 1990). Units are in °C

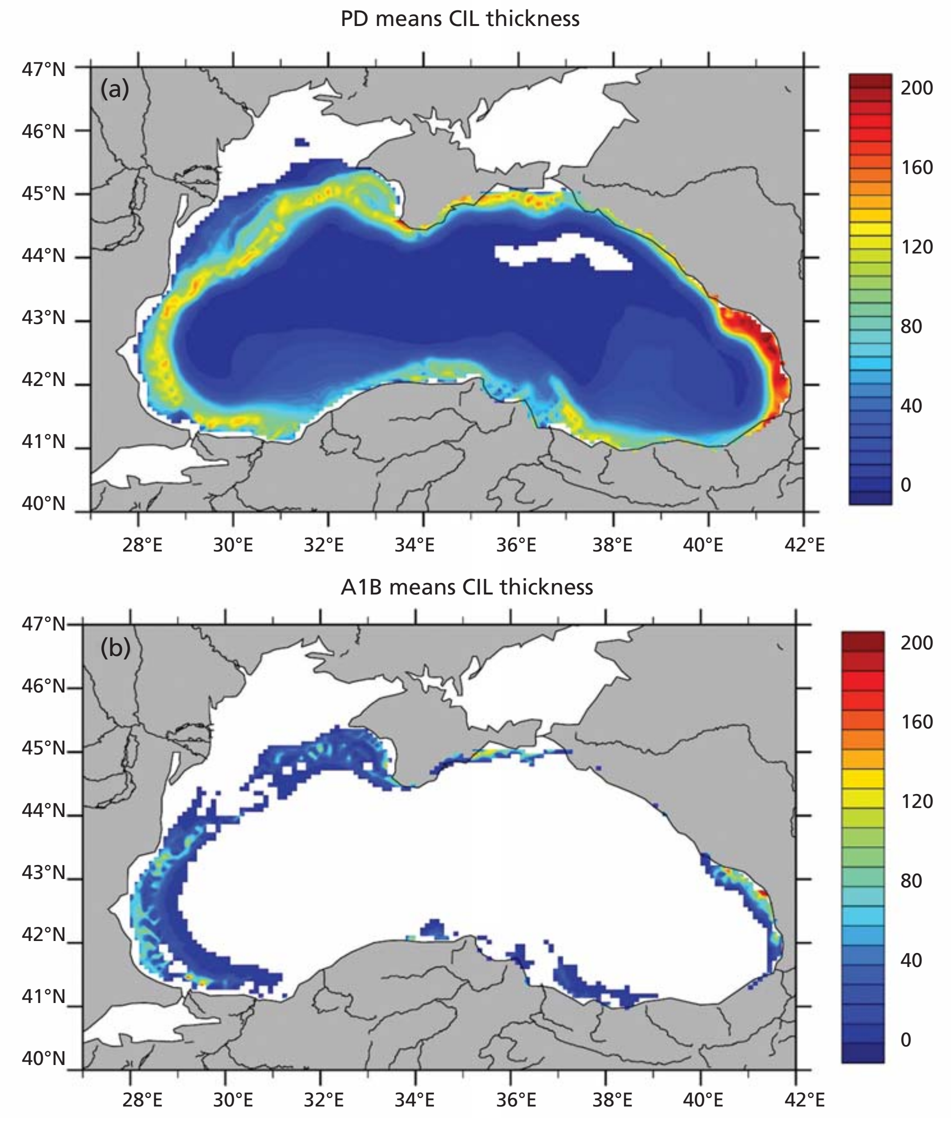


Source: Top map, adapted from Skliris *et al.*, 2012; Bottom map: adapted from Adloff *et al.*, 2015.

Recent warming of the Mediterranean Sea (from the early 1990s) results from the combination of natural climate variability (Atlantic Multidecadal Oscillation) and climate change (Macias, Garcia-Gorriz and Stips, 2013), with a resulting stronger trend in the Eastern Mediterranean from the early 1990s (Figure 7.2a; Skliris *et al.*, 2012). The available estimates of future surface warming in the Mediterranean range from +1.73 °C to +2.97 °C in 2070 to 2099 in respect to 1961 to 1990 (Figure 7.2b; Adloff *et al.*, 2015) while surface salinity anomalies are forecast to increase from +0.48 to 0.89 over the same period. The frequency of heatwaves is expected to increase from about two days per year in the past century to about 6 to 24 days per year in 2021 to 2050 (Fischer and Schär, 2010). Over 2100, the Black Sea is also projected to warm, from a maximum of 2.81 °C per century in summer to a minimum of 0.51 °C per century in winter (Shaltout and Omsted, 2014), with little spatial variability in the annual trends (Cannaby *et al.*, 2015). The sea surface salinity is estimated to have shown a gradual decrease (0.02/year) over the last 50 years (1960 to 2015; Miladinova *et al.*, 2017) while future projections indicate a possible increase by the end of the century (Cannaby *et al.*, 2015).

Likely sub-surface density changes are expected to lead to an increase in the water stratification in the western basin of the Mediterranean Sea and a decrease in the eastern basin. The Atlantic waters entering the Mediterranean are projected to be likely less dense in all simulations (Adloff *et al.*, 2015) and may alter the formation and structure of stationary fronts and dynamic mesoscale structures of high importance for fisheries in the Mediterranean (e.g. large pelagic fish; Alvarez-Berastegui *et al.*, 2016). In the Black Sea, the cold intermediate layer (CIL) is a key feature of the vertical thermohaline structure, influencing the position of the oxygen/anoxic boundary. Warming results in erosion of the CIL, both in terms of area covered and the thickness of the layer (Figure 7.3; Cannaby *et al.*, 2015; Miladinova *et al.*, 2017). This affects the exchange of oxygen across the oxycline and results in a decrease in the depth of the upper suboxic interface, below which the concentration of hydrogen sulphide increases.

FIGURE 7.3
Maps showing present day (PD, 1980 to 2000) and A1B (2080 to 2100) annual mean CIL thicknesses, averaged over the entire basin



Blank areas indicate an absence of the CIL during part of the year. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system – fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). Units are metres. *Source*: Adapted from Cannaby *et al.*, 2015.

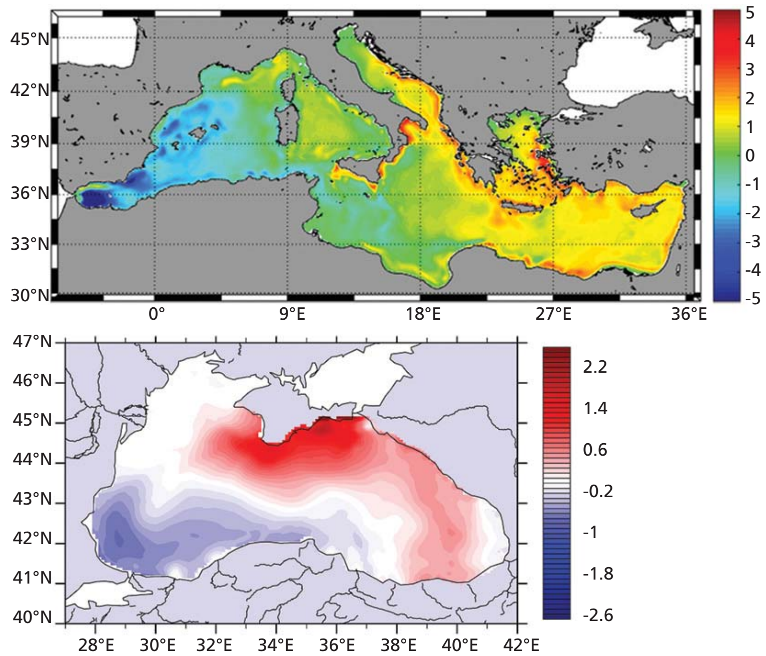
Sea level rise has been increasing during recent decades with rates of 2 to 10 mm year and 1.5 to 2.5 mm/year for the Mediterranean and Black Sea respectively (Gomis *et al.*, 2008), with projections supporting a very likely continuation of an increasing trend. Finally, a decrease in pH (i.e. acidification) in the Mediterranean Sea is considered likely given the high potential of water masses to sequestrate anthropogenic CO_2 and their relatively shorter residence compared to large oceans. Observations and expectations of an ongoing decrease in pH are in the order of 0.002±0.001 pH units per year in several locations, with high geographic variability (Lacoue-Labarthe *et al.*, 2016). In the Black Sea, significant acidification is not expected during this century.

7.2.2 Biological and ecological

A heterogeneous pattern of change in primary production has been observed in the last decades in the Mediterranean Sea, with some areas showing increasing trends and others degreasing (Colella *et al.*, 2016). However, the expected changes in stratification, the decrease in the strength and frequency of local upwelling events, and the decrease in precipitation (and run-off) are expected to reduce the overall primary production in the Mediterranean Sea in the future. With reference to the likely geographic differences in surface stratification, the western basin will become more oligotrophic in association with a surface density decrease, while surface production will increase in the eastern basin linked to a density increase (Macias, Garcia-Gorriz and Stips, 2015; Figure 7.4a). In the Black Sea, long-term model simulations show an increased retention of river nutrients within the euphotic zone that could likely exacerbate the impact of eutrophication (Cannaby *et al.*, 2015). Thus, projections show that net primary production and phytoplankton biomass could increase by approximately 5 percent but with high longitudinal variability (Figure 7.4b; Cannaby *et al.*, 2015).

FIGURE 7.4

Top map: mean primary production rate: the ensemble mean of forecast anomalies (2095 to 2099 minus 2015 to 2019) for simulations run under different IPCC scenarios. Bottom map: fractional change [(A1B, 2080–2100/PD, 1980 to 2000) – 1] in net primary production



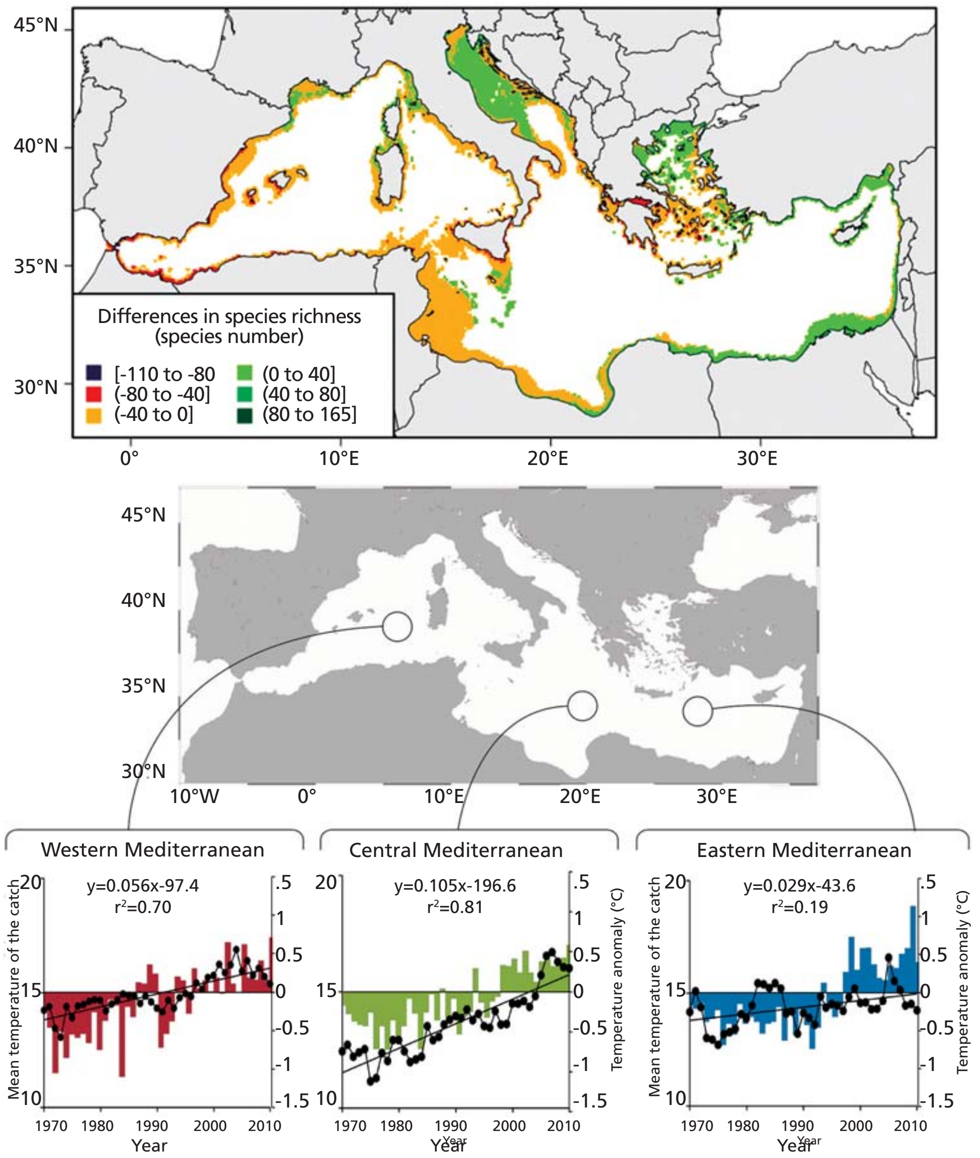
Source: Top map: Adapted from Macias, Garcia-Gorriz and Stips, 2015. Bottom map: Adapted from Cannaby *et al.*, 2015.

The Mediterranean zooplankton community is expected to synchronously change over the basin along with a likely decline of species richness (Benedetti *et al.*, 2017). The proliferation of gelatinous species is one of the main ecological consequences anticipated, partially attributed to climate change and largely observed in the Mediterranean (Danovaro, Umani and Pusceddu, 2009). The mass development of invasive gelatinous plankton in the Black Sea is related to North Atlantic Oscillation variability that, accompanied with high summer temperatures, established favourable conditions for outbreaks of invasive ctenophores in the early 1990s (Niermann, 2004).

In higher trophic levels, the main effects reported in the Mediterranean Sea across all taxa as a result of warming include changes in abundance, survival, growth, fertility/reproduction, migration and phenology (reviewed by Marbà *et al.*, 2015 from 464 studies). Mass mortality events induced by progressive warming and heatwave events are robustly attributed to climate change from the early 1980s (Lejeusne *et al.*, 2010). Examples of changes in species distribution and local abundance related to warming are widespread with two characteristic patterns: *meridionalization:* the northward extension, colonization and enhancement of thermophilic species into the colder north Mediterranean regions (Lloret *et al.*, 2015); and *tropicalization*: the increasing introduction and range extension of thermophilic, non-indigenous species, including Lessepsian species from the Red Sea and from the Indo-Pacific region (more than 900 species reported; Boero *et al.*, 2008). In the Black Sea, a progressive trend of arrival of Mediterranean species (*mediterranization*) is also evident, comprising phyto- and zooplankton, benthic invertebrate and fish species, along with species native to the Atlantic and Indo-Pacific Oceans (Shiganova and Ozturk, 2010).

Future projections show that regional changes in fish abundance and their distribution will alter species richness, with an expected increase in overall richness by the mid-twenty-first century in the Eastern Mediterranean, and a decrease in the western region (Figure 7.5; Albouy *et al.*, 2013). Similar changes in the community structure and diversity are predicted at smaller spatial scales (e.g. Gulf of Gabes; Hattab *et al.*, 2014). A likely decrease in connectivity between neighbouring ecosystems within the Mediterranean is expected because of a decrease in the size of the spawning areas and an increase in larval retention on smaller areas of the continental shelf.

FIGURE 7.5
Top: predicted differences in fish species richness between the baseline scenario (1961 to 1980) and (2040 to 2059) for the continental shelf of the Mediterranean.
Bottom: temperature anomaly (ºC, bars) and mean temperature of the catch (continuous lines, black dots) for the western, central and eastern regions from 1970 to 2010, calculated following Cheung *et al*. (2013) as the average inferred temperature preference of exploited species weighted by their annual catch



Source: Top: Adapted from Albouy *et al*., 2013. Bottom: Adapted from Tsikliras and Stergiou, 2014.

7.3 EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING THE MAIN FISHERIES

7.3.1 Distribution, abundance, seasonality, fisheries production

As noted above, *small and medium pelagic fish* are among the main fisheries resources in the region. These species are very sensitive to climate change because of their dependence on surface hydroclimatic conditions affecting primary production.

Important trends observed over the twenty-first century are a decrease in stocks of anchovy and sardine (several stocks of both species are currently overfished; FAO, 2016a; STECF, 2017), the expansion of other thermophilic species (round sardinella – *Sardinella aurita*; Sabatés *et al.*, 2006) and the contraction in distribution of cold-water species (sprat; Lloret *et al.*, 2015). The strong dependence of pelagic species upon river runoff variability and the very likely decrease in precipitation in the Mediterranean will have negative implications for pelagic species (Tzanatos *et al.*, 2014). In the Black Sea, SST is recognized as a key factor, affecting anchovy reproduction and metabolism and conditioning their migration and schooling behaviour (Guraslan, Fach and Oguz, 2017). The expected high river run-off could impact pelagic species such as whiting (*Merlangus merlangus*) and anchovy, possibly favouring reproductive success by increased productivity (Daskalov, 1999). For some anadromous species, an increase in water temperature triggers an earlier spawning, as observed for the Danube herring (*Alosa immaculata*; Nesterenko *et al.*, 2014). Climate change is also expected to change food availability and the ecological processes regulating the population dynamics of species such as sprat (Shulmann *et al.*, 2011).

Phenology and migratory patterns of *large pelagic species* seasonally entering the Mediterranean for spawning will likely be impacted by warming, e.g. bluefin tuna (*Thunnus thynnus*), in addition to the meridionalization of the migratory behaviour of resident tuna species, e.g. albacore (*Thunnus alalunga*) and dolphinfish (*Coryphaena hippurus*; Lloret *et al.*, 2015). Projected likely changes in thermohaline circulation, with the Atlantic water that enters the Mediterranean becoming lighter (Adloff *et al.*, 2015), is likely to trigger a change in the temporal and spatial dynamics of mesoscale oceanographic structures (e.g. eddies and fronts), which are key for the reproductive behaviour of large pelagic fish (Alvarez-Berastegui *et al.*, 2016).

The composition of the *demersal communities* has changed in the Mediterranean region in recent decades with a higher contribution of warm-water species (Figure 7.5b; Tsikliras and Stergiou, 2014), which are progressively colonizing northern areas concomitant with a regression of cold-water species (Lloret *et al.*, 2015). However, the high diversity of physical drivers impacting demersal species and the geographic variation of their effects makes regional projections by climate change models difficult and hinders the assessment of future directional changes. Regional distributions and abundances are highly dependent on SST through its influence on early life stage survival and on primary production (e.g. Puerta *et al.*, 2016). Winter hydroclimatic processes also shape primary production at subregional scales, impacting fish such as European hake and blue whiting (*Micromesistius poutassou*; Martin *et al.*, 2016), and can also produce cascading episodes in canyons (strong, dense shelf-water flows to bathyal and abyssal areas) and intense vorticity events that reduce the catchability of benthic crustaceans such as red shrimp (*Aristeus antennatu*; Amores *et al.*, 2014). Bathymetric and geographic distributions are also expected to shift because of the likely changes in salinity and temperature of intermediate and deep-water masses (e.g. deep-sea shrimps such as red shrimp or deep-water rose shrimp (*Parapenaeus longirostris*; Colloca *et al.*, 2014). Populations close to river mouths and depending on runoff are expected to decrease.

The progressive occurrence and establishment of warm-water species (Lloret *et al.*, 2015) is expected to generate both positive and negative effects on fisheries, especially on SSF because of their socio-economic and ecological sensitivity. There are numerous examples, from bluefish (*Pomatomus saltatrix*) and barracuda (*Sphyraena viridensis*) as examples of "*meridionalization*" in northern Mediterranean areas to mounting evidence of *tropicalization* of Indo-Pacific species (Lessepsian migrants) in the Eastern Mediterranean (Boero *et al.*, 2008), or the extension of the distribution ranges of Mediterranean species (*mediterranization*) and detection of non-indigenous species in the Black Sea. These species compete with native species (e.g. rapa whelk – *Rapana* *venosa*) or include highly damaging toxic species such as pufferfishes (e.g. silver-cheeked toadfish – *Lagocephalus sceleratus*; Ünal and Göncüoglu Bodur, 2017).

7.3.2 Combined effects with non-climate stressors

A number of non-climate stressors can buffer or strengthen the climate change effects on fisheries (Hidalgo *et al.*, 2011). Apart from depleting populations (FAO 2016b; STECF, 2017), overfishing can erode the age and size structure and spatial distribution of stocks making populations more susceptible to environmental fluctuations. This is particularly relevant for highly impacted areas and vulnerable species (e.g. elasmobranchs). Overfishing of top predators and pelagic resources has also been associated with trophic cascades and ecosystem regime shifts in the Black Sea (Daskalov *et al.*, 2017).

Pollution is an important threat in both the regions, and occurs in numerous localized pockets associated with urban areas and/or improper waste treatment. Large rivers appear as major sources of contamination, while diffuse sources of pollution may have spatially restricted but constant impacts on coastal areas. Of relevance for fisheries is the influence of coastal pollution on transition environments such as lagoons, estuaries, river deltas and wetlands. Rising temperatures may facilitate the occurrence and distribution of biotoxins (e.g. ciguatoxins, produced by dinoflagellates) or pathogens such as *Vibrio* bacteria (Lloret *et al.*, 2016). Noxious phytoplankton blooms can also deplete oxygen, suffocating and killing fish and benthos. Pollution is particularly important in the Black Sea, where the ecosystem has undergone different phases of eutrophication caused by increased input of nutrients, intensive farming and the use of agrochemicals and phosphate detergents. It is also noteworthy that the Black Sea and particularly the Mediterranean are hotspots for plastic pollution.

Fisheries, warming and ocean acidification contribute to the disappearance and modification of fragile and long-lived species that create biogenic structures or seagrass meadows, which provide important ecosystem services (Jordà, Marbà and Duarte, 2012).

7.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

7.4.1 Consequences for fisheries management and fishing activities

The Mediterranean and Black Sea are bordered by developed and developing countries and this heterogeneity generates difficulties for setting common strategies addressing cross-border issues. The communal nature of waters and resources distributed across country boundaries creates a critical need for a regional approach to environmental protection. There is growing international concern that for migrating, wide-ranging and sedentary species on specific habitats, international cooperation is of paramount importance for creating strategic networks that are more efficient than protection of isolated sites (Hills, Schoen and Nadcrinicinii, 2013). In the Mediterranean and Black Sea, the GFCM is the regional fisheries organization providing advice for sustainable exploitation of fish stocks, and is responsible for regional initiatives to cope with the impacts of climate change on fisheries management (see Section 7.6.1). Given the expected changes in species distributions and spatial structure of populations, appropriate adaptive measures, monitoring mechanisms and collaborative research will have to be adopted at regional level to address the impacts on stocks distributed across national boundaries. However, the strength of climate change impacts will be affected by the success of the management strategies adopted in the coming decades in the Mediterranean and Black Sea to reverse the current overexploitation.

Besides the availability, stability and access to fishing resources, the impact of climate change on fisheries and post-harvesting also depends on the vulnerability and adaptive capacity of the highly heterogeneous fishing fleets. Fisheries mainly targeting pelagic species (e.g. purse seiners, longlines) are less resilient and can potentially be affected positively or negatively. For example, in Malta, the total biomass landed and the generated incomes are expected to increase as a result of the enhanced catches of large pelagic fish. By contrast, catches by purse seiners dependent on anchovy and sardine are expected to decline as a result of the negative impacts of low precipitation and a decrease in primary production. In the Black Sea, the fishing industry is already threatened by overfishing and pollution, and could be further stressed by the impacts of a projected increase in water temperatures. The expected impacts limiting migrations and schooling of anchovy may affect the fisheries sector in Turkey, where this species forms the bulk of the commercial catch (Erdogan, Duzgunes and Ogut, 2009), while changes in their overwintering grounds (Guraslan, Fach and Oguz, 2017) could influence anchovy fisheries in Bulgaria, Romania and Ukraine.

The progressive establishment and colonization of thermophilic species in new areas and the expected changes in migratory behaviours could create new fishing opportunities in the whole basin (Lloret *et al.*, 2015). The multi-species nature of some Mediterranean fleets, particularly demersal and SSF, makes them more adaptable and therefore more resilient to changes in fish communities. As an example, in the Gulf of Gabes, the loss of seagrass meadows combined with warming temperatures contributed to the replacement of commercial species from the bluespotted seabream (*Pagrus caeruleosticus*), the speckled shrimp (*Metapenaeus monoceros*) and the brown comber (*Serranus hepatus*), to the black goby (*Gobius niger*), the European hake and the musky octopus (*Eledone moschata*) (Hattab *et al.*, 2014). However, such new market opportunities will depend on the acceptance by consumers of new species and the degree of adaptability of local markets. Warming could also strengthen the impact of introduced species, imposing threats to fisheries based on native species. For example, after the introduction of the Pacific mullet (*Planiliza haematocheila*) in the Black Sea, the production of local mullet species decreased as a result of food competition (Erdogan, Duzgunes and Ogut, 2009), while the invasion of rapa whelk has led to changes in applied fishing gears.

7.4.2 Communities and livelihoods

The Mediterranean and Black Sea local communities are heavily engaged to SSF. The potential vulnerability of this sector to the effects of climate change needs to be carefully considered, because of its socio-economic importance and vulnerability. Given the higher contribution of SSF to local and regional economies in the eastern and southern Mediterranean countries, these will be the areas of particular concern. Indeed, the high exposure to climate change (expected warming and increased colonization of thermophilic species) will have a higher impact on these countries and regions, with high relative importance of fisheries to their economies and diets, but with more limited societal capacity to adapt to potential impacts and opportunities. However, the extent to which the diversity of potential new fish opportunities will buffer the expected negative impacts is still uncertain (Hattab *et al.*, 2014), as is how traditions will adapt to new species (e.g. Lessepsian species) as a normal part of the diet (Öztürk, 2010). In the Black Sea, the southern, southeastern and western coasts have the more important SSF. Climate-driven changes in the Danube delta ecosystem may threaten livelihoods of the local communities, with impacts on employment in small cities in Romania and Ukraine (Nesterenko *et al.*, 2014).

7.4.3 Wider social and economic implications

The sensitivity of different countries to climate change varies according to the importance of employment in fisheries, economic dependence on the fisheries sector, and links to food security (Ding *et al.*, 2017). These factors include important elements such as number of fishers, the contribution of fisheries exports to the total national export value, the proportion of the population economically involved in the fishery sector, and total landings. These factors vary considerably across the Mediterranean countries. Taking them into account, Morocco, Tunisia and Egypt show moderate sensitivity because of their nutritional dependence on fish protein (Ding *et al.*, 2017; section below). In the Black Sea region, Turkey is a net exporting country and marine fisheries production accounts for a large proportion of the total domestic fish production, which makes this region and its economy more sensitive to climate change implications for the fisheries sector than other coastal states.

7.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES AND THOSE DEPENDENT ON THEM

No comprehensive evaluation of the vulnerability of fisheries to the effects of climate change has been carried out in the region until now. Based on the available studies, the following elements can be highlighted:

- The high heterogeneity in exposure, sensitivity and adaptive capacity over the Mediterranean is likely to create geographical differences in national vulnerabilities to climate change impacts on fisheries and food security (Ding *et al.*, 2017; Karmaoui, 2018). Fisheries in northern (developed) countries of the Mediterranean are expected to be less vulnerable because of their higher adaptive capacity, while southern Mediterranean countries are expected to be more vulnerable as a result of higher exposure and lower capacity to cope with climate change impacts (Ding *et al.*, 2017). Vulnerability in the Black Sea is expected to be more homogeneous among countries. In general, lower fisheries dependence would make Black Sea countries less vulnerable to the effects of climate change on fisheries (Ding *et al.*, 2017).
- Additional factors may increase the degree of vulnerability in the developing Mediterranean context that are not included in large-scale, country comparisons (above), such as remoteness, transboundary issues, geographic dispersion, natural disasters, the degree of economic openness, the relevance of small internal markets and a limited or damaged natural resource base (Karmaoui, 2018). In the Black Sea, the uncertain environment and socio-economic conditions, as well as national capacity for the efficient management of natural resources, including fisheries, are among the major challenges.
- Overall, the sectors and the communities more sensitive to the changes in primary production and river runoff will be particularly affected by climate change. For instance, the expected higher decrease of primary production in the Western Mediterranean (Macias, Garcia-Gorriz and Stips, 2013; Figure 7.4) is likely to increase the vulnerability of fisheries more sensitive to changes in primary production, such as small pelagic fisheries. In the Black Sea, the projected changes in net primary production (Figure 7.4; Cannaby *et al.*, 2015) and growing season length are expected to affect small pelagic fish stocks and related activities, with possible negative impact in the southern regions. Local communities relying on the runoff of the most relevant rivers (e.g. Ebro, Nile, Po, Tiber or Danube) are expected to be impacted by the projected changes.
- Most of the new opportunities and negative impacts for the Mediterranean fisheries will emerge in the SSF and the related communities, which are highly sensitive and exposed to the changes in distribution of species and the synergistic effect of the arrival of non-indigenous species (e.g. Ünal and Göncüoglu Bodur, 2017).
- It is not clear whether the diversity of Mediterranean fisheries in terms of species and fleets can contribute to the adaptive capacities of countries and regions, and whether they will contribute to promote stable revenues. Given the geographical differences expected in the Mediterranean fish diversity, special attention should

be paid to the risk of proposing measures that promote fisheries specificity versus diversity.

- The strong combination of stressors in addition to fishing (e.g. pollution, habitat degradation, demographic increase and increase in tourism) in several regions of the Mediterranean and Black Sea increases their vulnerability and decreases the capacity for providing effective mitigation and AMs because of the complex interactions between stressors (Coll *et al.*, 2012; Hills, Schoen and Nadcrinicinii, 2013).
- Major economic effects can result from rising sea level and increasing occurrence of extreme weather events with substantial impact on river deltas, coastal lakes and wetlands. There is a risk of flooding of low lying areas, caused by storm surges and heavy rainfalls, which can be exacerbated by increased coastal erosion.

7.6 RESPONSES AND ADAPTATION MEASURES

Climate change adaptation, as a "process of adjustment in ecological, social, or economic systems to actual or expected climate and its effects" (IPCC, 2014), can involve capacity building of individuals and organizations to adapt to changes as well as implementing adaptation decisions, as defined for example in regional and national strategies and commitments. Adaptation must be manifested through changes in institutions, livelihoods or to reduce risks and enhance resilience (Chapter 25). The text below briefly highlights some of the strategies, commitments and actions that can enhance the capacity to adapt to climate change in the Mediterranean and the Black Sea with a focus on institutional changes and the most relevant challenges.

7.6.1 Existing regional initiatives

Among the regional initiatives of relevance to the enhancement of adaptive capacity, the following can be highlighted:

- GFCM mid-term strategy (2017 to 2020) towards the sustainability of Mediterranean and Black Sea fisheries (Resolution GFCM/40/2016/2[1]), which foresees the development of an adaptation strategy to cope with the potential effects of invasive species and climate change on fisheries.
- The Black Sea Commission Strategic Action Plan (Black Sea Commission, 2009), which includes climate change and a Memorandum of Understanding with the GFCM on issues of common interest such as transboundary cooperation on fisheries.
- Various international cooperation projects[2,3], including the FAO regional projects and networks[4], which aim at fostering capacity building and cooperation among Mediterranean and Black Sea countries.
- The UN Environment Mediterranean Action Plan (UNEP/MAP) addresses issues related to the environmental status of the Mediterranean Sea and has a specific strategy to address climate change in close collaboration with the GFCM.
- The action plan for the Danube Delta, which develops activities in three countries (Romania, Ukraine and the Republic of Moldova) to preserve valuable shared coastal ecosystems and their services (e.g. fisheries) against threats associated with climate change (Nesterenko *et al.*, 2014).

7.6.2 Climate risks and policy opportunities at national level

NAPs in the EU[5] show very heterogeneous levels of detail in the measures to be applied for the fisheries sector, which are often merged with the goals of conservation

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1 http://www.fao.org/gfcm/decisions/en/
2 https://ec.europa.eu/maritimeaffairs/policy/sea_basins/mediterranean_sea
3 https://ec.europa.eu/maritimeaffairs/policy/sea_basins/black_sea
4 http://www.fao.org/gfcm/links/en/
5 http://climate-adapt.eea.europa.eu/countries-regions/countries

of marine biodiversity. In some cases (e.g. Italy and Greece), NAPs provide a well-structured and detailed list of measures aligned with the GFCM mid-term strategy (2017 to 2020)[6], including:

- creation of a network of monitoring and databases;
- adaptation to the new fisheries situations: consumer preferences, governance mechanisms, protection of vulnerable habitats;
- a better understanding of natural and ecological mechanisms of the impact of climate change (drivers of impact, mapping changes and ecosystems and populations indicators, vulnerability assessments);
- assessment of the economic impacts of climate change on fishing: fish production cost, public and private initiatives, diversification of activities, contingency plans, development of natural disasters risk management plans; and
- development of educational programmes: training, public engagement, fishing tourism.

For the Southern Mediterranean, at the time of writing, only Palestine had submitted a NAP[7] to the United Nations Framework Convention on Climate Change, which provides specific AMs on fisheries and other coastal and marine services (e.g. coastal agriculture and condition of beaches). The measures on fisheries focus on the enlargement of the fishing area, the improvement of fishing equipment and post-harvesting operations. On the other hand, Morocco launched the *Blue Belt*[8] as a collaborative platform to put into practice innovative solutions for the adaptation of the fisheries and aquaculture sectors to climate change, with actions focused on: monitoring, ecological certification, vessel safety and increasing the value of fish captured. In the Black Sea, most of the documents setting guidelines to implement immediate and long term measures lack information regarding the fisheries sector (e.g. NAPs of Bulgaria and Romania, and the Climate Doctrine of the Russian Federation).

Among the Mediterranean and Black Sea countries that submitted Intended and Nationally Determined Contributions (INDCs/NDCs[9]) only Palestine and Morocco make reference to measures oriented to the fisheries sector. The Morocco NDC sets fisheries as a primary sector in the country and outlines a detailed series of adaptation objectives that include: reduction in the quantity of meal created from fresh fish; the establishment of observation and monitoring networks; reduction of catches by 2020 and restocking of endangered species; the modernization of fleets; restoring damaged habitats; increasing the coverage of MPAs, and increasing the volume of commercialized products by 2030. Based on ongoing vulnerability assessments (FAO, forthcoming) and research activities supported by regional existing initiatives (Section 7.6.1), there are a solid basis and broad opportunities to revise and update the NDCs and NAPs of those countries currently providing limited AMs on fisheries.

7.6.3 Some potential directions on adaptation

The design of climate change adaptation actions in support of the Mediterranean and Black Sea fisheries must be based on the understanding of the regional priorities with often contrasting needs at national level. Some potential directions can be noted based on the situation described here and the general guidelines provided in Chapter 25.

From the institutional and management level, efficient and reliable partnerships between governments, non-governmental organizations, civil society, private and public sectors are needed for a holistic climate change adaptation planning and decision-making. Given the scale, interconnectedness and semi-enclosed nature of the Mediterranean and Black Sea, regional and cross-boundary cooperation is

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6 http://www.fao.org/gfcm/activities/fisheries/mid-term-strategy/en/
7 http://www4.unfccc.int/nap/Pages/national-adaptation-plans.aspx
8 http://www.laceinturebleue.org/en/
9 http://unfccc.int/focus/items/10240.php

paramount for addressing some of the ongoing and expected impacts of climate change on fisheries. Management should take into account the linkages and mechanisms influencing the system dynamics to protect ecosystem functions and diversity in the face of climate change. For instance, curbing fishing pressure may not suffice to recover stocks affected by other anthropogenic drivers. In line with ecosystem-based management, other measures such as controlling pollution, protecting critical habitats and biodiversity, as well as the management of the river basins that drain to the sea, may be essential to enhance the resilience of the fisheries to climate change.

The diversification of the livelihood portfolio will be a pillar in all adaptation plans that must be carefully considered at national level (i.e. NDCs). Enhanced cross-sectoral strategies and plans can also facilitate the identification of opportunities for livelihoods to buffer the impacts of climate change through a broader scope of opportunities. Considering the Mediterranean and Black Seas' social and economic characteristics, these may include aquaculture-related activities, non-fisheries economic activities such as tourism, or other agricultural and alternative land uses.

Given the likely risks, to a higher or lower degree, for most fisheries-related activities in the region, risk analyses and the development of strategies based on disaster risk management (DRM) plans are needed to support the implementation of several adaptive measures. These measures may include re-adjustments in the insurance market, improved weather warning systems coupled with improved communication platforms, improved measures for vessel safety or post-disaster recovery plans combined with political and economic plans for impact compensation. In addition, the adoption of DRM strategies may also need direct technical actions that enhance the resilience of socio-ecological systems. Technical actions could have a direct impact on the ecosystem such as the construction of hard structures (e.g. sea walls), while others have less impact on local ecosystem processes while protecting livelihoods such as the living shorelines approach (e.g. Nile delta; Shelton, 2014), restoration of buffer areas or appropriate ecological corridors in habitats that have been badly fragmented.

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Chapter 8: Climate change impacts, vulnerabilities and adaptations: Eastern Central Atlantic marine fisheries

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KEY MESSAGES

- **Significance of fisheries.** The FAO major fishing area 34 currently represents about 3 percent of world marine capture production and 80 percent of the catches are made by 21 African coastal states that derive various benefits from their fishing sectors including, at varying levels, employment, livelihoods, food for local and international consumption and foreign income. The artisanal sector and specifically the small pelagic resources play a pivotal role for food and nutrition security and poverty alleviation.
- **Main threats to fisheries sustainability.** Overfishing, among other anthropogenic pressures on ecosystems, threatens the marine resources of this area. Many of the bordering states have limited capacities to manage their fishing sector sustainably. The area is characterized by the presence of many transboundary fish stocks; more than a third of the monitored stocks are currently exploited at biologically unsustainable levels. Climate change may exacerbate this situation, and could be a potential additional threat to the sustainability of the fishing sector and to its contribution to national economies and to poverty and food insecurity alleviation.
- **Nature of climate change threat.** Climate change is expected to result in an increase in the occurrence of extreme events (swells, storms, extreme rainfall, rising temperatures, rising sea levels, etc.) affecting mainly the artisanal sector fishing communities along the coast. Marine ecosystems are likely to continue to experience warming, changes in ocean current patterns, nutrient inputs and oxygen concentration, potentially resulting in a changed regime of ecosystem productivity and a possible subsequent geographical readjustment of catch potential towards the higher latitudes of FAO major fishing area 34 and towards the more favouurable habitats inside the area.
- **Vulnerability and the need to adapt.** Climate change is already affecting some of the main small pelagic fish (SPF), tuna and tuna-like fish, with potentially heavy implications for tropical nations, given the role of SPF and the artisanal sector in many sub-Saharan countries. It is also very likely that in the short-term, non-climate issues will have a greater effect on fisheries than climate change. Weak governance, weak development of knowledge including in relation to climate change impacts, and persistent poverty in many countries will very likely limit the capacity of fisheries-dependent populations to adapt, which may increase their vulnerability.

- **Short-term priorities to increase socio-ecological resilience** should be to 1) promote mainstreaming of socio-ecological resilience in public policies; 2) ensure, through improved management planning, that fisheries and ecosystem governance improve in such a way to mitigate and prevent further degradation of the quality of marine ecosystems of the region; 3) build or further develop the institutional research and management capacities; and 4) take concrete actions to protect assets and fishing communities against potential impacts of climate change and increase socio-ecological resilience.

8.1 MAIN FISHERIES OF THE EASTERN CENTRAL ATLANTIC AREA (FAO MAJOR FISHING AREA 34)

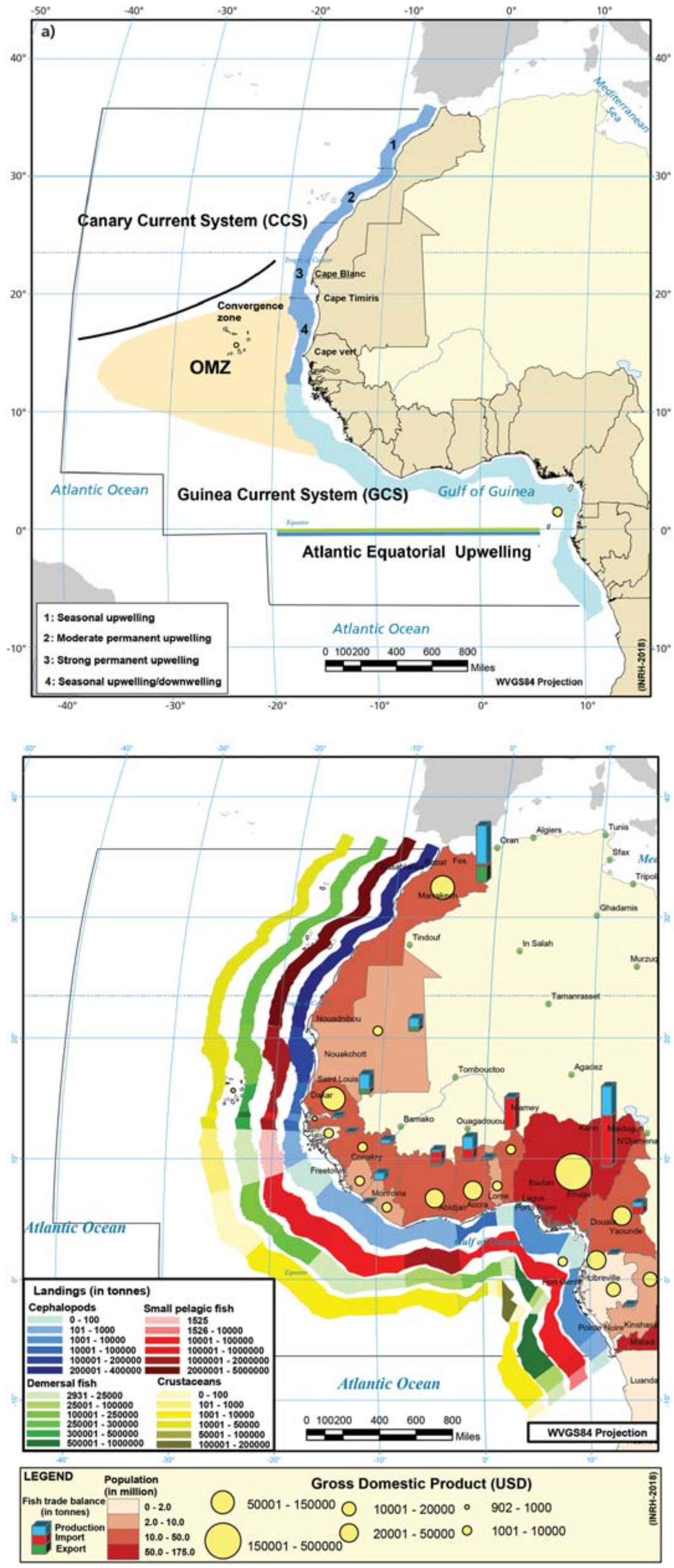
Most of the area (35°47’ north latitude, 5°55’ west longitude/6°07’ south latitude, 12°16’ east longitude; Figure 8.1) lies in tropical and subtropical latitudes and encompasses several marine biogeochemical provinces (Longhurst, 1998) that determine the nature of marine species assemblages and the potential for fishery production at a subregional scale.

FAO estimated the maximum production potential for the whole region at 4.3 megatonnes (Grainger and Garcia, 1996). After a steady increase in the late-1970s, marine catches have fluctuated around 4 megatonnes since the 1990s. Catches originate mainly from coastal stocks in the exclusive economic zones (EEZs) of the West African countries (WACs), whereas catches in areas beyond national jurisdiction on species other than tuna and tuna-like species are limited (FAO Fishstat, 2017). WACs’ catches accounted for 80 percent of the catches reported in the area in 2015 (FAO Fishstat, 2017). Domestic industrial fishing fleets were developed by several African countries after independence. These fleets remained stable until the 1990s, but gradually declined since then to near extinction in almost all the important fishing countries apart from Morocco (especially in Senegal, Ghana and Côte d’Ivoire). Nowadays, the industrial sector in almost all the WACs is comprised almost exclusively by foreign industrial fishing fleets operating under joint ventures or flags of convenience. These fleets’ catches are often quasi-exclusively directed towards the international market. On the other hand, the artisanal fishing effort has strongly increased in the area, especially in some countries of the sub-Saharan region such as Senegal and Ghana. Its level in 2010 had increased tenfold compared to 1950 according to Belhabib, Lam and Cheung (2016). It is important to note that this subsector absorbs a non-negligible part of the total national workforce in some sub-Saharan countries (e.g. Ghana). In Morocco, the largest marine capture fisheries country of the area, the industrial and semi-industrial domestic fleets are the main sectors harvesting fishery resources, even though the artisanal sector is of importance in terms of provision of some supply-chains and for the creation of jobs in some enclaved coastal regions. Many foreign vessels, operating under fishing agreements, are also harvesting living marine resources in several countries’ EEZs.

SPF are the most abundant resources of the area, providing more than 60 percent of the region’s marine catches. These species are mainly composed of European sardine (*Sardina pilchardus)*, round sardinella (*Sardinella aurita*), flat sardinella (*Sardinella maderensis*), bonga shad (*Ethmalosa fimbriata*), anchovy (*Engraulis encrasicolus*), Atlantic chub mackerel (*Scomber colias*), Atlantic horse mackerel (*Trachurus trachurus*), Cunene horse mackerel (*Trachurus trecae)* and false scad (*Caranx rhonchus*). Some other coastal and oceanic groups of high commercial value (cephalopods, shrimps, croakers, grunts, groupers, sparidae, and large migratory pelagic fishes such as tunas and billfishes), provide the main national fish supply chains, on which rely the economies of a large number of WACs as a source of income, creating jobs for 7 million West and Central Africans (de Graaf and Garibaldi, 2014).

FIGURE 8.1

Maps of the Eastern Central Atlantic area summarizing a) major current systems, upwelling sectors and oxygen minimum zone (OMZ) position; b) main fishery production regions, coastal states, declared landings of main fish groups, and national fish trade flows



Data source: FAO Fishstat, (2017); gross domestic product and human population per country (World Bank, 2017).

Fish also constitutes the staple food of the majority of the 400 million inhabitants of the area, who overall consume 7 million tons of fish annually (FAO Fishstat, 2017). Consumption of fish varies greatly between countries, however. SPF in particular contribute to animal protein accessible to the most vulnerable communities in sub-Saharan countries (i.e. nearly 200 million Africans; World Bank, 2017). SPF play a significant role in the food systems and greatly contribute to the supply of small-scale processing industries in almost all sub-Saharan countries (de Graaf and Garibaldi, 2014).

8.2 OBSERVED AND ANTICIPATED IMPACTS OF CLIMATE CHANGE ON MARINE ENVIRONMENTS RELEVANT TO FISHERIES

8.2.1 Physical and chemical impacts

The West African climate has evolved in recent decades according to the latest Intergovernmental Panel on Climate Change report, recognizing with high certainty the atmospheric and oceanic warming in all FAO major fishing area 34 subregions and on the contiguous continent (Niang *et al.*, 2014; Pörtner *et al.*, 2014).

Observed impacts

A cooling, resulting from the intensification of wind-driven upwelling under climate change, has been predicted for the Canary Current System (CCS), which extends from the Strait of Gibraltar to the south of Guinea-Bissau (Bakun, 1990). The CCS has, however, globally warmed over the permanent thermocline during the last three decades (Pörtner *et al.*, 2014; Vélez-Belchí *et al.*, 2015), and the seasonal warming occurs earlier in the subtropical and extratropical upwelling sectors (deCastro *et al.*, 2014). However, the more marked and significant warming trends are observed in the oceanic sector and near the coast in the Senegalo-Mauritanian tropical sector (Vélez-Belchí *et al.*, 2015). Changes in the occurrence of extreme sea surface temperature (SST) events, in parallel with warming, are also hypothesized to be related to climate change in this region (Lima and Wethey, 2012). Extreme hot and cold events have increased and decreased respectively in frequency in the area during the most recent decades (deCastro *et al.*, 2014; Lima and Wethey, 2012). The warming of the Senegalo-Mauritanian upwelling sector has been linked, on another hand, to the recovery of the downwelling favourable winds in the subtropics (Cropper, Hanna and Bigg, 2014). The southwesterly monsoon circulation that drives downwelling-favourable winds is likely strengthening in the subtropics (Cropper, Hanna and Bigg, 2014) and upwelling-favourable winds are likely enhancing in the extratropical sector (Bakun, 1990; Cropper, Hanna and Bigg, 2014; Rykaczewski *et al.*, 2015; Sydeman *et al.*, 2014). The low latitude regions, comprising the Guinea Current System (GCS) and the Atlantic Equatorial Upwelling System (AEUS) also experienced a marked sea surface warming, a relaxation of the AEUS activity, and an increase of tropical rainfall, which have resulted from a weakening of the southeasterly trade winds during the past six decades (Pörtner *et al.*, 2014; Tokinaga and Xie, 2011).

There is lack of knowledge on acidification and oxygen depletion in the low latitude sectors of FAO major fishing area 34 (i.e. GCS and AEUS), but in the CCS, the North Atlantic oxygen minimum zone (NAOMZ) associated with this upwelling system shows a tendency towards deoxygenation since the 1960s (Stramma *et al.*, 2008), probably as a result of a combination of anthropogenic impacts and natural climate variability (Hahn *et al.*, 2017). The OMZ core is extending towards the surface and northwards. Upwelling waters are typically low in pH and high in CO_2 and are likely to continue to show changes in pH and CO_2 resulting from rising atmospheric CO_2 (Pörtner *et al.*, 2014). The surface pH of seawater shows a decreasing trend since 1995 at the ESTOC[1] site in the Canary Islands (Pörtner *et al.*, 2014; González-Dávila and Santana-Casiano, 2015).

Predicted impacts

Although there is low agreement on the statement of a future intensification of the CCS upwelling (Pörtner *et al.*, 2014), global climate model predictions indicate that the ongoing strengthening trend of the upwelling activity in the extratropical CCS, will be maintained by the end of the twenty-first century under the representative concentration pathway (RCP)8.5 scenario (Rykaczewski *et al.*, 2015; Wang *et al.*, 2015). A considerable expansion of the upwelling season of several days per decade, between 1950 and 2099, will likely occur at higher latitudes of the CCS (Wang *et al.*, 2015). Rainfall will likely decrease concomitantly over Northern Africa by the end of the twenty-first century (medium to high confidence; Niang *et al.*, 2014). A continuation of the warming is predicted in the equatorial region by the end of the century under an RCP8.5 scenario (Figure 8.2); it is to be noted that there is also no consensus on this statement because of a lack of reliable data in the region (Niang *et al.*, 2014). It is also unclear how rainfall in the Gulf of Guinea and the Sahel subregions will evolve. Many studies attempting precipitation forecasting for the West African subregion allude to tropical Atlantic SST accounting for the largest proportion of variability observed in rainfall, particularly in the Gulf of Guinea (e.g. Agumagu, 2016). Agumagu (2016) further asserted that anomalously warm SSTs in the Gulf of Guinea generate copious rainfall in the Guinea coast region but drier conditions over the Sahel zone. Many model results suggest an increase in rainfall by the end of the twenty-first century, with a small delay of the rainy season, an increase in the number of extreme rainfall days over West Africa and the Sahel, and more intense and a more frequent occurrence of extreme rainfall over the Guinea Highlands and Cameroon Mountains (Niang *et al.*, 2014). These predictions, however, remain uncertain according to Niang *et al.* (2014). Thus, a decrease in mean precipitation would possibly lead to increased risk of drought while an increase in mean precipitation would lead to increased flooding (Agumagu, 2016).

Coastal systems and low-lying areas in many WACs are also facing increasing risks of erosion, inundation, and salinization of land and coastal waters because of the rise of sea level (IPCC, 2007). A one metre sea level rise (SLR) would lead to inundation and erosion, for example of 1 800 km^2 of lowland in Côte d'Ivoire, and more than 6 000 km^2 and 2 600 km^2 of land respectively in Senegal and Nigeria, most of which are wetlands (IPCC, 2007).

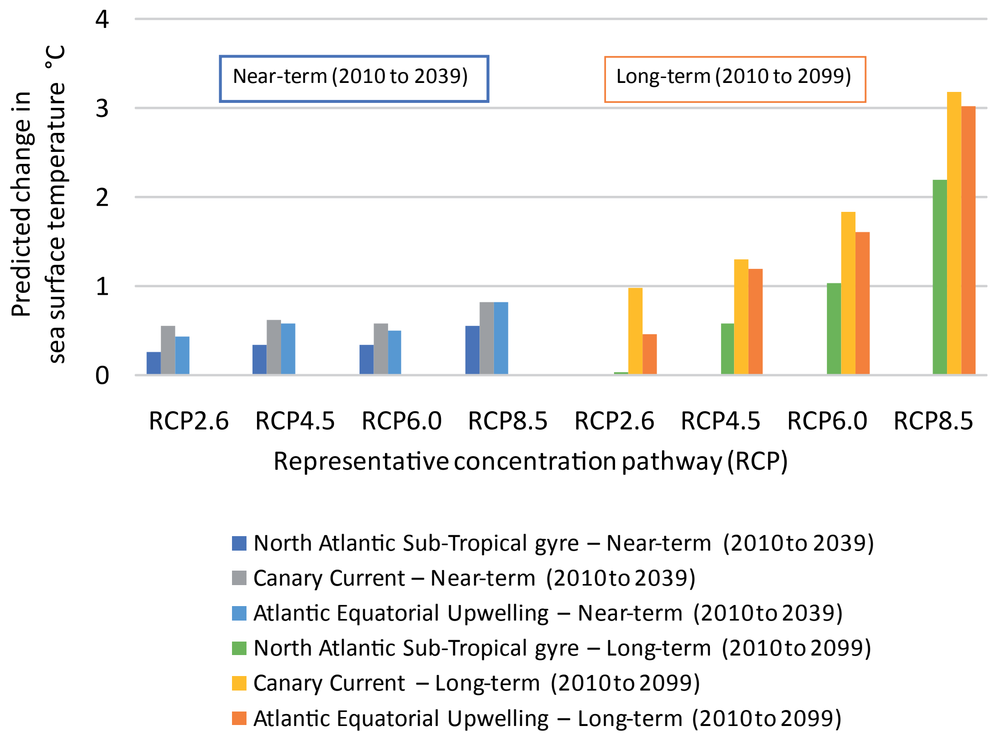
Because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics, there is a lack of consensus on the future volume of low oxygen waters in the NAOMZ. Modelling simulations in the CCS suggest also that although future ocean acidification in this upwelling system will likely be primarily driven by the rise of atmospheric CO_2, changes in local winds and conditions might accentuate or dampen this large-scale trend owing to the nutrient utilization efficiency in the system (Lachkar, 2014).

The pattern and magnitude of changes reported and their future long-term evolution remain a matter of debate. They likely could be a result of greenhouse gas effects, but the likelihood of significant natural climate-related interactions, such as natural low-frequency (interannual to multi-decadal) variability in the ocean-atmosphere system cannot be dismissed (Brandt *et al.*, 2015; Di Lorenzo, 2015). Additionally, the existing global climate models have no consensus on how these large-scale climatic modes will evolve in the future, so their impacts remain unclear. Limited spatial and temporal extent of observations, and changes in wind measurement methodologies during the

[1] European Station for Time series in the Ocean Canary Islands.

mid-twentieth century also hamper somewhat robust conclusions on the causes and direction of change of the upwelling systems' activity.

FIGURE 8.2
Projections of sea surface water temperature rise during the twenty-first century in different regions of the FAO major fishing area 34 under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios



Source: Pörtner *et al.*, 2014.

8.2.2 Biological and ecological impacts

Changes in the biological components of ecosystems in FAO major fishing area 34 and their eventual attribution to climate change are poorly documented. For the components at the base of the marine food chain, satellite observations over the last three decades in the CCS show that primary production displays an upward trend in the subtropics and mid-latitudes sectors, north of 23°26'13.0"N, and a downward trend in the tropical sector (Demarcq and Benazzouz, 2015). Data from the continuous plankton recorder in the Gulf of Guinea prior to 2008 also display a significant decline in abundance of phytoplankton and zooplankton as SST increases (Wiafe *et al.*, 2008). According to (Wiafe *et al.*, op. cit.), this could have serious implications of rippling effects on productivity of especially SPF species such as *Sardinella aurita* and *S. maderensis* in the region. However, the lack of continuous zooplankton observations in the area and also of empirical data examining the potential biological and ecological consequences of climate change on lower parts of the food chain, make it difficult to draw any sound conclusion on the direction of change at these trophic levels and also on knock-on effects through food webs and into fisheries. Existing model projections for the CCS (Lachkar and Gruber, 2013) suggest, for example, that a doubling of the wind stress will double net primary production (NPP) in central and northern CCS whereas the NPP increase will be less than 50 percent in the Senegalo-Mauritanian sector (south of 21 °N). According to Lachkar and Gruber (2013), these differential biological responses to wind stress may have implications for ecosystem food web structure and biogeochemical features in both sectors that would require a further study.

The effects of climate change on fish spawning habitat and larval connectivity patterns are poorly explored. Nevertheless, several studies conducted essentially on the main SPF of the area, concluded that, overall, the reproduction strategies and spawning habitat of these species are related to specific ranges of environmental conditions (e.g. Tiedemann *et al.,* 2017). Changes in meteorological and oceanographic conditions such as precipitation regime, alteration of current patterns, alteration of winds, and changes in nearshore biophysical processes under the anticipated climate change scenario, may affect these species' spatio-temporal reproduction patterns as well as adult distribution and abundance. Additionally, early life stages of many marine organisms of the area are being challenged by ocean warming, acidification and hypoxia, but their physiological responses to these environmental changes still remain poorly studied. Several studies, conducted mainly in Portugal, demonstrate that predictions of change in the ocean temperature, pH and ventilation may compromise the development of early life stages of some commercial fish such as *Sardina pilchardus* (Faleiro *et al.*, 2016), *Solea senegalensis*, *Sparus aurata* and *Argyrosomus regius* (Pimentel, 2016). Preliminary studies on impacts of ocean acidification on fish diversity in Ghana by Nunoo, Quansah and Ofori-Danson (2016) showed also possible impacts of this phenomenon on diversity and abundance of fish species such as *Sardinella aurita*, *S. maderensis* and *Chloroscombrus chrysurus*. Larvae of some species of the family Peneaidae and Portunidae such as *Peneaus notialis* and *Callinectes sapidus* were also identified to be susceptible to ocean acidification.

The tropical subregion in this area has one of the world's most important mangrove forests. Mangroves exist in semi-arid tropics, which probably makes them especially vulnerable to changes in hydrology and thus salinity, as well as deposits of desert dust from the northeasterly trade wind. Mangroves play an important role in West Africa's coastal fisheries and coastlines, providing some protection among other services. Mangroves are, however, recolonizing many areas in Guinea, the Gambia, and Senegal since 2000 (CILSS, 2016), after decades of loss resulting partly from prolonged and damaging drought in the 1970s and 1980s. According to Andrello *et al.* (2017), field observation in Senegal seems to demonstrate that natural regeneration of mangroves is more important than reforestation and has likely resulted from the recovery of rainfall in the mid-1990s that has enabled the mangrove regrowth.

The effects of relative SLR are also reported as a threat to the survival of mangroves (IPCC, 2007). Given the rates of SLR and the predicted future shoreline calculations, the West African mangroves face the threat of being completely inundated should sea levels rise beyond levels they are able to cope with. For example, in Ghana, SLR is expected to cause the shoreline of the Keta coastal zone to migrate about 8 km inland in the next 100 years (Boatemaa, Kwasi and Mensah, 2013). The muddy coastal regions of Cameroon face being flooded and eroded. The finfish and shellfish of Cameroon make use of these muddy coastal regions as breeding grounds and nurseries, and these regions are also critical for Cameroon's main fisheries production.

The advancement of tropical planktonic species poleward, presumably because of global climate warming, has been recently documented for the tropical dinoflagellate *Gambierdiscus* spp. These harmful algae began to be reported during the last decade in the subtropical upwelling sector of the CCS off Morocco, Canary Islands and Madeira Islands archipelagos, providing evidence of the biogeographical expansion of this genus towards higher latitudes with increasing sea temperatures in the region (Pitcher and Fraga, 2015). An unprecedented massive accumulation of pelagic seaweed, sargassum, also occurred recently on the coasts of several tropical countries in West Africa, suggesting that this phenomenon, linked to climate change, may potentially result in the formation of hydrogen sulphide (toxic), oxygen depletion, and eutrophication (Pfaff, 2015).

8.3 CLIMATE CHANGE EFFECTS ON STOCKS SUSTAINING THE MAIN FISHERIES

8.3.1 Impacts of climate change on fishery resources

Several changes in abundance and distribution have been reported for some of the main fishery resources over the last decades. The European sardine and round sardinella, the main species in terms of volume of catches in FAO major fishing area 34, have experienced a readjustment in their distribution and abundance since the 1990s. In the CCS, the most important European sardine stock, located principally off the Sahara, have experienced large fluctuations in abundance and distribution from the mid-1990s. A northward shift of sardine distribution in the southern limit was noticed during the intermittent extreme warming events that occurred off Northwest Africa. For the period 1982 to 2011, six warm events (1983, 1984, 1997, 1998, 2008 and 2010) have occurred (Oettli, Morioka and Yamagata, 2016), resulting in some years (e.g. 1997, see Strømme, Burgos and Kada, 1997) in a drastic decline of the stock abundance and/or the southern limit moving north by two to three degrees. These warm events, generally coincident with a displacement of the thermal front further north, and a decrease in upwelling and intensities of southward currents, likely induce a northward contraction of favourable habitat for the European sardine, which is tightly associated with the North Atlantic Central Water (NACW). At the same time these conditions seem to have benefitted the round sardinella (Zeeberg *et al.*, 2008), the abundance of which has increased several times in the subtropical sector to the north of Cape Blanc, even though the overall abundance of this tropical species has decreased in the CCS during the last decade (CECAF, 2015b, 2016). The bulk of the stock was located on Sahara Bank during some warm episodes, representing more than 50 percent of the regional stock (Braham and Corten, 2015; Strømme, Burgos and Kada, 1997). At the same time, round sardinella abundance has shown a decline in the Western Gulf of Guinea where its catches display a relatively steady decrease since 1999 and its stock is now considered as over-exploited (CECAF, 2015a). It remains, however, difficult to disentangle the relative contributions of climate change, natural variability and exploitation to the dynamics of these species during the last decades. It is worth noting that the period following the mid-1990s is also marked by an expansion of the sardine habitat to the North Sea, linked to ocean warming and to some climate natural oscillation modes (e.g. Alheit *et al.*, 2014). According to Thiaw *et al.* (2017), in a scenario of future decrease of upwelling-favourable winds in the equatorward region of CCS, in terms of both duration and intensity, a decrease in abundance of both round sardinella and flat sardinella in Senegal may occur as a result of this weakening of upwelling-favourable winds. In addition, a northward shift of upwelling may increase the northward migrations of round sardinella during summer, while flat sardinella may stay in Senegalese waters because of its higher tolerance to environmental fluctuations and less migratory behaviour.

The bonga shad is another important SPF of the tropical inshore waters and one of the most targeted species by artisanal fisheries from Mauritania to Angola. Unlike sardinella (especially round sardinella), bonga shad is physiologically adapted to cope with a wide range of environmental conditions and represents an example for clupeid fishes reproducing under extreme conditions in habitats such as estuaries. As a result of its high adaptive potential and euryhaline physiology, bonga shad will be less likely to suffer from the impacts of climate change on its spawning habitat. Nevertheless, in a scenario of further decrease in precipitation, inversion of estuaries, and a concomitant rise of ambient salinities (e.g. in estuaries of the semi-arid tropic), its reproductive potential is likely to be limited inside many habitats (Döring *et al.*, 2017).

Warming and expansion of the NAOMZ has been shown to affect the distribution of some highly migratory species of tunas and billfish by compressing their vertical habitat towards the surface water and increasing, consequently, their vulnerability to surface fishing gear (Prince *et al.*, 2010). The warming trend of the Atlantic subtropical regions (20 °N to 30 °N and 20 °S to 30 °S) during the past decades may also have resulted in a large-scale "tropicalization" of tuna populations and an increasing dominance of catches of warmer water species at higher latitudes (Monllor-Hurtado *et al.*, 2017).

Pörtner *et al.* (2014) anticipated that global warming will lead to changes in the biogeographical distribution of species resulting in a large-scale redistribution of overall catch potential towards the high latitudes to the detriment of the tropics (see also Chapter 4). The projections obtained by ensemble studies from global models, predict that the Guinea Current subregion will suffer a substantial decrease in marine catch potential by 2050 (Cheung *et al.,* 2010; Lam *et al.*, 2012; Chapter 4 of this volume). Another study (Barange *et al.*, 2014) predicted, contrariwise, an increase in the catch potential in Northern and Western Guinea Current subareas by 2050, which in turn will decrease in the Canary Current and in Central and Southern Gulf of Guinea as well.

8.3.2 Other non-climate stressors

Fishing activities

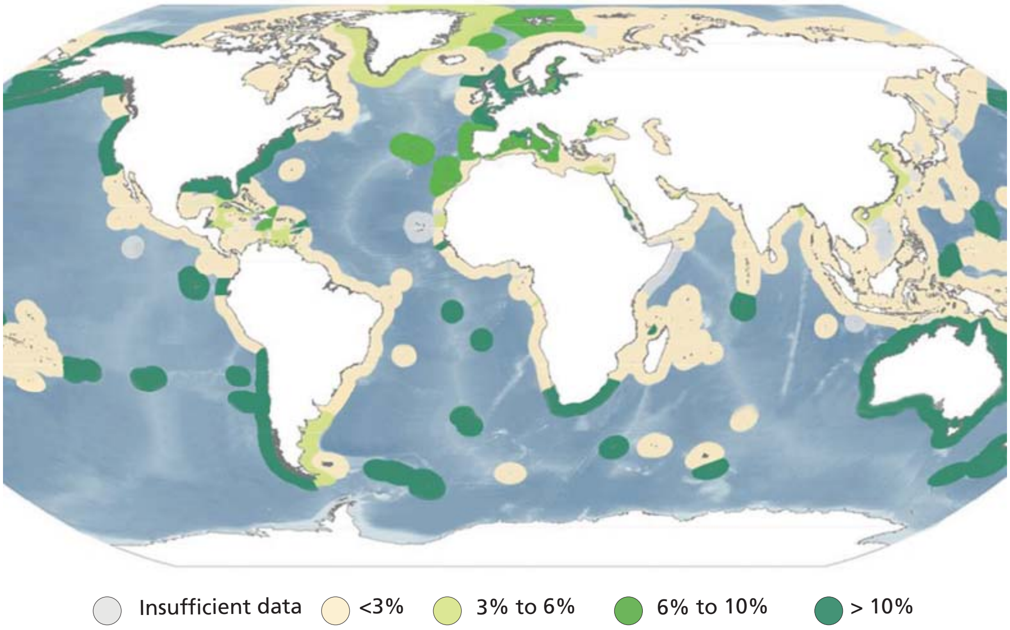
Ecosystems and natural resources have been intensively exploited in the last decades for development purposes, food security, and as an alternative to loss of arable lands (Binet, Failler and Aggosah, 2015; Morand, Sy and Breuil, 2005). The expansion of the fishing activities during the last decades has driven negative impacts on many fish-food production systems. These factors, amplified in many countries by weak fisheries management, regulation and control systems, have led to overexploitation of many fish stocks. Overall, the Eastern Central Atlantic coastal area has 46.5 percent of its assessed stocks fished at biologically unsustainable levels, and 53.5 percent within sustainable levels (CECAF, 2016). Although the FAO Fishery Committee for the Eastern Central Atlantic (CECAF) regularly made recommendations on fisheries management measures (total catch, fishing capacities, etc.), implementation remains voluntary and weak in many member states. Some recent worldwide surveys show that the FAO major fishing area 34 is one of the most impacted by illegal foreign fishing fleets (Greenpeace, 2017).

Other sources of threats

Other anthropogenic pressures on marine, inshore and wetland ecosystems come from adjacent land uses. The growing coastal populations have led to unplanned urbanization with consequences for many natural habitats. Mangroves have suffered losses from conversion into agricultural uses and wood harvesting (including for post-harvest artisanal activities of smoking of fish). About 30 percent to nearly 70 percent of the original mangrove vegetation is estimated to have been lost in many countries of the area (UNEP, 2007). The proportion of marine areas within national EEZs covered by protected areas remains under 10 percent (UN, 2017; Figure 8.3). Pollution from sewage, chemicals (including fertilizers and pesticides) and waste, dam construction, sand mining, and hydrocarbon exploitation in several EEZs, especially in the Gulf of Guinea, are some of the many threats to many ecosystems. Eutrophication is a major concern for the Guinea Current large marine ecosystem (Figure 8.4) where human-induced eutrophication has resulted in several dead zones (e.g. Korle lagoon in Ghana). Additionally, these stressors are often transboundary issues, resulting from ineffective management in most countries of the region (CCLME, 2016a; UNEP, 2016).

FIGURE 8.3

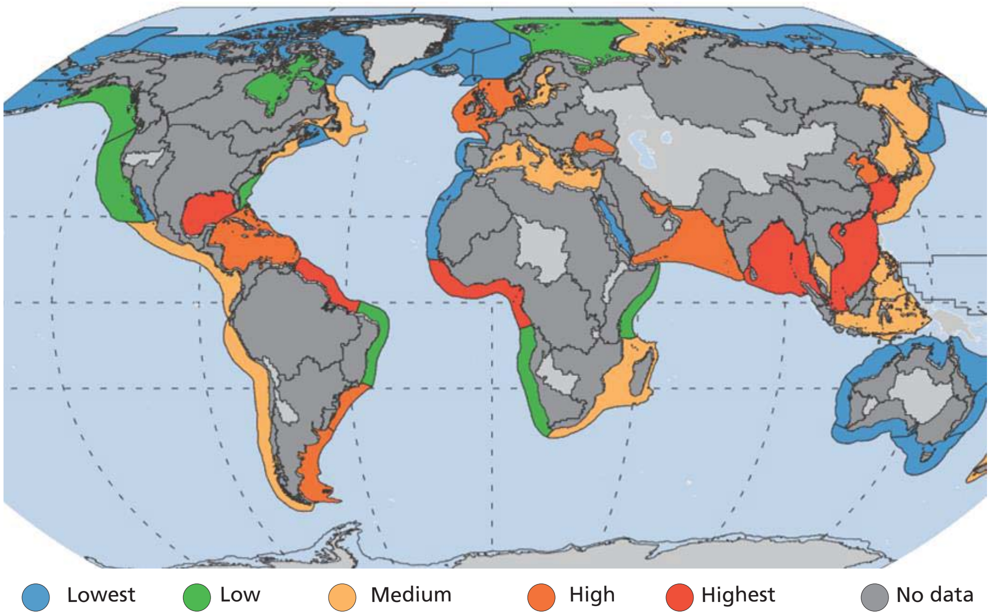
Proportion of marine areas within national jurisdiction (0 to 200 nautical miles) covered by protected areas, 2017 (percentage)



Source: UN (2017).

FIGURE 8.4

Merged nutrient risk indicator of large marine ecosystems projected to 2050



Source: UN (2017).

8.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

8.4.1 Implications for fishing and post-harvesting operations

Fishing will likely become an even more dangerous activity, especially for the artisanal sector. West African coasts are regularly buffeted by storm surges and are currently at risk of extreme storm events and tidal waves that may increase (IPCC, 2007). This will likely affect human safety, in particular artisanal fisher folks (Westlund *et al.*, 2007), and increase the risk of losing the means of fishing (canoes and fishing gear). Moreover, a gradual scarcity of resources in productive areas will have an impact on the profitability of artisanal fishing operations because of the increase in the time spent searching for fish, fuel expenditure and irregular catches. Overall, the quantities of fish caught per kWday by artisanal fisheries has dropped from 5 kg per kWday in the 1950s to 1.5 kg per kWday in the 2000s, which is 11 times less than industrial catches per unit effort (Belhabib, Lam and Cheung, 2016). Hundreds of thousands of artisanal fisher folks are trapped into a vicious cycle of increasing fishing effort, with many using subsidized fuel (e.g. in Ghana; Nunoo *et al.*, 2015) while fishing is becoming unsustainable.

Despite recent improvements in some countries, value chains still suffer from underdevelopment of cold chains in many sub-Saharan countries. The absence of cold storage facilities in many landing sites makes the labour-intensive traditional processing methods very important in the value chains. In Senegal for example, this post-harvest activity transforms more than 30 percent of landings. Whilst this activity plays an important role in reducing fish waste, losses still account for nearly a quarter of fish production in sub-Saharan Africa (FAO, 2016). Unchanged conditions in processing, handling for trade, and hygiene practices combined with an anticipated increase of temperatures, precipitation, moisture, and inundation in tropical areas will likely increase post-harvest losses and will likely result in a further decrease of the efficiency of artisanal value-chains.

8.4.2 Implications for communities and livelihoods

The most productive coastal zones (upwelling areas, mangrove swamps, lagoons and estuaries) attract the bulk of the fishing and processing activities conducted by communities representing about 7 million people (Ndiaye, 2016), two thirds of whom are found in sub-Saharan countries, who are mostly engaged in artisanal activities. Artisanal fisher folks and fishing communities, particularly in sub-Saharan countries, have developed different livelihood strategies to cope with natural resource fluctuations on seasonal and interannual scales, including the diversification of income sources, the exploitation of marine and terrestrial natural resources, and "seasonal" or "circular"[2] fishing migration depending on the resources' distributions (Morand, Sy and Breuil, 2005; Nunoo *et al.*, 2015).

It is also important to highlight the switch in micro-economic strategies that followed the Sahel drought of the 1970s and 1980s and other structural difficulties of the agricultural sector in this part of Africa. The switch was from a traditional model of multi-active artisanal fishers combining fishing and agriculture occupations (e.g. rice farming) to a model of full-time fishers making "seasonal" or "circular" fishing migrations. According to Morand, Sy and Breuil (2005), this historical switch in micro-economic strategies, combined with other factors such as the increase and generalization of motorization of the canoes and the widespread use of destructive fishing gears, has likely contributed to increase the fishing effort and to a degradation in fishing productivity and incomes.

[2] i.e. between African countries.

With the depletion of fish stocks, that could be further exacerbated by the anticipated climate change-driven effects on fishery production, and the enforcement of policy actions by neighbouring countries that limit migration opportunities, migrant fisheries might reach their limits, and see their territories reshaped, with some conflicts resulting from this situation (Binet, Failler and Aggosah, 2015). In the southern CCS for example, Senegalese canoes and fishers have become so numerous since the latter decades of the twentieth century that the fishing effort they are deploying goes far beyond the country's EEZ, extending as far as Mauritanian and Guinean waters (UEMOA, 2014), generating many problems as a result. Some of these problems have been partly solved by international agreements (e.g. agreement between Senegal and Mauritania giving access to 200 artisanal purse seiners of Saint Louis, Senegal to the Mauritanian EEZ during the season of northward migration of sardinella), but others remain a source of concern.

The phenomenon of "seasonal" and "circular" fisher folk migrations is thus becoming a challenge for fisheries management at the regional scale (Binet, Failler and Aggosah, 2015). This issue is all the more important given the anticipated exposure of populations and assets to SLR in many low-lying coastal zones that shelter these communities. SLR and coastal erosion have been reaching significant levels in some coastal sectors of countries, putting infrastructure and fishing villages at risk (e.g. IPCC, 2007). SLR is also expected to threaten the mangrove areas that provide the primary means of subsistence for a large number of collectors of oysters and other invertebrate species, who are mainly women (Cormier-Salem, 2017). The major actors in the artisanal sector post harvesting activities in the sub-Saharan region are also women traditional processors. This activity makes them play a pivotal role in the rural economy in several countries, but makes them also one of the most vulnerable social categories to detrimental climate change-driven impacts through many pathways (increase of losses, irregular fish supplies, coastal erosion, and inundation that threatens assets).

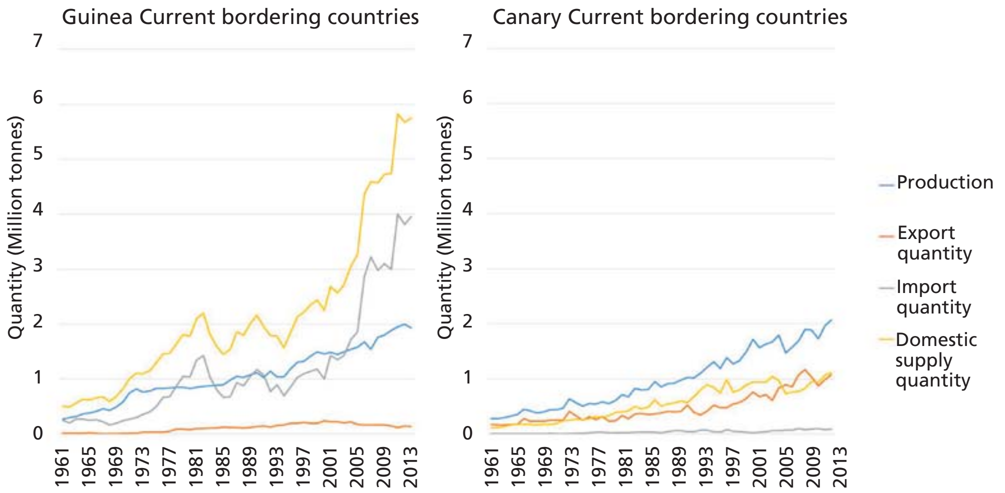
Additionally, the opportunities for fishing communities in almost all countries are quite often limited by a lack of alternative occupations, low education levels, weak social safety nets, and limited access to infrastructure, equipment, and services (see e.g. UEMOA frame survey report; UEMOA, 2014). Artisanal fishing community occupations also often compete with other uses for access to the sea front and coastal waters, which limits their socio-economic space. Therefore, climate change impacts could jeopardise their livelihoods and likely further shrink their survival perimeter in several countries, with the risk of extending poverty traps and fostering "forced" migrations (Alex and Gemenne, 2016).

8.4.3 Implications for larger societies and economies

Many of the interacting economic and social causes of migration and conflicts in West Africa are sensitive to climate change impacts (Niang *et al.*, 2014), with the poor being particularly dependent on natural resources and hence more vulnerable. A large proportion of the population is involved in fishing in many coastal regions and in some small island developing states (SIDS) of the area, where fisheries are a major source of work and income. Fisheries consequently make a multifaceted contribution to their national economies. Countries from Senegal to Nigeria are among the most economically and/or nutritionally fisheries-dependent nations (Barange *et al.*, 2014), with almost all of them being currently low-income food-deficit countries (LIFDCs) and/or least developed countries (LDCs). The proportion of dietary protein that comes from fish is very high in many of these countries (more than 60 percent in Sierra Leone and Ghana, 47 percent in Senegal), even if average per capita fish consumption is, overall, among the lowest in the world (OECD, 2016). The region's overall food supply is already disturbed by climate impacts on its agricultural food production system and now depends largely on imports. Almost all sub-Saharan countries are currently net importers of staple foods. Climate change is expected to increase pressure on already pressured fishery resources and increasingly disrupt crop and livestock production in almost all the region, which could put a further threat on food security in the region (Niang *et al.*, 2014; Lem, Bjorndal and Lappo, 2014; Rhodes, Jalloh and Diouf, 2014). The increasing quantities of fish products imported by many Guinea Current bordering countries (Figure 8.5), is worsening the deficit in value of the food trade balance of almost all West African LIFDCs, the majority of which are also impacted by a decrease of sardinella stock productivity in the main productive area of the Gulf of Guinea. The imports of these countries are mainly composed of SPF (FAO Fishstat, 2017). Major importing countries like Nigeria, Ghana and Côte d'Ivoire are now looking for alternatives to sardinella, by importing herring from Europe with consequences for fish prices (Caillart and Beyens, 2015). The imports value is generating currently an overall annual shortfall of more than 2 billion USD for trade balances of LIFDCs in the area (Figure 8.6). At the same time, sardine and other SPF exports by Morocco (as the main producer and net exporting country of SPF in the region) continue to be mainly oriented towards developing countries' markets (DEPF, 2015). The processing of SPF for fishmeal, boosted by global market demand, is on the other hand showing a marked tendency to increase in the CCS region. Morocco, Mauritania and Senegal are ranked among the top ten fishmeal-producing countries in Africa (FAO Fishstat, 2017). In Morocco, fishmeal production is based on by-products and surplus landings that cannot be absorbed by the canned and frozen product industries. The amount of fishmeal produced is expected to decrease by 50 percent by 2020 and the volume of valued transformed products increased by the same proportion by 2030 according to Morocco's sustainable development goals (SECDD, 2017). The situation seems to be different in Mauritania, where the development of an export-oriented fishmeal industry, transforming sardinellas, would, according to Caillart and Beyens (2015), entail risks for Senegal to maintain its fish food self-sufficiency since sardinellas stocks are shared. However, over the past two decades, a number of fishmeal factories were also implemented in Senegal. The fishmeal production in that country may likely have socio-economic impacts as the fishmeal industry might divert fishery products (SPF) that, previously, were transformed by artisanal women processors. For Senegal, negative consequences of the development of the fishmeal industry is therefore not only for employment, but also for the food security of the rural populations of the whole hinterland of Senegal and also some inland countries, such as Burkina Faso. The population and total food fish consumption demand are expected to rise substantially in the region by 2050, while the anticipated overall fishery production increase will likely be marginal (Grainger and Garcia, 1996) or may decrease according to many estimations (e.g. Chapter 4 of this report). The potential response of international seafood trade to climate change, changes in seafood demand and supply or in local population dietary patterns are uncertain, but some estimates indicate that fish imports in sub-Saharan countries are likely to be 11 times higher by 2030 than the level in 2000 (World Bank, 2013).

FIGURE 8.5

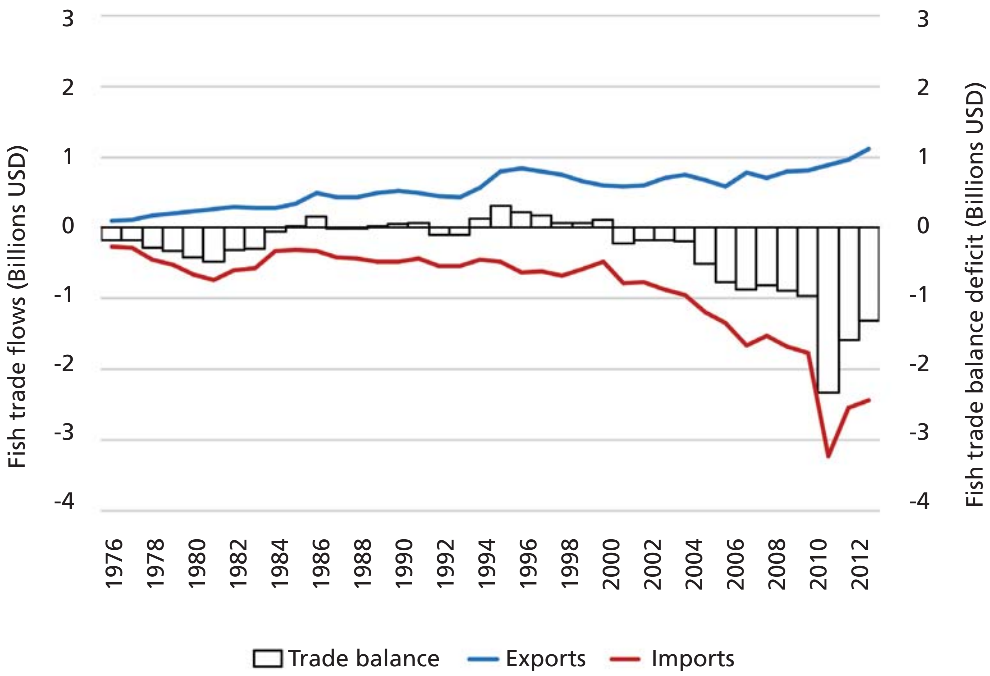
Fish trade flows and fish supply quantity in Guinea Current bordering countries (on the left) versus Canary Current bordering countries (on the right). The bulk of fish-food supplies is made of imports in the Guinea Current region, while most of the production made in the Canary Current region, is exported



Source: FAOSTAT (2017).

FIGURE 8.6

Trends in fish-trade flows and fish trade balance of low-income food-deficit countries bordering the FAO major fishing area 34 from 1976 to 2013. Overall annual shortfall in fish trade balance of LIFDCs resulting from the increasing trend of fish-food imports by these countries, has reached more than 1 billion USD since 2010



Source: FAO Fishstat (2017).

8.4.4 Consequences for fisheries management

The recent trend in abundance and distribution of the main stocks and the uncertainties related to climate change have increased awareness of policymakers of the urgency to take action and improve the management strategies for coastal marine resources. Even if efforts are still needed, many advances have been made in several countries in developing fishery management plans (e.g. in Guinea, Senegal, Mauritania, Morocco), upgrading fishing effort control (through licensing, establishment of a coastal zonation for different types of harvesting), implementing a rights-based approach to coastal fisheries and co-management (Virdin, 2017). An adaptive fisheries management approach was applied for several fisheries in Morocco and Mauritania including individual transferable quota (ITQ) systems. A number of localized territorial use rights fisheries (TURFs) have been established in Cabo Verde, Senegal and Sierra Leone (Virdin, 2017). Mechanisms for supra-national coordination of several marine protected areas (MPAs) in Senegal, Cabo Verde and the Gambia have also been initiated in order to promote a protected marine eco-region (WWF, 2017).

Combining different management or regulatory systems may produce significant socio-ecological climate resilience synergies. The benefits of some spatial tools of fishing regulations and conservation could, however, likely be compromised by climate change impacts. Because of their spatial nature, implementation of tools such as TURFs and MPAs should take into account the likelihood of possible shifts in species distribution patterns and also a possible alteration of currents that could modify the larval connectivity (Andrello *et al.*, 2017). Monitoring of fisheries systems, for example, is not often coupled with MPA research, while pooling of efforts could benefit both management systems (Garcia *et al.*, 2013). Research capacities in the region also remain weak with regard to the scientific advice needed for the sustainable management of fishery resources and marine ecosystems (see e.g. Masumbuko *et al.*, 2011). CECAF and the International Commission for the Conservation of Atlantic Tunas (ICCAT) provide advice for coastal fishery resources and Atlantic tunas and tuna-like fish stocks on a regular/semi-regular basis, but national data collection systems and scientific monitoring capacities have to be improved in many countries of the area (CECAF, 2016; Chavance *et al.*, 2007). Where adaptive fishery management has been implemented (e.g. Morocco), the robustness of the decision-making process varies among fisheries, depending on how much data and scientific analysis are available. This is particularly problematic for the transboundary stocks.

The Regional Fishery Bodies (RFBs) call repeatedly for collaborative management of regional shared stocks, but little progress has been made until now (CECAF, 2016). A strategic action plan for the integrated management of the transboundary Canary Current Large Marine Ecosystem (CCLME) towards 2030 was adopted by the states of the FAO/Global Environment Facility (GEF) CCLME project (CCLME, 2016b), but cooperative governance arrangements between the bordering countries still need to be effectively established. A community-based management approach such as local TURFs could likely be an advantage for diversifying local livelihoods and enhancing social resilience, but presents little flexibility regarding species migration and migrant fisheries (which are some of the most important features of the region), or regarding possible climate-driven change in the species distribution and migration patterns. Connected TURF networks (at national and supra-national level) could be a solution to cope with both. Whilst complex, a management system, tailored at a national and/ or regional scale, combining rights-based fisheries regimes (e.g. connected TURF networks and/or multi-species quota/ITQ systems that take into account the multi-species context and the impact of the tenure length and rules regarding transferability, which may affect resilience) could present many potential socio-ecological resilience benefits. Such a system could, as stated by Ojea *et al.* (2017), give rights owners more incentive to implement climate change mitigation and adaptation strategies to maintain their investment and incomes rather than simply exploiting the remaining population to maximize short-term gain. On the other hand, the importance being given to mangrove ecosystems and mangrove social communities in West Africa to generate and sell mangrove carbon credits to multinational companies within the framework of reducing emissions from deforestation and forest degradation (REDD+) and blue carbon projects, raises some issues, according to Cormier-Salem (2017). These are the issues of administration of land rights and community-based decision-making that are of importance to avoid land grabbing, which can impair the socio-ecological equilibrium required to achieve resilience. Local communities are often unaware of the REDD+ mechanism and the negotiation approach is not always participatory, so that the charter signed with some multinational companies leads in some case to traditional harvesters (e.g. oyster harvesters) losing the right to exploit the reforested areas for several decades (Cormier-Salem, 2017). This underlines the importance of the development of knowledge management skills at different levels of decision-making regarding the issue of climate change socio-ecological resilience.

8.5 SYNTHESIS OF VULNERABILITY AND OPPORTUNITIES OF THE MAIN FISHERIES AND DEPENDENT COMMUNITIES AND ECONOMIES

The future climate conditions will likely pose significant uncertainties for countries with a high contribution of fisheries to income, economies, and food security, but tropical LIFDCs and LDCs will likely be socio-economically most vulnerable to climate change. This is not only because the impacts of climate change on infrastructure and the main fish stocks (such as sardinella, tuna and tuna-like fish) will further jeopardize state revenues from fishing, their food security, assets and source of income for many fishing communities, among other consequences, but also because of the weak capacity of these countries to absorb the cost of adapting to climate change (AfDB, 2011; Allison *et al.*, 2009; Rhodes, Jalloh and Diouf, 2014). Considering the position of the labour-intensive artisanal fisheries sector in West Africa, already threatened by many factors as well as increased climate change driven risks, the communities involved are clearly among the most vulnerable. Literature on poverty traps suggests that the poor are unable to mobilize the necessary resources to overcome either shocks or chronic low-income situations. Many were attracted to fishing by the opportunities provided in the fishing sector, but a significant majority were driven into fishing by external circumstances (Binet, Failler and Aggosah, 2015) and now many lack alternatives and are entrenched in a poverty trap. Poverty indices measured for small-scale fisheries in Ghana, for instance, by Asiedu *et al.* (2013) revealed high poverty with up to 80 percent falling below the international poverty line benchmark, with accompanying high vulnerability and marginalization indices. Increasing resilience of these communities will require that artisanal workers who are already entrenched in the poverty trap and those near that threshold must be targeted for assistance such as poverty reduction and alternative livelihood opportunities. For example, some micro-credit mechanisms have been established for local fishing communities in four MPAs in Senegal to support alternative income creation (WWF, 2017).

Some countries of subtropical and mid-latitude regions could benefit from geographical redistribution of stocks, which could create a supplementary opportunity for some net export countries (e.g. Mauritania and Morocco) to further foster their industrial capacities and exports. Tuna and tuna-like species are currently also of economic importance for some tropical countries and SIDS of the area. A climate-driven range shift in the distribution and abundance of these species will likely also create "winners" and "losers" among fishing nations of the region. A climate-driven shift in distribution of SPF stocks will require a management framework for these resources shared within the CECAF regions and a strengthening of the RFBs' mandates (e.g. CECAF). Furthermore, tuna and tuna-like fishes' distribution shifts could also require adaptive adjustments of ICCAT quotas among member states.

It is, however, important to highlight that at this state of knowledge, many uncertainties remain, which require an urgent development of the regional scientific capacities and a regional strategy for knowledge management. These major uncertainties currently prevent decision-makers from considering the climate change factor. Nevertheless, these uncertainties could be an opportunity to boost value additions in fisheries to enhance the contribution and socio-economic impact of marine ecosystem services. It is estimated that the services impact of the two large marine ecosystems of the area (Guinea Current Large Marine Ecosystem [GCLME] and CCLME) is currently 5 percent of the GCLME countries' summed gross domestic products (GDPs) and 11 percent of the CCLME countries' summed GDPs. The greatest share of this impact appears to be from the fisheries sector in the GCLME and "opportunities for tourism and recreation" in the CCLME (UNEP, 2016). Short-term priority to increase socio-ecological resilience should be to ensure that fisheries and ecosystem governance improve in such a way as to mitigate and prevent further degradation of the quality of local and large marine ecosystems of the region and the services they provide.

8.6 RESPONSES (ADAPTATION)

The National Adaptation Plans (NAPs) process is an opportunity for West Africa to promote a mainstreaming of resilience and efficiency in the development policy. The cost of anticipatory adaptation could likely be important for LDC economies (AfDB, 2011) but would actually result in lower long-term costs than reactive adaptation. Without adaptation, GDP in West Africa is projected to decline by two to four percent by 2100 (Rhodes, Jalloh and Diouf, 2014). Key recommendations for proactive adaptation proposed, on the basis of orientations such as those of the African Union 2063 Vision (AU, 2015), the African Union Strategy on Climate Change (AU, 2014), the United Nations Economic Commission for Africa African Blue Economy Policy Handbook (UNECA, 2016) and the Strategic Action Programme for protecting the CCLME (CCLME, 2016b), could be as follows in Table 8.1.

TABLE 8.1
Key recommendations for proactive adaptation

Recommendation	Level of action
Institutional and management	
• The coastal states should 1) promote and support mainstreaming climate resilience, disaster risk management and risk reduction strategies in the social, economic and environmental sectors related to marine and coastal resource exploitation and uses; and 2) ensure that actions taken consider sustainability of ecosystem goods and service provisioning as well as rights of local fishing communities, traditional users and their tenure.	National and regional
• Build or further develop institutional research capacities (competence and research infrastructure) in marine and fisheries sciences and other scientific branches that produce relevant and impactful knowledge, services and tools responding to societal needs.	National
• Develop a framework of multi-disciplinary observations and scientific research: data collection, monitoring, capacity in regional climate modelling, ecosystems, change scenarios, process, prediction, climate change detection, attribution and assessment of all risk factors, early warning, including technology and other tools required.	National and regional
• Support cooperation and synergies to 1) foster collaboration between research institutions and academies; 2) create knowledge networks among researchers and links to professional associations, industry bodies and government ministries; 3) increase regional scientific networking and visibility; 4) foster regional collaboration in fisheries management; and 5) harmonize standards, data collection, management measures, etc.	National and regional
• Improve skills to enable flexible governance and adaptive management to allow for continuing adjustments and improvements, with a focus on strengthening adaptive capacity of fishing sector stakeholders and communities.	National and regional
• Implement adaptive fisheries management plans for priority resources (e.g. shared pelagic and demersal stocks) based on an ecosystem approach to fisheries, including harmonization of management measures (e.g. technical measures, quota systems, MPAs, TURF networks, etc.) and taking into account the climate change added risks.	National and regional
• Take mitigation measures to reduce the negative impacts of human activities on coastal processes, sediment dynamics and essential habitat to enhance marine fisheries resources and ecosystem resilience.	National and regional
Livelihoods and resilience	
• Build preparatory resilience plans to secure livelihoods, income, infrastructure essential for the fishing sector, and take concrete on-the-ground actions such as hazard mapping, strengthened natural barriers (e.g. mangrove protection, sea walls, flood protection), safety at sea, measures to make assets more resistant to damage such as safer fisher folks' village landing sites and location of processing facilities, etc.	National and sub-national
• Design and adopt strategy exit plans and/or other options to create alternative socio-ecologically resilient employment opportunities directed at workers involved in overexploited fisheries, climate vulnerable fisheries and vulnerable fishing communities.	National and sub-national
• Take concrete measures to improve value chains' efficiency and enhance locally the fish-products' added-value: 1) scale up cold chains and sanitary practices; 2) reduce fish product losses and waste; 3) promote climate-smart fishing and processing technologies, involving complementary adaptation and mitigation techniques and practices; and 4) facilitate access to insurances, micro-credits and business skills training to small-scale stakeholders (including artisanal fishing communities).	National and sub-national

8.7 CONCLUSIONS

Overfishing, as well as other anthropogenic impacts on coastal and marine ecosystems, threatens the marine resources of FAO major fishing area 34. The capacity of many of the bordering states to manage their fishing sectors sustainably is limited and more than one third of the monitored fish stocks are currently exploited at biologically unsustainable levels. Climate change may add further pressure, and is potentially an additional threat to the sustainability of the fishing sector, and therefore also to its contribution to economies of these countries and to the alleviation of poverty and food insecurity. The capacity of fisheries-dependent populations to adapt to climate change is very likely to be limited by weak governance, weak development of knowledge including in relation to likely impacts of climate change, and persistent poverty in many of the countries, which collectively may increase their vulnerability. Anticipatory adaptation is recommended as an important means to increase socio-ecological resilience. Though its cost is likely to be an important factor for many countries in the area, such an approach would be likely to result in lower long-term costs than one of reactive adaptation to the projected climate change impacts.

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Chapter 9: Climate change impacts, vulnerabilities and adaptations: Western Central Atlantic marine fisheries

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KEY MESSAGES

- Negative impacts from climate change that are already obvious in this region include coral bleaching, increasing frequency of high intensity storms and hurricanes, increased sea level, and sargassum influxes that are disrupting fishing operations, fish landings and fisher livelihoods.
- Because most species in the Western Central Atlantic are already at their maximum thermal tolerance and the Gulf of Mexico and Caribbean Sea are constrained by land barriers, there are expected to be few "winners" under future climate change with regard to the commercially important fishery species, which are expected to suffer population declines and reduced productivity in this region.
- Smaller catches can be expected to have significant socio-economic implications for those working in the harvest and post-harvest sectors. This will also have implications for national governments such as reduced domestic productivity in the fishing sector, food security and international trade and foreign currency earnings, especially for those countries with export-oriented fisheries.
- The fisheries sectors of the region's small island developing states are the most vulnerable to climate change.
- Fisher conflicts will increase as fish resources become scarcer. Conflicts will also arise between consumptive users and non-consumptive users within the fishery sector and between sectors.
- Fish resources in the region are typically shared by multiple nations and climate-induced changes to their distribution may require changes to multi-lateral or international agreements, whilst changes in genetic connectivity of stocks may impact the effectiveness of marine reserve networks in protecting source populations.
- Increasing sea surface temperatures in this region, in combination with increased nutrient loading, have implications for the safety of fish and shellfish consumption, given the expected increases in the occurrence of toxic algal blooms, ciguatera fish poisoning and the increasing prevalence of various shellfish diseases.
- Climate change stressors such as sea level rise and increased frequency of severe hurricanes in the region will continue to have significant negative impacts on the safety of fishers, fisheries infrastructure, boats and fishing equipment, and coastal fishing communities.
- Adaptation measures already being undertaken across the region include: development of mobile apps for tracking and early warning; investment in improved infrastructure and facilities; improving resilience of fisherfolk and aquaculturists, and mainstreaming climate change into fishery policy and planning.

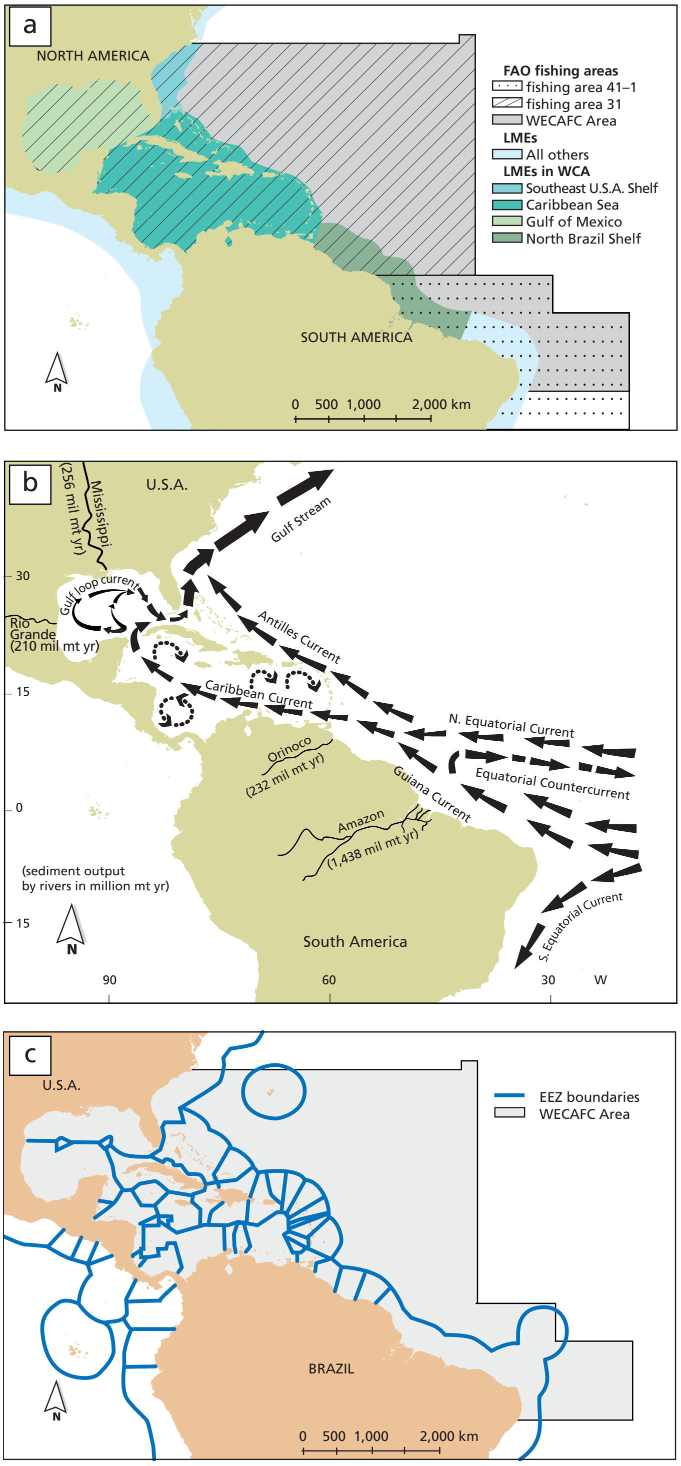
9.1 INTRODUCTION

9.1.1 The Western Central Atlantic region

The Western Central Atlantic (WCA) represents the area covered by the FAO Western Central Atlantic Fishery Commission (WECAFC), which includes FAO major fishing area 31 and the northern part of FAO major fishing area 41 (Figure 9.1). This area encompasses four distinctly different biogeographic regions considered as different large marine ecosystems (LMEs): the northeast coast of South America (North Brazil Shelf), Caribbean Sea, Gulf of Mexico (GOM) and the southeast shelf of the United States of America (SE USA), as well as a large area of open ocean linked by major ocean currents. It covers 14 644 544 km^2 of which 10.5 percent is continental and island shelf, incorporates two of the world's largest semi-enclosed seas, and is influenced by the discharge of some of the world's largest rivers (e.g. Amazon, Orinoco, Mississippi). The WCA includes the exclusive economic zones (EEZs) of 28 nation states and 16 territories belonging to the Netherlands, The United Kingdom of Great Britain and Northern Ireland, France and the United States of America, of which 29 are considered small island developing states (SIDS) and has five official languages, making it one of the most geopolitically complex and vulnerable regions of the world. It is also one of the most bio-diverse areas of the world's oceans, exhibiting a wide range of oceanographic and hydrographic features, a great diversity of tropical, subtropical, estuarine, coastal, shallow-shelf, deep-slope and oceanic habitats, including around eight percent of the world's coral reefs and six percent of the seamounts, and supports a wide diversity of commercially important fishery species (Table 9.1).

FIGURE 9.1

Maps of Western Central Atlantic region showing a) LME boundaries and FAO fishing areas, b) major surface currents, and c) EEZ boundaries[1]. Quantitative data are given in Table 9.1



1 The designations employed and the presentation of material in the map(s) are for illustration only and do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers or boundaries.

TABLE 9.1

Summary of main oceanographic features and fisheries characteristics of the LMEs in the Western Central Atlantic

LME key oceanographic features[a]		Main target groups	Socio-economic importance of fisheries	Fisheries governance arrangments[e]
NORTH BRAZIL SHELF Area: 1 000 000 km², 47% shelf, 1.7% protected. Contains <0.1% world's coral reefs and seamounts. Tropical, very high annual primary production (>300 g C/m²). Dominated by a branch of the South Equatorial Current, the North Brazil Current (NBC) flowing NW towards the Caribbean, and by nutrient rich, high sediment Amazon River discharge.		Brazilian sardinella, penaeid shrimps (seabob, white, brown, pink), groundfishes (weakfishes, croakers, sea catfishes), deep slope (southern red snapper, spiny lobsters). 50% stocks overfished or collapsed[b]	Annual production (2014): 450 250 tonnes, worth USD1 041 million[b]. Includes five nations (Brazil, French Guyana, Suriname, Guyana, and the Bolivarian Republic of Venezuela). Significant dependence on fish protein throughout the region. Very important export-oriented shrimp fisheries. In Guyana the fishery sector is critical to the national economy (6% GDP) and social well-being with per capita fish consumption[c] at 30 kg/yr.	No regional fisheries management organisation (RFMO). Shared responsibility for assessment and management of shrimp and groundfish resources of the Guianas/ Brazil shelf is recognized under the Western Central Atlantic Fishery Commission and Caribbean Regional Fisheries Mechanism (WECAFC/CRFM). No shared fishery information system. National legislation and management plans for some key species across the different countries.
CARIBBEAN SEA Area: 3 200 000 km², 16% shelf, 3.9% protected. Contains 7.1% world's coral reefs including second largest barrier reef and 1.4% seamounts. Tropical, annual hurricanes, moderate annual primary production (150–300 g C/m²). Influenced by nutrient-poor North Equatorial Current and seasonally by nutrient-enriched NBC forming the Caribbean Current flowing NW and into GOM.		Reef fishes, conch, spiny lobster, coastal pelagics (sardines, pilchards, anchovies), oceanic pelagics (dolphinfish, wahoo, billfishes, tunas), deep slope finfishes (snappers, groupers). 58% stocks overfished or collapsed[b].	Annual production (2014): 440 250 tonnes, worth USD 986 million[b]. Includes 38 nation states and dependencies and has a current population around 84 million people. Many SIDS highly dependent on fish for food with annual individual per capita consumption rates[c] twice world average* (e.g. Antigua/ Barbuda 53 kg, Barbados 40 kg, Saint Kitts and Nevis 37 kg). Non-consumptive use of reef resources (SCUBA diving, ecotourism, education, research) economically important.	No overarching RFMO or shared fishery information system despite significant percentage of transboundary stocks. There is a Caribbean Community Common Fisheries Policy for insular Caribbean. The Central America Fisheries and Aquaculture Organization (OSPESCA) has a common fisheries and aquaculture policy for Central America. Regional Fishery Bodies (e.g. OSPESCA, WECAFC, and CRFM) have subregional management plans for some key species. Some tuna species under quota management by the International Commission for the Conservation of Atlantic Tunas (ICCAT). States have national legislation. Local co-management arrangements in place for a few fisheries.
GULF OF MEXICO Area: 1 500 000 km², 38% shelf, 1.6% protected. Contains 0.6% of world's coral reefs and <0.1% seamounts. Annual tropical storms, moderate annual primary production (150–300 g C/m²). Characterized by estuaries, strongly influenced by 47 major rivers, the Loop Current and associated upwelling. Extensive deoxygenated dead zones develop in the summer in the northern gulf.		Coastal pelagics (Gulf menhaden), penaeid shrimps (brown, white), groundfishes (croakers and weakfishes), shellfishes (blue crab, American cupped oyster, octopus). 60% stocks overfished or collapsed[b].	Annual production (2014): 1 391 990 tonnes, worth USD 3 628 million[b]. Includes two nations (United States of America, Mexico). Coastal population around 55 million people. Very important contributor to United States of America fishery production[d] (25% of United States of America commercial fishery landings, 40% marine recreational fishing effort, 78% of shrimp landings, 62% of oyster landings).	Mexican national government shares fishery management responsibility with government of local states and municipalities. United States of America Gulf States have management plans for many key species through the Gulf of Mexico Fishery Management Council and some joint plans with the South Atlantic Fishery Management Council (SAFMC). State and federal regulations may differ. Regional partner organizations involved in fisheries governance including the Gulf States Marine Fisheries Commission and National Oceanic and Atmospheric Administration (NOAA).
SOUTHEAST UNITED STATES OF AMERICA SHELF Area: 300 000 km², 48% shelf, 2.4% protected. Contains 0.3% of world's coral reefs. Subtropical-temperate, moderate annual primary production (150–300 g C m²). Characterised by estuaries, extensive coastal marshes, bays and barrier islands. Influenced by warm north-flowing Gulf Stream.		Shellfishes (blue crab, American cupped oyster, quahog clam), jellyfishes, oceanic pelagics (wahoo, dolphinfish, billfishes). 56% stocks overfished or collapsed[b].	Annual production (2014): 106 000 tonnes, worth USD 423 million[b]. Includes single nation (United States of America). Around 96 million residents with coastal population growing at 2% per year. Oceanic pelagics and spiny lobster highly valued for recreational fishing.	The SAFMC is responsible for the conservation and management of fish stocks in this LME in collaboration with the National Marine Fisheries Service Southeast Fisheries Centre, NOAA playing a regional role and also guiding fishery adaptation through its 2015 Fisheries Climate Science Strategy. State and Federal regulations may differ.

Data sources: [a] www:seaaroundus.org, Sherman and Hempel (2009); [b] www:seaaroundus.org 2014 data; [c] FAOSTAT 2013 data; [d] Ward (ed., 2017); [e] Singh-Renton and McIvor (2015), Ward (ed., 2017).

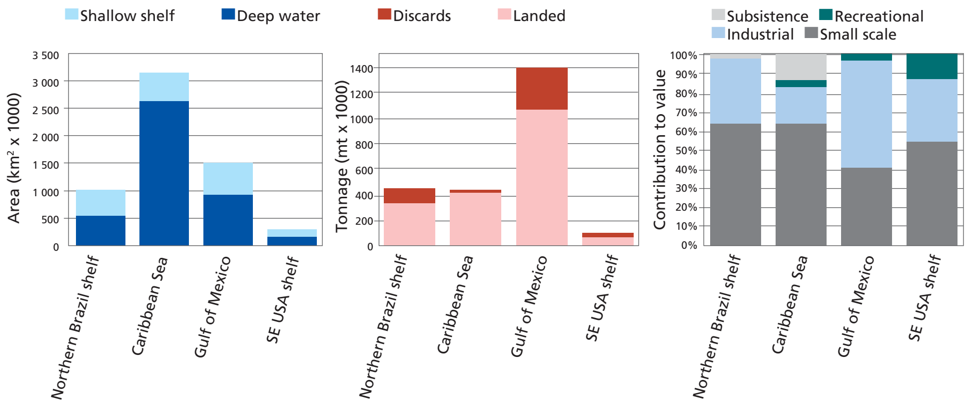
*Note that these figures are apparent consumption by the local population and do not include tourist visitors which may be significant in some of these countries.

9.1.2 Main fisheries of the region

This heterogeneous region has a high reliance on marine capture fisheries and exhibits a wide range of fishery types from single to multispecies and from small-scale subsistence and small-scale commercial operations to large-scale semi-industrial and industrial fisheries to private recreational and sports-fishing charter operations (Figure 9.2; Table 9.1). Fishery production is also highly variable across the region with the GOM LME landing more than twice the tonnage of the Caribbean and North Brazil LMEs and more than 10-fold that of the SE USA LME (Figure 9.2). Small-scale fisheries (SSF) are important across the entire region and represent the most valuable sector across all LMEs except the GOM where industrial trawl and purse seine fleets predominate (Figure 9.2). The governance arrangements are also highly variable among fisheries and nation states, from unmanaged free-access (typical of SSF) to highly regulated (typical of the larger-scale fisheries, particularly in the United States of America; Table 9.1).

FIGURE 9.2

Comparison of the four LMEs found within the WCA, showing size, fishery production and relative economic value by sector. Fishery data are for 2014 and represent reconstructed estimates based on the FAO FishStatJ database



Data sourced from: www.seaaroundus.org.

The broad, multi-species groups of greatest importance to fisheries of the WCA are given in Table 9.1 by LME and are considered separately in Section 9.3. These include coastal benthic and reef-associated species of which there are over 100 commercially important finfish species belonging to many different families such as snappers (Lujanidae), groupers and hinds (Serranidae), grunts (Haemulidae), squirrelfishes, (Holocentridae), parrotfishes (Scaridae), surgeonfishes (Acanthuridae), triggerfishes (Balistidae) and wrasses (Labridae) *inter alia*. This group also contains the high-value shellfishes such as queen conch (*Strombus gigas*), spiny lobster (*Panulirus argus*), American cupped oyster (*Crassostrea virginica*), quahog clam (*Mercenaria mercenaria*), blue crab (*Callinectes sapidus*) and octopuses (common, *Octopus vulgaris;* red, *O. maya*). The coastal schooling pelagic finfish group includes many species of sardines and pilchards (Clupeidae) (e.g. Gulf menhaden, *Brevoortia patronus*; Brazilian sardinella, *Sardinella brasiliensis*), anchovies (Engraulidae) and jacks (Carangidae). The benthic continental shelf shrimp and groundfish group contains the penaeid shrimps (e.g. various pink and brown species, *Farfantepenaeus* spp.; white shrimps, *Litopenaeus* spp.; seabob, *Xyphopenaeus kroyeri*), weakfishes (e.g. *Cynoscion* spp.; bangamary, *Macrodon ancylodon*), croakers (e.g. corvina, *Micropogonias furnieri*) and sea catfishes (Ariidae). Another commercially important group is the deep-slope benthic finfishes including deepwater grouper species (e.g. misty, *Epinephelus mystacinus*; red, *E. morio*), deepwater snappers (e.g. southern red, *Lutjanus purpureus*; queen, *Etelis oculatus*; vermilion, *Rhomboplites aurorubens*) and greater amberjack (*Seriola dumerili*). Also important is the highly migratory oceanic pelagic finfish group including the common dolphinfish (*Coryphaena hippurus*), wahoo (*Acanthocybium solandri*), mackerels (*Scomberomorus* spp.), small tunas (e.g. skipjack, *Katsuwomis pelamis*, blackfin, *Thunnus atlanticus*), large tunas (e.g. yellowfin, *Thunnus albacares*; bigeye, *T. obesus*; albacore, *T. alalunga*), and billfishes such as blue marlin (*Makaira nigricans*), white marlin (*Kajikia albidus*), Atlantic sailfish (*Istiophorus albicans*) and swordfish (*Xiphias gladius*).

9.2 IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT

The climate change stressors on the marine environment of greatest significance to fisheries in the WCA are increasing sea surface temperature (SST), ocean acidification (OA), sea level rise (SLR) and increased frequency of extreme weather events (e.g. storms, hurricanes, precipitation anomalies). The projections published in the most recent assessment (AR5 2013 to 2014) of the Intergovernmental Panel on Climate Change (IPCC) are considered here, together with global climate change models downscaled to smaller regional scales where available.

9.2.1 Physical and chemical

Sea surface temperature

With respect to the WCA, air temperatures could rise between 0.5 °C to 0.9 °C by 2100 for the lowest carbon emissions scenario (representative concentration pathway – RCP2.6) and in excess of 4 °C under RCP8.5. This will ultimately cause SSTs to rise considerably, but the increases are likely to be variable across the region. For example, SST increases to date have shown considerable disparity across the WCA, influenced by major sea surface currents. The North Brazil Shelf is considered among the slow to moderate warming LMEs of the world with a 0.38 °C increase in SST over the period 1957 to 2012, whilst the Caribbean and GOM are among the slow warming LMEs with increases of 0.15 °C and 0.16 °C respectively, and the SE USA shelf LME has actually cooled by 0.28 °C over the same period (Belkin, 2016). Regional downscaling of global models indicates that the present spatial heterogeneity of SST in the Caribbean basin will change during this century from a seasonal warm pool that expands out from the Western Caribbean each spring/summer and retracts each fall/winter, to be replaced by two warm pools centred over the Western and Eastern Caribbean that will merge, blanketing the entire region (Nurse and Charlery, 2016). As a result, the small annual range in SST, characteristic of this area, will continue to decrease from a current average of 3.3 °C to just 2.3 °C by the end of the century, such that seasonal "warm" and "cool"periods will become less differentiated over the coming decades.

Increasing SSTs over most of the region will mean stronger ocean temperature stratification and reduced oxygen content in the upper layers. Concomitantly, increasing air temperatures have promoted a poleward shift in the large-scale atmospheric Hadley circulation that dominates the tropics and has resulted in a northward shift of the intertropical convergence zone and weakening of the trade winds that drive surface circulation and upwelling in this region (Taylor *et al.*, 2012). A shallowing of the oxygen minimum layer (representing a hypoxic habitat boundary for high oxygen demand species) has already been observed in the tropical Atlantic (Stramma *et al.*, 2012), diminished upwelling and increased stratification have been recorded in the southern Caribbean off the Bolivarian Republic of Venezuela (Taylor *et al.*, 2012) and seasonal dead zones (lacking sufficient oxygen) in the northern GOM are continuing to expand every summer (Helleman and Rabalais, 2009). In addition, the Atlantic meridional overturning circulation (AMOC), a branch of the global thermohaline circulation is predicted to slow down under future climate change. This will further affect the North Brazil Current, the dominant feature of the North

Brazil LME and responsible for bringing episodic nutrient-enriched, lower salinity, South Atlantic water (and pelagic sargassum seaweed) into the Caribbean, because it is strongly linked to the AMOC and to surface winds (Rühs *et al.*, 2015). This change in the North Brazil Current is expected to affect the strength of the Caribbean Current, and will result in a decrease in the strength of the Yucatan and Loop currents in the Gulf of Mexico (Ward and Tunnell, 2017) and a weakening of the Gulf Stream. The latter has already been implicated in the slight decrease in the SST recorded for the SE USA shelf (Phillips and Perez-Ramirez, eds., 2017).

Ocean acidification

In the WCA, a recorded decrease in the pH of the open sea has followed the global trend and has been accompanied by a sustained decrease in the aragonite saturation state (Ωar) (albeit seasonally and spatially variable as influenced by SST and salinity) from an annual mean value of Ωar 4.05 to 3.39 in just 11 years (1996 to 2006; Gledhill *et al.*, 2008). With increases in mean atmospheric pCO_2 to 450 µatm, the Ωar values in this region are expected to reach 3.0–3.5, whilst pCO_2 reaching 550 µatm will reduce Ωar to <3.0, a value associated with net erosion of coral reef framework (Gledhill *et al.*, 2008).

Sea level rise

Over the last six decades the mean SLR of 1.8±0.1 mm/yr recorded for the wider Caribbean region has tracked the global mean value (Palanisamy *et al.*, 2012). However, the annual rate of SLR has increased significantly in this century and for the WCA region mean sea level is projected to increase by between 0.35 to 0.65 m (depending on which emissions scenario is followed) by the end of this century (2081 to 2100) relative to the period 1986 to 2005 (Church *et al.*, 2013). The multiple factors affecting local SLR vary across the WCA (e.g. the Mississippi delta in the GOM is experiencing relative SLR three times greater than world average) and the coastal impact of increases in mean sea level also varies regionally with tidal range and frequency of storm surges (SS; Losada *et al.*, 2013). This implies that the Caribbean and GOM, both of which experience micro-tides and increasing SS, will be most affected, whilst the North Brazil LME with its macro-tides and lower storm frequency will be least affected. Comparing the decades of 1950 to 1960 and 1998 to 2008, SLR has already led to a significant increase (20 percent to 60 percent) in the frequency of sea level extremes across the Caribbean, whilst there has been little to no change along the North Brazil Shelf (Church *et al.*, 2013; Losada *et al.*, 2013).

Extreme weather events

The IPCC AR5 recognizes that unusual extreme weather events have been affecting the WCA (especially the Caribbean, GOM and SE USA) region over the last few decades (Magrin *et al.*, 2014). There is also evidence that more tropical storms in the Atlantic are developing into dangerous category four and five hurricanes (Murakami, Mizuta and Shindo, 2012). Projections indicate that further enhanced hurricane intensity is likely in this region under climate change with continued increases in SSTs, although the current understanding of tropical cyclone generation and frequency is still limited.

9.2.2 Biological and ecological

Increasing SSTs, OA, SLR and extreme weather events driven by climate change have already had significant impacts on essential coastal habitats and the wider ocean ecosystem of the WCA, and have certainly exacerbated the impacts of chronic anthropogenic stressors on marine communities such as overfishing and poor water quality linked to coastal development and agriculture (e.g. Jackson *et al.*, eds., 2014). In particular, coral reefs in this region have suffered large declines in live coral cover in recent decades due to high SST-induced mass coral bleaching events and associated mortality (especially in 1998, 2005 and 2010; Eakin *et al.*, 2010). Furthermore, such events are predicted to increase in frequency and even become annual events in this region by the mid-twenty-first century (van Hooidonk *et al.*, 2015). Contributing to the degradation of coral reefs is the increasing prevalence of coral diseases linked to increasing SSTs (Bruno and Selig, 2007), and larger more damaging storms in the Caribbean, GOM and SE USA (such as those experienced in 2005 and 2017). As a result there has been a significant loss of reef architectural complexity (Alvarez-Filip *et al.*, 2009), a loss of coral reef species (Newman *et al.*, 2015), changes in the dominant species assemblages and, in some cases, a complete phase shift to algal dominated reef communities (e.g. Hughes *et al.*, 2007) providing significantly altered ecosystem services. Many coral reefs in the region are already experiencing significant reductions in carbonate production rates with 37 percent of surveyed sites showing net erosion (see Melendez and Salisbury, 2017 and references therein).

Other tropical and subtropical essential habitats such as seagrasses, mangroves and estuarine salt marshes are also being impacted. Within the Caribbean and Gulf of Mexico basins in particular there have been significant declines in seagrasses (van Tussenbroek *et al.*, 2014; Ward and Tunnell, 2017), although much of it caused by chronic anthropogenic stressors other than climate change, such as coastal development and eutrophication (increased nutrient load). Likewise there have been substantial declines in mangroves across the WCA caused largely by coastal development (including aquaculture) and timber harvesting (Ward *et al.*, 2016). Under future climate change, mangroves in the WCA are expected to be most impacted in the Caribbean (especially the SIDS with significant coastal infrastructure development and limited coastal land for mangrove habitat to retreat inland) and GOM because of the micro-tidal regime and increasing storm intensity in these LMEs. In the SE USA there is some evidence that the distribution of mangrove habitat has already responded to increasing temperatures through a northerly extension along the southeast coast and this is expected to continue (Phillips and Perez-Ramirez, eds., 2017). Extensive mangroves along the coast of the North Brazil LME will be least affected given the macro-tidal regime and rarity of catastrophic storms here (Ward *et al.*, 2016).

Estuarine environments are being affected by changes in freshwater inflow and SLR and those with high nutrient loads, particularly in the GOM, have been further impacted by climate change associated increases in SST resulting in an increase in the size and extent of summer “dead zones” (seasonal hypoxia) where oxygen levels in the water column are too low to support most marine life (Phillips and Perez-Ramirez, eds., 2017; Tunnell, 2017). Seasonal hypoxia is expected to become more severe with increased rainfall and warmer water (Phillips and Perez-Ramirez, eds., 2017).

Increasing levels of eutrophication and increasing SST together also enhance the blooming of pelagic (floating) algae, resulting in more frequent “green tides” and toxic algal blooms (Smetacek and Zingone, 2013). Such events are becoming more common in the WCA, and since 2011 the wider Caribbean region has been experiencing unprecedented influxes of pelagic sargassum (Franks, Johnson and Ko, 2016). These extraordinary sargassum blooms, entering the Caribbean Sea through the Lesser Antilles as large floating mats of algae, have resulted in mass coastal strandings throughout the region and significant damage to critical coastal habitats such as mass mortality of important seagrass beds and associated corals through shading, anoxia and excessive nutrient loading (van Tussenbroek *et al.*, 2017). Changes in biological productivity of any of the coastal habitats will have impacts on their ecosystem services and the trophic linkages among them, and will affect both the nearshore and the oceanic pelagic food chain such that impacts will not be limited to these coastal areas.

9.3 EFFECTS OF CLIMATE CHANGE ON FISHERY RESOURCES

The key climate change stressors will have numerous interrelated impacts on commercially important fishery species in the WCA, through 1) direct effects on their physiology and life processes (e.g. neurotransmission, respiration, growth and development rate, reproduction, longevity); and 2) indirect effects arising from significant impacts to essential habitats affecting nursery areas, living space, refuge and predator-prey relationships; and from physical and biological oceanographic changes affecting survival, dispersal and settlement of early life history stages, and migration and distribution ranges of adults, *inter alia*. Together these are expected to significantly affect the distribution, abundance, seasonality and fisheries production of the key fishery resources in the WCA (see Oxenford and Monnereau, 2017 for a detailed review of the literature). Although there is a relative dearth of studies on the impacts of climate change specifically on fishery species in the WCA (Oxenford and Monnereau, 2017), implications can be drawn from the literature covering similar species from outside the region and projections for climate change stressors within the WCA. Here we consider implications for the main fishery species groups important to the WCA (shown by LME in Table 9.1).

9.3.1 Coastal benthic and reef-associated species

The impact of climate change on this group (reef fishes, molluscs, spiny lobsters and crabs) although highly species-diverse, is almost undoubtedly the most serious of the commercially important fishery groups across the WCA. Their particular vulnerability arises from the fact that: 1) most species are highly reliant on critical coastal habitats (coral reefs, mangroves, estuaries) that are themselves already significantly degraded, not only from climate change stressors, but also from other anthropogenic activities (e.g. coastal development, sewage and agricultural runoff, over-harvesting); 2) they have biphasic life histories involving a pelagic early life stage and a requirement to settle in specific benthic nursery habitat for development into juvenile through to adult stages; and 3) many of these stocks in the WCA are already compromised by overfishing, significantly reducing their genetic biodiversity, productivity and hence resilience to further environmental changes.

Of particular concern are those species with an obligatory relationship to coral reefs, one of the most sensitive of all marine ecosystems to climate change and other anthropogenic stressors. Research to date has identified significant negative impacts on tropical reef fishes, conchs and spiny lobsters not only from loss of nursery and adult habitats, but also from increasing SST and OA (see Oxenford and Monnereau, 2017 for review).

Reproduction in reef fishes examined to date shows a high sensitivity to SST, with reduced pairing, lower fecundity and smaller eggs and larvae being produced, or even a complete cessation of spawning at climate change-relevant increases of 1.5°C to 3 °C (Pratchett, Wilson and Munday, 2015). Temperature is an important spawning cue, not only for reef fishes (e.g. Erisman and Asch, 2015) but for many other species in this group including conch (Aldana Aranda *et al.*, 2014) and spiny lobster (Phillips and Perez-Ramirez, eds., 2017). There is also evidence that pelagic larval duration (PLD) of many species will be shortened by small increases in temperature. As such, changes to SST will have far-reaching effects on the reproductive success of this commercially important group by affecting spawning behaviour (timing and/or location), the quality and quantity of reproductive output (eggs/larvae) and the PLD which will affect the dispersal, survival and settlement success of larvae as a result of potential mismatches with other environmental factors that ensure adequate food and return of post-larvae to suitable settlement habitat. Spiny lobsters with their uniquely long PLD (6 to 12 months) are particularly vulnerable (Phillips and Perez-Ramirez, eds., 2017). Unlike those of temperate and polar species, growth rates in adult tropical reef fishes have also been shown to slow down with marginal increases in SST (Munday *et al.*, 2008). Increasing SST has also been implicated in disease outbreaks in commercially important species in this group in the WCA, such as oysters in the GOM (Phillips and Perez-Ramirez, eds., 2017; Tunnell, 2017). Furthermore, the *Panulirus argus* Virus 1 (PaV1) which is usually lethal to juvenile Caribbean spiny lobsters is likely dispersed via pelagic larval stages, demonstrating how any climate-induced changes in the hydrology of the Caribbean Sea could significantly affect the spread of the disease (Kough *et al.*, 2015).

As OA increases, affecting the concentration of ions (especially H^+) in seawater, calcifying organisms will find it increasingly difficult to build calcareous skeletons and shells, although the impact on the region's important shellfish species (queen conch, spiny lobster, cupped oysters, quahog clams, penaeid shrimps) to near-future ocean pH levels is largely unknown. OA has also been shown to result in impairment of a diverse suite of sensory and behavioural abilities in reef fishes, especially the early life history stages which affect the ability to escape predation, habitat selection and timing of settlement to coral reef habitats (Devine, Munday and Jones, 2012).

Increased storminess, changes in precipitation and SLR in the WCA have already impacted other important species in this group. For example, many important oyster reefs in the GOM have been smothered by sediments as a result of hurricanes in recent years (Phillips and Perez-Ramirez, eds., 2017; Tunnell, 2017). Blue crabs, heavily reliant on healthy estuaries for reproduction, recruitment and survival, are particularly vulnerable to changing patterns of salinity linked to SLR and/or changes in precipitation patterns (Tunnell, 2017).

Reduced population sizes and productivity are expected across this multi-species group under near-future climate change, with significant impacts on production of SSFs across the region, particularly in the SIDS of the Caribbean LME where reef-associated species are often exclusively targeted (Table 9.1).

9.3.2 Coastal schooling pelagic species

Most of the coastal pelagic species (e.g. menhaden, sardinella, anchovies) are highly reliant on critical estuarine habitats (mangroves/saltmarshes) which, like coral reefs, are particularly sensitive to climate change, in particular SLR and storminess, and other anthropogenic stressors. Under increasing SSTs, coastal pelagic fishes, especially menhaden in the GOM, will be increasingly affected by the enlarging seasonal areas of hypoxia, resulting in direct mortality or sub-lethal effects such as reduced growth and impaired reproduction (Langseth *et al.*, 2014). Small schooling pelagics also typically have short life spans, meaning that response time of populations to climate change will be rapid. For example, menhaden population abundance in the GOM is highly sensitive to interannual changes in SST and salinity, which have resulted in significant impacts on fishery production in this region. Off the coast of the Bolivarian Republic of Venezuela, climate-induced reductions in seasonal coastal upwelling have been associated with a change in phytoplankton productivity and a coincident 87 percent drop in catches of planktivorous sardines at Margarita Island (Taylor *et al.*, 2012).

Localized (subregional) reductions and increased interannual variability in productivity of these coastal pelagic species are expected under near-future climate change across the WCA, significantly affecting fisheries production in GOM and North Brazil Shelf LMEs with large industrial fisheries for these species (Table 9.1).

9.3.3 Continental shelf shrimp and groundfish species

The penaeid shrimp and groundfish (e.g. weakfishes, croakers, sea catfish) species in this group mostly rely on estuarine nursery areas, and offshore deeper soft bottom areas as adults. The early life stages will therefore be particularly vulnerable to further degradation of estuarine habitats expected under climate change and continuing eutrophication (e.g. changes to salinity, increased hypoxia), although, the adult habitats will likely be less impacted by climate change and adults could probably move to deeper offshore soft-bottom habitats. This group also has biphasic life cycles and will therefore share the same potential threats posed to early life stages as all of the other fishery groups (i.e. shorter PLDs and changing currents impacting successful dispersal and delivery of new recruits to suitable estuarine settlement habitats and nursery grow-out areas for population replenishment) and the early life stages will also be vulnerable to the myriad of potential effects of elevated SST and OA, with the latter likely to impact shrimps in particular. Penaeid shrimps in the northern GOM where the development of seasonal hypoxic areas is particularly severe and increasing under climate change are expected to suffer significant impacts, since the adults will be unable to pass through the hypoxic zones to spawn in open water (Tunnell, 2017).

Declining productivity of shrimp and groundfish populations are expected in the WCA over the near- to medium-term with significant reductions in fisheries production in the North Brazil Shelf, continental countries of the Caribbean, and the GOM where these species are targeted by industrial fleets and SSFs (Table 9.1).

9.3.4 Deep slope species

The impacts of climate change on this group (e.g. snappers, groupers) in the WCA have received little to no specific attention, but, considering their biological characteristics (biphasic life history; use of shallow reefs and associated habitats as nursery areas; use of reef spawning aggregation sites) and current exploitation status, the impacts are likely to be similar to, or perhaps slightly less severe than, the coastal reef-associated species group. The fact that the species in this group tend to be longer lived than their shallower relatives, means however, that the impacts of climate change on stock biomass and abundance will likely be delayed, but any recovery will also take longer. Likely declines over the near- to medium-term will particularly affect the fisheries production of the GOM and North Brazil LMEs where these species are particularly important (Table 9.1).

9.3.5 Oceanic pelagic species

This group of highly migratory large pelagic species (billfishes, large tunas) and smaller more regionally migrating species (dolphinfish, wahoo, mackerels, small tunas) have also received little attention in this region, but will likely be less impacted by climate change, at least in the short-term, than the other four groups. This is largely because of their high mobility, lack of a biphasic life history, less vulnerable reproductive behaviour, and the fact that the open ocean is less impacted by other anthropogenic stressors than coastal habitats. Furthermore, the regionally migrating species are also generally not overexploited and therefore more resilient to future change.

Nonetheless, for many species, increases in SST will mean changes to their productivity and distribution as they move northwards and out of the WCA area to more favourable temperatures. For some species, such as bluefin tuna, this could mean abandoning their spawning area in the GOM (Muhling *et al.*, 2011).

As such, reductions in productivity of the oceanic pelagic species are expected over the medium- to long-term, affecting fisheries production across the WCA, but especially in the Caribbean and SE USA LMEs where ocean pelagic species are among the top species landed and also support significant recreational fleets (Table 9.1).

9.4 SOCIAL AND ECONOMIC IMPLICATIONS OF CLIMATE CHANGE

Despite some progress made in advancing climate change science in the WCA in recent years, there are very few impact studies focused on social and economic implications for the fisheries sector. Furthermore, there have been no quantitative studies specifically related to impacts on changes in fisheries production, fish size or fish distribution for the region or the direct socio-economic consequences thereof. Here we consider food security, livelihoods, economic and fisheries management implications of climate change for the fisheries sector of the WCA. This is based on the observed and expected changes in fishery resources within this region (see Section 9.3), the heterogeneous nature of the region's fisheries (see Section 9.1) and the additional observed and expected direct impacts of climate change on the harvest and post-harvest sectors.

9.4.1 Food security

The fisheries sector of the WCA is important to food security with an annual harvest in excess of an estimated 2.3 million tonnes (2014 data, see Table 9.1). Fisheries are especially important to food security within the Caribbean and the North Brazil LME where: fish consumption (per capita supply) is well above the world average in many of the SIDS (Table 9.1); fish represents more than 20 percent of the animal protein consumed in Guyana and French Guiana (FAO, 2016a); subsistence fishing is still important; and SSF contribute more than 55 percent of total landings by weight and 60 percent by value (Figure 9.2). Personal income derived from the fisheries sector is also important in this region, in providing financial access to food.

Climate change is expected to negatively affect food security in the WCA by reducing species' productivity and availability and hence reducing fishery catch per unit effort (CPUE) and ultimately total landings in all of the main fishery species, but especially the reef-associated species group which supports mostly SSF. The coastal pelagic species will also be impacted in the short-term, but will have fewer implications for food security at the regional level given that most landings in this species group across the WCA are by industrial fleets and used for non-consumptive products (e.g. fish meal, fish oil). The impacts on food security are expected to be greatest in low-income fishing communities where subsistence fishing is still important (or where at least some of the commercial catch is always retained by the crew for personal consumption); where fish are generally consumed locally, or sold and used for income; and where populations are often already vulnerable and food insecure.

More intense and frequent extreme weather events are also expected to have negative impacts on food availability, accessibility, stability and utilization. The poor will face the greatest risk of food insecurity as a result of loss of assets (e.g. fishing boats, engines and gear) and lack of adequate insurance coverage. Increasing SSTs and extreme weather events such as hurricanes are expected to increase the geographic extent and occurrence of ciguatoxic reef fish (Tester *et al.*, 2010). As such, food security in the region is expected to be affected by increases in ciguatera fish poisoning in humans, which will affect trade in reef fishes and the health of local communities, since consumption of ciguatoxic fish can lead to gastrointestinal distress, severe neurological and cardiovascular symptoms that can persist for months or even years and, in rare cases, can result in death (Tester *et al.*, 2010).

Fisheries for high value species (e.g. snappers, groupers, shrimps, conchs, spiny lobsters, large tunas) in the North Brazil LME and the Caribbean (e.g. Guyana, Suriname, the Bahamas, Belize, Grenada, Jamaica) are often export-oriented and generate significant foreign earnings. As fisheries face increasing pressures from climate change impacts as well as other challenges, coupled with human population increases, it will become more critical for countries to consider their policy options regarding the relative advantages of trading fish internationally versus having fish available for the domestic food market.

9.4.2 Livelihoods

The fisheries sector of the WCA generates landings valued in excess of USD 6.1 billion annually (2014 data, see Table 9.1) and helps support the socio-economic viability of coastal communities across the entire region by providing direct employment, livelihood and benefits to thousands of people across 42 countries. Expected reductions in the productivity of the region's fishery resources (especially in the reef-associated group), increased interannual variation in availability (especially in the coastal pelagics group), and changes to their distribution (to cooler water) as a result of climate change (Section 9.3) means that fishers in the WCA are expected to face declining catches, lower CPUE, lower fishery-related income and increased levels of conflict. This would especially affect the large number of small-scale coastal fishers targeting benthic, reef-associated species in the region, as they would be forced to fish longer and may need to travel further and/or fish deeper, change their target to offshore pelagic species or find alternative employment outside the fishery sector to maintain their income. The implications include: reduced fisher safety (e.g. travelling further offshore, diving longer and deeper); the need to invest in training and new gear (e.g. mechanized reels, fish aggregating devices) and new and/or larger boats and engines; and increased levels of income uncertainty. This could in turn lead to more demands on government social security and unemployment benefits.

Climate change stressors such as SLR and increased severity of hurricanes in this region will continue to have significant negative impacts on: fisheries infrastructure (safe harbours, jetties, coastal markets, landing sites); gear (boats, fishing equipment); and coastal fishing communities (housing, facilities), especially in the micro-tidal, storm-prone Caribbean and GOM LMEs. For example, in 2017 alone, two of the strongest hurricanes ever recorded caused extensive damage to the fisheries sectors of several Eastern Caribbean SIDS[2] (Horsford, 2017). This will translate into significant economic losses especially for SSFs since most small-scale fishing enterprises, particularly in the Caribbean, are privately owned and currently have no access to affordable insurance. This was revealed by Tietze (forthcoming) who reported that 97 percent of fishers in the 11 Caribbean countries studied have no insurance for their boats or other assets, indicating high economic risk for a significant number of fishers in this region under future climate change. Fishers could very well be left without a safety net or access to financial resources to cope with an increasingly difficult economic situation. In other areas, such as the GOM and SE USA, where storms and hurricanes have severely disrupted or destroyed the infrastructure necessary to support fishing in the recent past, insurance is more readily available in the harvest and post-harvest sectors. However, although fishers in these areas are generally insured, the recovery is often a slow process, having to settle insurance claims before the repair and restart of fishing operations.

The ability of fisherfolk to cope with climate change depends on a variety of factors including the existing cultural and policy context, as well as socio-economic factors such as social cohesion, household composition, gender, age, and the availability and distribution of assets and economic alternatives. In the Caribbean area whilst men typically dominate the harvest sector, women play a critical role in the post-harvest sector in fish processing and trade and also in ancillary activities, such as financing (McConney, Nicholls and Simmons, 2013). As such, in this area as well as the North Brazil LME, women will be the most disadvantaged by the negative impacts of climate change in the post-harvest sector.

9.4.3 Economic

As fish resources in the WCA become less available and the CPUE decreases (resulting in lower profits), and more high intensity storms occur in the coming decades (resulting in higher risks), investments in the fisheries sector will become less attractive in this region (Monnereau and Oxenford, 2017). Climate change has the potential to impact the fisheries sector at the national level in the WCA through various pathways, for

[2] 10 Oct 2017. FAO assesses the impact of Hurricanes Irma and Maria on agriculture sector in Antigua and Barbuda, Dominica and St. Kitts and Nevis. http://www.fao.org/americas/noticias/ver/en/c/1043252/

example, by alterations in revenues for governments as a result of changes in total fish production volumes available for the local and export markets; changes in the ability of nations to achieve food security; and the necessity to make changes to fisheries policies and legislation. The impacts of these on economic development can be expected to differ by country, especially given the diversity of countries in this region (from some of the world's richest to poorest). For example, changes in availability of high-value species that support export-oriented fisheries will impact export trade volumes and national economies (especially in the SIDS). High value species that are not exported are generally sold directly to high-end markets such as hotels and restaurants supporting the local tourism industry. With the expected decline in availability of these resources, the tourism sector will have to look for alternatives, possibly driving up market prices of species consumed by the local population. Alternatively, more fish will have to be imported to satisfy tourist demand, in a region that is already importing most of the fish consumed. For example, the Caribbean region is currently a net importer of fish with an astounding USD 8.5 billion deficit between exports and imports of fish products to the region (FAO, 2016b). Decreases in foreign exchange for countries because of declining exports of high value fish species could thus have implications for a country's food import bill, an important issue especially for many SIDS with little available land for local food production. Processing plants relying on local fish resources will be affected by decreasing sales unless they invest in developing more value-added products, which will in turn have implications for local employment opportunities, particularly for women.

9.4.4 Fishery management

Fish resources in this region are typically transboundary and shared among multiple nations over short distances (especially in the North Brazil and Caribbean LMEs). Climate-induced changes to their distribution and abundance could therefore impact fisher access under current management arrangements, and may require changes to multi-lateral or international agreements and quotas. For example, changes in distribution of tunas and tuna-like species as a result of rising SSTs and changes to ocean circulation patterns, could lead to a need for renegotiating ICCAT quotas among member states (Mahon, 2002). On a smaller regional scale, change in the abundance and/or distribution of flyingfish (*Hirundichthys affinis*), a key fish species in the Eastern Caribbean, which may be occurring as a result of the climate change related influxes of sargassum to the area (Franks, Johnson and Ko, 2016), could affect the relevance of limit and target reference points agreed to in the recently adopted Eastern Caribbean sub-regional Flyingfish Management Plan. Likewise, the recent influxes of sargassum have raised concern about the large numbers of small juvenile dolphinfish that are now being caught by pelagic fleets in the Lesser Antilles, which has highlighted the need to agree upon and impose a minimum legal size for dolphinfish in this subregion (Monnereau and Oxenford, 2017).

Reduced availability of fishery resources will increase fisher competition resulting in increased levels of conflict and the likelihood of increased illegal, unreported and unregulated fishing, requiring management interventions and improved surveillance and cooperation between nations. There is also likely to be an increasing level of tension between different stakeholder groups using marine space and resources for different purposes. For example, climate change could exacerbate existing conflicts between extractive and non-extractive user groups requiring policy decisions on how resources are to be shared among groups and on new regulations to control access.

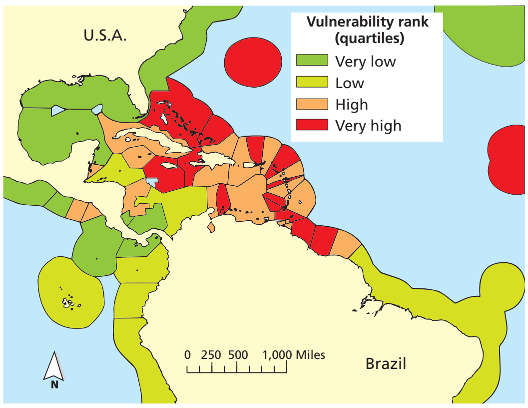
The effectiveness of management regulations such as closed areas and seasons, gear limitations, and minimum sizes may be affected by climate change impacts. For example, closed areas (fishery reserves, marine protected areas) may currently be protecting spawning stock biomass of important commercial species, or critical locations such as nursery grounds, fish spawning aggregation sites (SPAGS), regions that feature high species diversity or high rates of endemism, and areas that contain a variety of habitat types in close proximity to one another. However, under climate change, the locations and/or ecological health of these critical areas are likely to shift, highlighting the importance of integrating climate change projections with management measures. For example, the location of protected multispecies SPAGS located along the Mesoamerican barrier reef and other islands in the Caribbean might need to be revised (Erisman and Asch, 2015). Likewise, the timing of closed seasons implemented to protect the main spawning period for many other species throughout the WCA (e.g. conch, lobsters, groupers, snappers) are likely ultimately to need changing to match expected changes in their phenologies. Expected climate-induced changes in genetic connectivity of stocks, particularly the reef-associated group, could also impact the effectiveness of current marine reserve networks across the WCA in protecting source populations. This will need addressing to ensure their continued value in conservation of spawning stock biomass of commercially valuable species.

Climate change is expected to increasingly exacerbate the ongoing decline of fish resources in the region, caused largely by overfishing and degradation of the marine environment. With close to 60 percent of commercially important stocks already collapsed or overfished in the Caribbean, North Brazil and SE USA LMEs (Table 9.1), there is clearly a need for more effective and flexible fisheries management and fisheries policies in the region, that take climate change impacts into consideration.

9.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES

The impact of climate change in the WCA is expected to be considerable because of its high level of exposure to climate change variables, the high economic dependence on the fisheries sector, and the low adaptive capacity of many of the countries in the region (Monnereau *et al.*, 2017). This is especially true for the Caribbean SIDS because of their specific characteristics such as small size, susceptibility to natural disasters, vulnerability to external shocks, concentration of population and infrastructure in the coastal zone, high dependence on limited resources including marine resources; fragile environments, and excessive dependence on international trade (Nurse *et al.*, 2014; Monnereau *et al.*, 2017). Monnereau *et al.* (2017) in their recent assessment of climate change vulnerability of the fisheries sector at the national level across 173 countries (based on 35 indicators including exposure, sensitivity and adaptive capacity) revealed that the fisheries sector in SIDS, especially within the Caribbean, and the North Brazil shelf area, is extremely vulnerable to climate change (Figure 9.3).

FIGURE 9.3
Vulnerability assessment of the fisheries sector to climate change for the Western Central Atlantic based on 35 indicators. Each country is delimited by its EEZ boundary. Colours represent relative vulnerability ranked across 173 countries



Data sourced from: Monnereau *et al.* (2017).

9.6 RESPONSES AND ADAPTATION OPTIONS

Responses and adaptation actions to moderate the actual and potential impacts of climate change, and to take advantage of new opportunities will need to be tailored to national contexts. With regard to the fishery sector, countries in this region are generally focusing on adaptation through reducing risks from climate change and natural hazards, and improving resilience of fisherfolk and aquaculturists (see detailed assessment of the wider Caribbean region by McConney *et al.*, 2015). Here we present some examples of national and local level adaptation measures that have been recommended or are already taking place in the region.

At the national level, adaptation activities within the framework of the international climate change regime (the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement) are set out in countries' five-year Nationally Determined Contributions (NDCs). Within the WCA 24 independent nations have submitted NDCs of which 14 (mostly the Caribbean SIDS) specifically mention the fisheries sector, but mostly only in the context of highlighting its vulnerability to climate change. Only two of these countries make specific reference to fisheries in terms of mitigation, although ten countries list some aspect of fisheries within their stated adaptation plans. Proposed actions include: general improvements in fishery habitats (through implementation of marine protected areas, rehabilitation of mangroves, seagrasses and coral reefs; improved environmental impact assessments; and integrated coastal zone management); paying greater attention to the role of fisheries in food security; implementing updated fishery legislation; and considering alternative livelihood opportunities. Only in a few cases are concrete and specific measures listed such as provision of affordable insurance schemes for fishers (in Dominica, and Antigua and Barbuda). In several NDCs the need for additional (international) financing is highlighted, as well as the need for technical support, including capacity building and technology transfer in order to carry out the mitigation and adaptation measures. Further, there is no specific mention of the fisheries sector in the nationally appropriate mitigation actions prepared and submitted to the UNFCCC by six of the developing nations within the WCA, nor in the very few national adaptation plans.

Factors that can influence the success of adaptation include raising awareness of climate change impacts on the fisheries sector and coastal communities, as well as awareness on possible adaptation measures for the fisheries sector. Better communication and information sharing on these issues can, and in some cases already has, fostered innovative solutions and development opportunities within the sector. Other factors affecting success include capacity building activities through training and education which empower local stakeholders and facilitate collective self-governing action (e.g. by fisherfolk organizations). Mainstreaming climate change adaptation (CCA) and disaster risk management (DRM) into new or improved fisheries legislation, policies and plans is also important (McConney *et al.*, 2015).

A select number of adaptation measures which are already taking place or currently being developed in the region are summarized here. These activities include anticipatory and reactive measures as well as private and public initiatives, and are grouped here under three broad categories.

9.6.1 Innovation and capacity building

- Development of innovative context-appropriate mobile applications designed to improve early warning and safety of small-scale fishers with regard to approaching storms and hurricanes *inter alia*, as well as improving responses to crisis (e.g. training in methods of recording of damage and losses post-disaster).
    - An example of this is the award-winning, open source "mFisheries" suite of applications, developed by The University of the West Indies in collaboration with the local fisher community, specifically for smartphone use by SSF in

Trinidad and Tobago[3]. This suite has now been tailored for Eastern Caribbean fishers under the climate change adaptation in the Eastern Caribbean Fisheries sector (CC4FISH) project, and Fisheries Early Warning and Emergency Response (FEWER) modules have recently been developed under the Pilot Programme for Climate Resilience (PPCR) project.

- Improvement in adaptive capacity and resilience of the fishery sector to climate change through improved safety, improved earnings and savings, and better access to assets insurance and social security.
  - There are many examples of successful hands-on training courses being provided to SSF across the WCA by various international and regional non-governmental organizations (e.g. FAO-WECAFC, CRFM), Caribbean Natural Resources Institute, Gulf and Caribbean Fisheries Institute, Caribbean Network of Fisherfolk Organisations). These have included sponsored courses in: improved safety-at-sea; design of safer fishing vessels; use of tracking devices; improved fish handling; value-added processing; and developing business skills (see McConney *et al.*, 2015; Monnereau and Oxenford, 2017).

9.6.2 Improving physical environment

- Investments in safer harbours and boat hauling sites as well as other climate-smart fisheries infrastructure to protect fisheries assets and prevent disruption in the fisheries market chain.
  - Examples of investments in purpose-built safer harbours for SSF in the region include the Bridgetown Fisheries Complex in Barbados, Grand Riviera fishing harbour in Martinique, Marigot Fisheries Complex in Dominica, and Basseterre fishing harbour in Saint Kitts all of which have substantive harbour walls and haul-out facilities. However, in all cases the facilities are not adequate for the entire fishery fleet. For example, limited access to sufficient safe harbour space and hauling sites was a key factor resulting in USD 2.9 million in damages and losses to the fisheries sector (mostly boats and engines) in Dominica with the recent passage of Hurricane Maria in 2017 (Government of Dominica, 2018).
- Mitigation of local-level, human-induced stressors that are degrading critical fishery habitats, and rehabilitation of damaged coastal ecosystems (e.g. coral reefs, seagrasses, mangroves and saltmarshes) to improve their resilience to future climate change and maintain their natural ecosystem services.
  - There are many small and large initiatives across the region that are relevant to these challenges. For example the Caribbean and North Brazil Shelf Large Marine Ecosystems (CLME+) 10-year strategic action plan politically endorsed in 2017 by 25 countries and six overseas territories across the Caribbean Sea and North Brazil LMEs outlines many actions to address the three key threats identified for these LMEs (unsustainable fishing, habitat degradation and pollution) and their root causes, along with climate change[4].
  - Another example is the Caribbean Challenge Initiative (CCI), a long-term, public-private partnership presently covering nine Caribbean countries, which has at its core, two time-bound "20 by 20" goals to: 1) effectively conserve and manage at least 20 percent of the marine and coastal environment by 2020, and 2) achieve by 2020 fully functioning sustainable finance mechanisms to provide long-term and reliable funding for the CCI in each participating country[5].

[3] http://www.cirp.org.tt/mfisheries
[4] https://www.clmeproject.org
[5] http://www.caribbeanchallengeinitiative.org

9.6.3 Mainstreaming climate change

- Mainstreaming climate change through incorporation into fisheries and coastal development policies, plans and legislation to improve the effectiveness of reducing climate change impacts on the fishery sector.
  - There are a number of regional examples of on-going efforts in this regard, such as the comprehensive 2013 to 2021 CRFM-FAO strategy and action plan for *Climate change adaptation and disaster risk management in fisheries and aquaculture in the CARICOM and wider Caribbean region* (McConney *et al.*, 2015). Under the 2017 to 2020 FAO CC4FISH project seven countries are receiving support to put mainstreaming of climate change in fisheries policies, plans and legislation into practice. This is intended to strengthen regional and national cooperation and develop capacity to address climate change impacts and disasters in the fisheries and aquaculture sector (particularly on SSF and small-scale aquaculture). This also includes development of a protocol to integrate CCA and DRM into the Caribbean Community Common Fisheries Policy, and ensure integration at all points in the fish chain (McConney *et al.*, 2015).
  - In the United States of America (covering much of the GOM and SE USA shelf LMEs) the NOAA Fisheries Climate Science Strategy was developed in 2015 to help reduce impacts and increase the resilience of the valuable living marine resources, the people, businesses and communities that depend on them, through increased production, delivery and use of climate-related information using a nationally consistent blue-print (Link, Griffis and Busch, eds., 2015).

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Chapter 10: Climate change impacts, vulnerabilities and adaptations: Northeast Tropical Pacific marine fisheries

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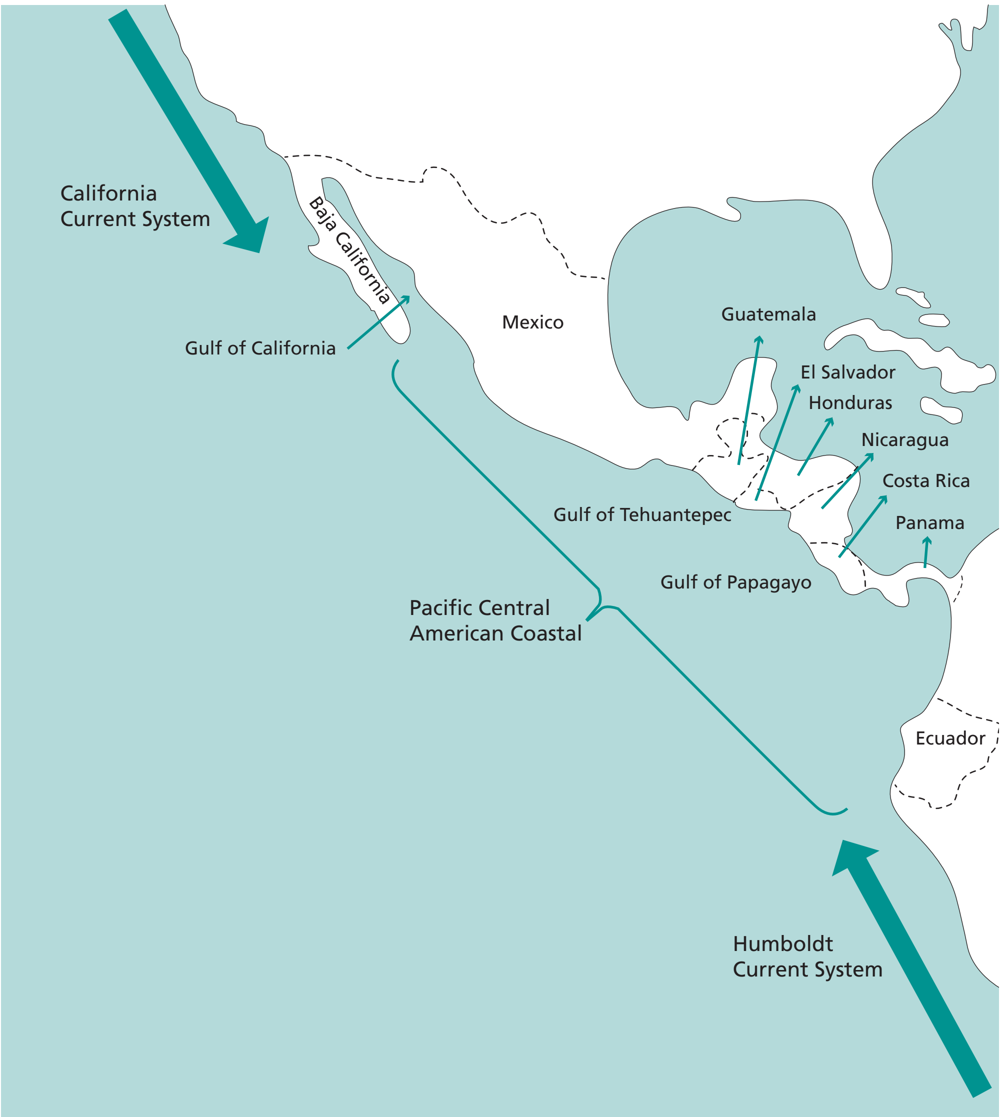
KEY MESSAGES

- Projections of climate change for the region are uncertain in comparison to other regions, particularly regions in higher latitudes.
- Ecosystem impacts:
    - In the extratropical extremes, off Baja California and Ecuador, the major process determining the ocean dynamics is coastal upwelling, for which strong debate exists on how it may respond to climate change.
    - Major threats for the Gulf of California appear to be ocean acidification, hypoxia and harmful algal blooms.
    - In the Pacific Central American Coastal large marine ecosystem (LME), high sensitivity to climate change is related to coastal ecosystems' degradation.
    - Overall, impacts are expected from poleward species shifts and local extinctions, expansion of the globally largest oxygen minimum zone, and coral reef communities suffering from ocean acidification.
- Impacts on fisheries:
    - For small pelagics, interannual changes and multi-decadal trends will likely continue to be the dominant drivers of this fishery during this century.
    - Squid fisheries can be expected to be episodic and opportunistic, with high variability in abundance and availability, which limits the possibility of building long-term sustainable industries based on this group.
    - Although highly uncertain, latitudinal distribution shifts in tuna may affect industrial and coastal fisheries.
    - Impacts in shrimp fisheries may be positive because of better recruitment.
    - Even when small-scale multi-specific fisheries can rapidly adapt to available resources, many of the species on which they depend are highly vulnerable because of critical habitat degradation (coral reefs, mangroves, and saltmarshes).
- Adaptation options for the fisheries sector include improving research, management, planning and policy frameworks (including related technical, administrative, organizational adaptive capacities, and communication). For example:
    - Modelling-based projections should incorporate historical patterns of fisheries and climate variability, and better data.

- The fishing industry may partially cope with climate change by developing sustainable new fisheries, particularly aimed at deep- and mid-water unexploited fish and crustaceans.
- Other actions that would help reduce risk in fisheries would be the full implementation of the *FAO code of conduct for responsible fisheries*, *the Voluntary guidelines for securing sustainable small-scale fisheries*, and the establishment of information systems aiming to provide early warning of market price volatility.
- Aquaculture as an adaptation option for the region's economy and food security depends on technology development that allows for change between farmed species, the adequate use of genetically improved and robust organisms, and adoption of energy and carbon efficient practices.

FIGURE 10.1
The Northeast Tropical Pacific region and the LMEs falling within it



10.1 INTRODUCTION

10.1.1 The Northeast Tropical Pacific

A total of nine nations share the Northeast Tropical Pacific (NETP) region: Ecuador, Colombia, Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala and Mexico (see Figure 10.1). While this includes fewer nations than some other regions included in this volume, observed and projected climate trends and their impacts are diverse, partly because of the different potential responses of the main regional oceanographic processes to climate change but also because of the substantial differences in ecological and fisheries-derived characteristics. Based on the analysis of the variability in sea surface temperature, chlorophyll concentration, primary productivity, and fisheries-derived ecological indices, Muller-Karger *et al.* (2017) found strong dissimilarities between the LMEs along the Eastern Pacific (California Current, Gulf of California, Pacific Central American Coastal, and Humboldt), not only in the physical setting, but also in species composition of fisheries landings and the human-related ecological pressures. An implication of this heterogeneity is that information should be disaggregated for, at least, the major subregions to better inform managers and stakeholders about potential impacts, vulnerabilities, and opportunities for mitigation and adaptation.

Multi-annual predictive skills in climate models largely depend on the model capacity to capture accurately the internal (local to regional) features and the external forcing (boundary conditions). For some regions of the world, such as the North Atlantic and the Southern Ocean, forecasts of multi-annual temperature trends have already proved useful for decision-making, even promising at the decadal scale (Tommasi *et al.*, 2017). For the Eastern Pacific, forecasting is intrinsically more limited because of the dominant atmospheric forcing and the timescales at which many of the ocean processes occur. The region is strongly affected by the El Niño-Southern Oscillation (ENSO; for which interannual predictability is very low), but also by extratropical activity from the North Pacific and Atlantic Oceans, and local-to-regional dynamics. In addition, ocean monitoring and large-scale studies are scarce and mostly based on satellite imagery analyses. One major implication is that climate change projections for the NETP are largely uncertain.

10.1.2 Fisheries of the region

The marine fisheries in the NETP include a high diversity of species, fleets and fishing gears; as a consequence of which, societal impacts are also diverse. Small pelagics caught include sardine (*Sardinops sagax*), tropical oil sardines (*Opisthonema libertate, O. bulleri, O. medirastre, Scomber japonicus, Etrumeus teres, Cetengraulis mysticetus, Oligoplites saltus, O. refulgens, O. saurus*), anchovy (*Engraulis mordax*), etc. Most of the production takes place in the upwelling areas of Ecuador and the west coast of Baja California, and inside the Gulf of California, and is caught by industrial fleets, but coastal fisheries resources are also targeted by artisanal fishers. The historical annual maximum production, just for sardine in the Gulf of California, was over 500 000 tonnes in 2008, and over 1.2 million tonnes in Ecuador in the mid-1980s. Jumbo squid (*Dosidicus gigas*) and octopus (*Octopus vulgaris, O. hubbsorum, Octopus* spp.) production exceed 41 000 tonnes per year, over 80 percent of this being jumbo squid. The fishery for this species occurs in oceanic waters, and vessels are adapted from the industrial fleet (for example shrimp trawlers), but an opportunistic coastal fleet also has a prominent and sometimes massive participation that follows pulses in abundance of the resource. Shrimp (predominantly *Farfantepenaeus* spp., *Litopenaeus* spp., *Solenocera* spp., *Sicyonia* spp., but also *Xiphopenaeus* spp., *Trachypenaeus* spp., *Heterocarpus* spp.) is important in seven countries; with a combined average annual catch close to 60 000 tonnes, with most of the production (over 80 percent) coming from the Gulf of California and Gulf of Tehuantepec, both in Mexico. Shrimp fisheries are usually sequential and multi-specific, and take place on the continental shelf near the coast, where industrial and small-scale fleets coexist.

Tuna fisheries (over ten different species) are important for all the countries in the NETP. In recent years, the average yearly production in the region has been around 140 000 tonnes. The largest catches are obtained by industrial fleets operating in oceanic waters, using both seines and longlines, but there are also continuous small-scale operations along the coastlines of the different countries. In general, it is estimated that resource exploitation remains at levels close to the maximum sustainable yield. Sharks; mostly families Carcharinidae (*Carcharinus falciformis, C. limbatus, Prionace glauca,* among others) and Sphyrnidae (*Sphyrna mokarran, S. tiburo, S. lewini*), and rays represented by the orders Squantiniformes (*Squatina califórnica*), Squaliformes (*Echinorhinus cookie*), Hexanchiformes (*Hexanchus griseus*) and Pristiphoriformes (*Pristis perotteti*) (34 000 tonnes), lobster, mainly spiny lobsters (*Panulirus interruptus, P. gracilis, P. inflatus, P. penicillatus, P. argus*); but also other species of Scillaridae (2 744 tonnes), and miscellaneous coastal pelagic fish (52 000 tonnes), are reported as relevant resources in six countries. Other resources such as snappers, mainly genus *Lutjanus* spp. (11 500 tonnes) and various crabs (*Cancer* spp., *Callinectes* spp.) (9 000 tonnes) are relevant in five countries; while molluscs such as gastropods (several genera and species including *Haliotis* spp., *Strombus* spp.) (12 000 tonnes), and bivalves (several families and species, including *Crassostrea virginica, Mercenaria mercenaria, Mya arenaria, Mytilus edulis; Chione* spp.) (9 000 tonnes), and several species of Sciaenids (10 000 tonnes), are relevant in four countries. Other resources considered important in three or less countries are groupers (family Serranidae, mostly *Epinephelus* spp.) (6 500 tonnes), king crab (*Paralithodes* spp.) (5 900 tonnes), sea cucumbers (*Strongylocentrotus* spp.) and other echinoderms (3 700 tonnes), flatfish (several species of the families *Paralichthyidae, Pleuronectidae, Bothidae, Achiridae, Soleidae* and Cynoglossidae) (3 400 tonnes). Catches of the rest of the fisheries are highly multi-specific and carried out by artisanal, small-scale fleets, with different degrees of technological sophistication. In some countries, billfish (*Xiphius gladius, Istiophorus platypterus, Makayra indica, M. nigricans, Kajikia albida, Tetrapturus pflugeri*) (2 300 tonnes) are of great importance for sport fishing, and in some cases also for commercial longline fleets.

In essence, all the above fisheries are subject to some type of control, which varies according to the type of resource but are mostly traditional strategies such as temporal or spatial closures, limited access and quotas. Fishing reserves have recently started to be incorporated. Some resources are considered over-exploited; however, most of the conventional resources in this region are considered fully exploited (FAO, 2016a). In general, all fisheries retain large (e.g. shrimp trawl) or small (e.g. squid) degrees of bycatch. In some cases, these bycatches include threatened species (e.g. sea turtles). Regulations around this issue depend on the target and bycatch species, and the existing scientific knowledge. In some cases, such as tuna purse seiners, gillnets, and shrimp trawls, regulations have succeeded in reducing mortality of threatened species; while for cases such as the fishery for Totoaba (a species of corvina –family Sciaenidae-endemic to the upper Gulf of California), greater efforts are still needed.

The fishers are organized in three general models: individuals, cooperatives and private companies, the latter generally associated with industrial development. Governance in the fisheries sector in the Latin American countries is institutionally organized within the central government. Ministries are responsible for decision-making, and in some cases are supported by a different governmental institution providing technical and scientific knowledge to support the decisions, and defining instruments for regulation and control. These entities are also responsible for implementing control and surveillance actions. In some countries, such as Costa Rica, Ecuador and Mexico, non-governmental conservationist entities interact intensively with the production sector and with government entities, and in some systems assume a bridging role between government and producers. Internationally, the creation of the Central America Fisheries and Aquaculture Organization (OSPESCA) stands out, and established, through the Fisheries and Aquaculture Integration Policy in the Central American Isthmus, a regional framework for fisheries development planning. Highly migratory species, particularly tuna, are evaluated and managed by the Inter-American Tropical Tuna Commission (IATTC).

10.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT

The region includes the extratropical Eastern Boundary Currents: the California Current System (CCS) in the north and the Humboldt Current system in the south, both mostly dominated by wind driven coastal upwelling; the Gulf of California, an enclosed sea hosting a large portion of the total Mexican fisheries production (both in volume and value) and the region from the southern part of the Gulf of California to Colombia (the Pacific Central American Coastal LME), where a warm and relatively low productivity coastal system coexists with a highly seasonal group of ocean enrichment systems off the Gulf of Tehuantepec (Mexico), Papagayo (Costa Rica), Panama, and the Costa Rica Dome.

Temperature trends are diverse through the NETP, with the strongest warming occurring off Central America (Lluch-Cota *et al.*, 2013), where several components of the biological communities are already exposed to suboptimal conditions. Hypoxia represents a major issue, as the oxygen minimum layer, lying between the pycnocline and intermediate waters, is remarkable in this region for its size and degree of hypoxia (Fiedler and Lavin, 2017). Ocean acidification may also represent a reason for concern, as projections reveal this is one of the regions more rapidly reaching aragonite limitation for coral reef development under future scenarios. Other indirect effects, such as reshaping of ecosystems and food webs may also prove important.

In the extratropical extremes, off Baja California and Ecuador, the major process determining the ocean dynamics, including surface temperature, oxygen, pH, and primary productivity, is coastal upwelling. Despite being of major scientific interest today, there is still strong debate on how this process might respond to climate change. At the global scale, ocean stratification has increased as a result of the gain of heat in the surface layer, resulting in more wind energy being required to bring deep waters to the surface through upwelling. However, some evidence indicates that wind strength is increasing, at least in some of the major coastal upwelling systems, as a result of the differences in warming rates between land and ocean (Bakun, 1990). Whether wind stress can offset the increased stratification is of paramount importance when projecting climate change impacts in these highly productive systems.

Increased upwelling is expected to enhance primary productivity, and therefore the food that is available to fish. However, the export of organic material from the surface to deeper layers may increase microbial activity and oxygen depletion. Once this water returns to the surface through upwelling, benthic and pelagic coastal communities could be exposed to acidified and deoxygenated water, which would affect marine biota and the ecosystem structure of the upper ocean. Shelf hypoxia conditions have been well documented for some upwelling systems, including the CCS, and even blamed as the potential mechanism shaping the dynamics of the small pelagic species (Bertrand *et al.*, 2011). Another scenario could be that increased primary productivity could sequester carbon and export it to other regions through direct advection and through the movement of pelagic fauna. On the other hand, decreasing upwelling activity would directly limit the productivity of important fisheries, such as small pelagics.

Within the Gulf of California, a positive but slow, long-term warming trend has been reported for the twentieth century. However, when looking only at the last 50 to 60 years, during which time the global surface air temperature series shows the fastest increase, no significant warming trend can be detected and, in fact, the slope is negative (Lluch-Cota *et al.*, 2010). Further, paleo-reconstructions have shown that wintertime temperatures have been similar during the last 170 years. In addition, annual temperature amplitude is highly variable between years, with changes occurring everywhere in the Gulf except for the region around the Midriff Islands. Statistical relationships between these variations in annual amplitude and climate signals have proved to be significant only in ENSO-related processes. Ocean circulation models at the scale of the Gulf, forced with downscaled Intergovernmental Panel on Climate Change (IPCC) scenarios, have resulted in very small differences between future and present conditions, and much smaller than those observed during interannual (ENSO-like) events. Therefore, it can be argued that with the currently existing observations and models, no reliable long-term projection of climate change can be proposed for the Gulf of California, and temperature trends do not show evident threads for the Gulf ecosystem so far.

No reports on acidification of the Gulf of California region exist; however, potential impacts of such a trend, if there is one, could be highly relevant as the region is located at the boundary of aragonite saturation levels, and most of the reefs have been classified as existing within marginal environmental conditions. Therefore, for all the ocean acidification projections based on IPCC scenarios, the Gulf of California is found outside of the suitable habitat. Another reason for concern in this subregion is oxygen. Despite there being very little data, observations of hypoxic or nearly anoxic environments in very shallow water in the southern gulf (less than 100 m depth), and observations of the oxygen minimum zone off the coast of Sinaloa being totally devoid of benthic macrofauna, suggest this may become a critical issue under climate change conditions. Further, massive mortalities of marine organisms inside the Gulf have been associated with harmful algal blooms, and evidence exists from at least one long-term observation effort that the number of toxic species and the frequency and duration of events are increasing.

The major issues in the Pacific Central American Coastal (PCAC) region are closely related to degradation of coastal ecosystems arising from habitat use for aquaculture, tourism, urbanization, pollution, run-off from urban and agricultural lands, and deficient fisheries management. These factors have already increased the sensitivity of the region to climate change related stressors. Biological communities are highly diverse, most fisheries are multi-specific and data deficient, and long-term observations and modelling capabilities are no better than those described previously but, because of its properties, some issues can readily be considered reasons for concern.

The PCAC region exhibits large interannual variability in surface temperature, winds, and thermocline structure. Decadal scale variability is less easily detected, but is evident in some variables, especially those related to the offshore winds at Tehuantepec, Papagayo, and Panama. Long-term climate change can also be detected; over the last century, sea surface temperature has increased by close to 1 °C, and warming is expected to continue, increasing by around 2 °C for a doubling of atmospheric CO_2 (Fiedler and Lavin, 2017); according to the A2 scenario of the IPCC, this two-fold increase could be reached by the year 2080 (Portner *et al.*, 2014). Model projections suggest a shallower but steeper thermocline in the future and, with the increase in stratification, nutrient enrichment of surface waters and phytoplankton production are expected to decrease. Climate change is expected to drive indirect changes in biological communities as a result of poleward shifts in species' distributions and local extinctions, mostly linked to temperature changes. Observations and models are consistent in these trends, more noticeably in the Western Tropical Pacific, but still worrisome for the PCAC.

Surface waters above the pycnocline tend to be nearly saturated with dissolved oxygen. However, off the PCAC, oxygen levels between the pycnocline and intermediate waters are very low, shaping one of the largest and more intense oxygen minimum zones in the world's oceans. Observations indicate that these zones have expanded vertically during the past 50 years, and climate models generally predict further expansion (Fiedler and Lavin, 2017). Great concern exists on the potential impacts for coastal ecosystems.

Another major threat in the subregion is ocean acidification. Today, the lowest surface pH values in the world are now found in the Eastern Tropical Pacific (Fiedler and Lavin, 2017). Further climate change and ocean acidification are expected to impact the reefs in the subregion negatively, as they are already at the environmental limits for reef development.

10.3 EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING THE MAIN FISHERIES

Large-scale models projecting the impacts of climate change in catch potential, mostly based on temperature, oxygen limitation and primary productivity, and neglecting possible synergistic effects of ocean acidification and fishing effort, have shown a reduction of the catch potential in most of the tropical oceans (Pörtner *et al.*, 2014; see also Chapter 4); however, the magnitude of the reduction is less in the NETP than in most of the tropics.

Small pelagic fishes (i.e. sardines and anchovies) captured mostly in upwelling regions off Baja California, Ecuador, and the Gulf of California, are known to react quickly to changes in the ocean climate, showing particularly notorious fluctuations at multi-decadal scales. Regarding temperature, future climate change scenarios have been used to predict a drop of 35 percent in catches of sardines and an increase of anchovy, or increased sardine abundance because of warmer conditions in the California Current. However, ecological change affecting small pelagic species may also include changes in productivity and composition of lower trophic levels, distributional changes of marine organisms, and changes in circulation and their effects on recruitment processes. Further, particularly for the fish populations off the southern NETP, oxygen limitation has been proposed to strongly influence the pelagic ecosystem shape, which is particularly relevant given that the distribution of oxygen in the ocean is changing with uncertain consequences. Other type of models that incorporate historical variability of the environment and catches, indicate that regional climate scenarios would modify slightly the fishery catches and seem unlikely to cause foreseeable breakdowns of natural cycles. These results therefore suggest that as long as no dramatic inflection point is reached in climate, interannual changes of both species and multi-decadal trends will likely continue to be the dominant drivers of this fishery during the current century (Lluch-Belda *et al.*, 2013).

The squid fishery is relatively new in Mexico and only starting in Ecuador, and therefore there is limited knowledge on its long-term dynamics. Evidence indicates that jumbo squid can dramatically and extremely rapidly change its latitude distributions. At the same time, it is very plastic in terms of diet, respiration, vertical distribution (even through the oxygen minimum zone), and reproduction, which makes it a highly resilient group to changing environment. However, this same ability to change distribution and habits makes the fishery highly unpredictable. The expected impacts of climate change could therefore be the episodic development of opportunistic fisheries, with reduced possibilities to build around long-term sustainable industries.

For tuna and tuna-like fisheries, impacts of climate change have been proposed to be similar to those observed during some of the El Niño events, although this is highly uncertain. Divergent responses of yellowfin tuna catches at different locations show that the principal impact of ENSO on tunas is on their regional redistribution.

The warming of surface waters and the decline in primary productivity could result in a redistribution of tuna resources to higher latitudes or areas where the ocean productivity has been less or not affected. This could result in changing migration patterns, forming more dispersed and less numerous schools, which would negatively affect fishing operation costs and yields.

Impacts on shrimp fisheries are also uncertain. In general, warmer waters and increased rainfall during warm events (i.e. El Niño) favour the reproduction and recruitment of shrimp populations, and fisheries are favoured. There could also be some degree of poleward expansion into more productive systems. The ways in which fisheries operate would change, such as bycatch reduction, sharing catches between industrial and artisanal fleets, among others, but these have not been analysed.

Small-scale, coastal multi-specific fisheries could be seen as highly resilient, because they can rapidly adapt to changing target species, market preferences, and location of new fishing banks. Furthermore, redistribution of fishing camps may be faster and easier than relocation of large-scale industrial fisheries infrastructure. However, these small-scale fisheries are highly sensitive because many of the most important species are more or less dependent on coral reefs, mangroves, and seagrasses, which are vulnerable and in some cases already threatened ecosystems. Also, non-industrialized fishers are more closely dependent on short-term income, their capacity to influence markets is more limited than well-organized, large-scale industries, and management and enforcement are more complex.

10.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

At the local to regional levels, an important segment of the societies from the nine countries is highly dependent on fisheries. Industrial fisheries represent, for some regions, a major economic activity and impacts of climate change could affect these industries. However, by far the largest number of people dependent on fish is located in the small-scale fisheries, which is also a more sensitive sector because of higher poverty levels, and reduced access to alternative economic activities.

Poverty undermines the resilience of social-ecological systems such as fisheries. A combination of climate-related stresses and widespread over-exploitation of fisheries reduces the scope for adaptation and increases risks of stock collapse (Allison, Beveridge and van Brakel, 2009). It is clear that fishing pressure has already imposed significant problems on several coastal multi-specific fisheries across the NETP countries, mostly because management faces serious limitations in terms of technical information and permanent, reliable monitoring programmes. In addition, the management strategies are much less developed than those for industrial fisheries, and the lack of communication, enforcement, and potential for participation in co-management schemes make the adoption of such strategies by small-scale fishers virtually impossible.

Adaptive institutions and new management strategies would increase the capacity of ecosystems and people to accommodate future changes and conditions. Strengthening adaptive governance and reducing vulnerability are both mutually reinforcing and synergistic with building capacity to adapt to climate change. Adoption of better management practices, including increasing technical and scientific capacity, communication and participatory strategies, and strengthening institutional arrangements, are the best adaptation options for small-scale fisheries under a changing climate. These and other adaptation options are discussed further in Section 10.6 below.

10.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES AND THOSE DEPENDENT ON THEM

The region includes the Pacific coast of Ecuador, Colombia, Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, and Mexico, covering 35° in latitude, three large marine ecosystems, and tropical and subtropical climatic regions. Most important industrial fisheries target small pelagics, mostly sardines and anchovies, jumbo squid, tuna, and shrimp. Small-scale fisheries occur along the entire coast, partly based on the same resources exploited by industrial fleets, plus a high diversity of fish, molluscs and crustaceans.

Large-scale models projecting the impacts of climate change in catch potential have shown a reduction of the catch potential in most of the tropical oceans, with a relatively smaller reduction in the NETP (Cheung *et al.*, 2009; Pörtner *et al.*, 2014; Chapter 4). However, this is one of the world ocean regions where climate and oceanographic models are more limited, and therefore climate change projections are highly uncertain. Also, the diversity of species and fisheries makes it impossible to make a single, general assumption on the potential effects of climate change on regional fisheries. Modelling-based projections should incorporate historical patterns of fisheries and climate variability, and better data.

Major environmental reasons for concern are 1) temperature trends, particularly off Central America; 2) deoxygenation, as the region already lies within the largest area of the world ocean with severe hypoxia; and 3) ocean acidification, as projections reveal this is one of the regions more rapidly reaching aragonite limitation for coral reef development under future scenarios. Potential impacts on major fisheries are: for small pelagic fishes, interannual changes and multi-decadal trends which will likely continue to be the dominant drivers of this fishery during the remainder of this century. Squid fisheries can be expected to be episodic and opportunistic fisheries, with reduced possibilities to develop long-term sustainable industries. Although highly uncertain, latitudinal distribution shifts in tuna may affect industrial and coastal fisheries, and impacts on shrimp fisheries may be positive thanks to better recruitment.

Although small-scale fisheries may appear to be relatively resilient because they can rapidly adapt to changing target species, market preferences, and location of new fishing banks, major consequences for livelihoods can be expected because many of the targeted species depend on threatened ecosystems (coral reefs, mangroves, and seagrasses), and fishers are more closely dependent on short-term income, their capacity to influence markets is more limited than that of well organized, large-scale industries, and management enforcement is more complex.

10.6 RESPONSES AND ADAPTATION OPTIONS

Fisheries governance and regulations (i.e. harvest control rules and incentives driving fisher behaviour) partly determine the socio-ecological resilience of the sector to climate change impacts. However, there is yet no recipe for a regulatory regime that can clearly increase fisheries resilience (Ojea *et al.*, 2017). For the small-scale fisheries, adaptation options include improving technical, administrative and organizational aspects of fisheries management and the social education of the fishers. This should promote development of organizational mechanisms such as integrating value chains and training for diversifying fishing activities (Flores-Nava, 2010).

To some extent, industrial fisheries have already been dealing with changes in resource availability because of having to cope with natural climate variability. The adoption of policy initiatives and management measures for reducing vulnerability in the fishing sector could benefit from the lessons and strategies learned by fisheries that have successfully managed change by incorporating environmental stress factors into their strategies.

Global circulation models are the only tool that is available today for estimating the effects of climate change on fisheries, so their deficiencies when representing regional processes (e.g. upwelling), reduce the possibility of generating plausible future scenarios of the environment and its influence on fish production. This is particularly critical in this region. Incorporation of historical patterns of fisheries and climate variability, and more intense data collection, including systems for ocean monitoring, could increase significantly the accuracy of climate and ecological models (Lluch-Cota *et al.*, 2017).

In order to sustain economic and social benefits to the fishing industry facing climate change impacts, one option may be the sustainable development of new fisheries based on currently under-exploited resources. This seems feasible in the region because of the existence of known deep and mid-water unexploited populations of fish and crustaceans, such as hake and giant king crab.

In terms of adaptation, the full implementation of the *FAO code of conduct for responsible fisheries* (FAO, 2016b) and the *Voluntary guidelines for securing sustainable small-scale fisheries* (FAO, 2018), may prove to be the best strategy. Precautionary approaches are recommended, particularly measures to reduce levels of fishing mortalities, especially in populations currently at maximum exploitation rates and over-exploited. Moreover, the industrial and coastal fisheries sector is likely to face the challenge of moving from one fishing site to another as well as changing target species. To carry them out successfully, these challenges imply the development of better organizational skills in order not to exceed extraction efforts beyond the stock's replacement capabilities in a changing environment. In addition, national and multilateral agreements enabling the mobility of fleets should be promoted, considering also the legal change of target species, as required, and governmental support for purchasing more efficient equipment.

Another recommendation refers to the establishment of information systems aimed at providing early warnings of volatility in market prices. Market warnings would allow rapid adoption of strategies that may include creating specific funds, extending insurances coverage, incorporating probabilistic analysis to risk management, and considering uncertainty during the planning of the sector's activities.

One major option to mitigate the adverse impacts of climate change on marine fisheries is aquaculture, the fastest growing food production sector and with the potential to contribute significantly to the region's economy and food security. Apart from Ecuador and Northwest Mexico, which host important shrimp farming enterprises, marine aquaculture based on different species still has great development potential in the NETP. However, for aquaculture to become an effective climate change adaptation option, two major challenges should be addressed. One is that reared species, for which technology development may take several years, may face suboptimal physiological conditions under future climate (especially temperature). Secondly, that increasing the use of waterbodies and coastal areas for culture, together with the direct impacts of climate change, may increase the outbreaks of known and new pathogens or parasites. Therefore, the ability to change between farmed species, and the adequate use of genetically improved and robust organisms, should become a major technological priority. Further, to represent a sustainable option for food production, aquaculture will also face the challenge of rapidly becoming a more energy and carbon efficient practice (Sae-Lim *et al.*, 2017) and less reliant on capture fisheries for feed.

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Chapter 11: Climate change impacts, vulnerabilities and adaptations: Southeast Atlantic and Southwest Indian Ocean marine fisheries

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KEY MESSAGES

- Throughout the region, the complexity and high natural variability of marine ecosystems on all scales, aggravated by major declines in some marine resources from over-exploitation, make it very difficult to detect climate change signals against a high noise background.
- The environmental changes over the past few decades for which there is most evidence are increased sea surface temperature in all regions; increased sea level in most regions; a remotely-driven southward (poleward) shift in the position of the Angola/Benguela Front and a poleward shift of the St. Helena Anticyclone; and a recent decrease off Namibia and longer-term increase off the South African south coast in upwelling-favourable winds.
- Hydrobiological changes in the region include a roughly ten-fold increase in copepod abundance in the Benguela upwelling ecosystem since the 1960s and a corresponding change in copepod size structure, both considered a result of changes in predation pressure from pelagic fish. Declines in coral reef and mangrove forest cover off Mozambique and the United Republic of Tanzania have been primarily or partly attributed to climate change.
- The best-documented changes in marine resources in the past few decades have been a southward shift in coastal fish species important to Angola's small-scale fishery, the eastward shift of commercially-exploited small pelagic fish and west coast rock lobster in South Africa, and the poleward (south) shift of several marine and estuarine subtropical species on the east coast of South Africa to an expanding warm–cool transition zone on the south coast.
- The fisheries rated as most vulnerable to climate change in Angola and Namibia were the artisanal and demersal trawl fisheries, respectively, while in South Africa they were small-scale line- and net-fisheries and that for small pelagic fish. No comparable vulnerability assessments have yet been carried out for the marine fisheries in Mozambique and the United Republic of Tanzania, but it seems likely that the large number of artisanal fishers along the coasts of these two countries are the most vulnerable.
- Institutional climate change adaptation measures include creating early warning systems for flooding and storms (Angola); promoting integrated fisheries and

coastal zone management for the protection of marine resources, strengthening of joint management of shared fish stocks (Namibia), expanding and tailoring research and monitoring to inform and assist adaptation initiatives; and involving artisanal and small-scale fishers in local resource co-management initiatives (South Africa, Mozambique and the United Republic of Tanzania).

11.1 INTRODUCTION

This chapter covers the continental shelves of the Southeast Atlantic and South-West Indian Oceans. The region can be very broadly sub-divided into the following oceanographic regimes (Figure 11.1):

- A subtropical zone north of the Angola/Benguela Front, which is essentially a transition zone between the wind-driven Benguela Current upwelling system to the south and the Equatorial Atlantic, from where the seasonal cycle is remotely driven.
- The Benguela upwelling system, which lies roughly between 14 °S and 37 °S and extends in a broad sense to include the western Agulhas Bank, and is divided into northern and southern systems by strong perennial upwelling in the region of Lüderitz, at approximately 26 °S.
- The central and eastern Agulhas Bank on the South African south coast, which has characteristics of both an upwelling and a warm temperate shallow shelf system, and is increasingly influenced by the strong southward flow and meanders of the Agulhas Current as the shelf narrows to the east.
- A subtropical zone along the east coast, which becomes increasingly tropical towards the north. This zone is strongly influenced by the Agulhas Current south of the Mozambique Channel and the Somali Current to the north of it, both of which are driven by wind patterns in the Western Indian Ocean.

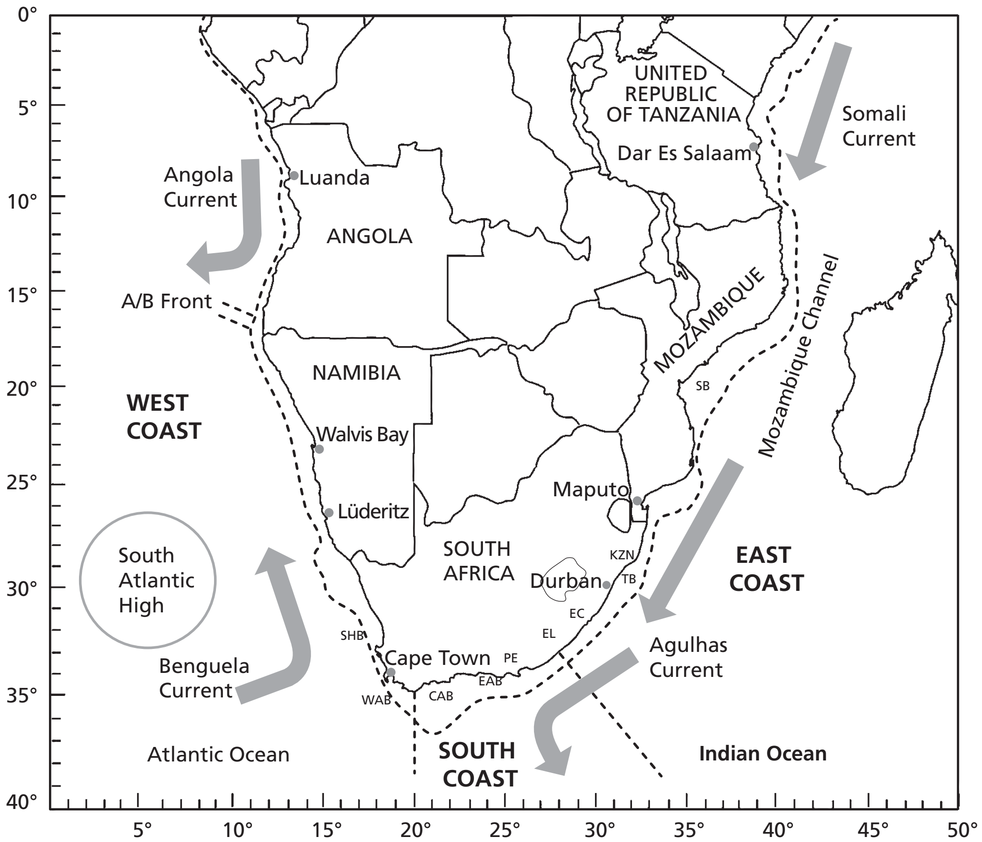
The region as a whole supports commercial fisheries for demersal, midwater and small pelagic species (mainly off the west coast and the South African south coast), rock lobster (*Jasus lalandii*), prawns and other crustacea, and (off the South African south coast), chokka squid (*Loligo reynaudii*). In addition, in all but Namibia and the extreme south of Angola, there are extensive small-scale and artisanal near-shore fisheries for a wide range of species caught by a variety of small gear operated from small boats or from the shore. These fisheries are extremely valuable in terms of the number of people involved and affected, and the importance of the catch for food security.

For convenience, this chapter is sub-divided into three areas (Figure 11.1), viz:

1. The **west coast**, incorporating the coasts of Angola, Namibia and the west coast of South Africa including the western Agulhas Bank to Cape Agulhas (20 °E).
2. The South African **south coast**, stretching from Cape Agulhas to about East London, encompassing the central and eastern Agulhas Bank.
3. The **east coast**, incorporating the coasts of the Eastern Cape and KwaZulu-Natal in South Africa, and the coasts of Mozambique and the United Republic of Tanzania.

These areas are dealt with separately as far as possible, recognizing that there are substantial regions of overlap in some fisheries.

FIGURE 11.1
Map of the Southeast Atlantic and Southwest Indian Ocean fisheries regions



Countries and places mentioned in the text (cities/towns are indicated by a grey dot with PE being Port Elizabeth, EL being East London, and EC and KZN indicating the approximate locations of the Eastern Cape and KwaZulu-Natal coasts of South Africa, respectively); important oceanographic features with major currents indicated by grey arrows (A/B Front being the Angola/Benguela Front, SHB being St. Helena Bay, WAB, CAB and EAB being the western, central and eastern Agulhas Banks, respectively, TB being the Tugela Bank and SB being the Sofala Bank); the approximate extent of the continental shelf as shown by the 200 m depth contour (dashed line); and the division of this region into the three areas (west coast, south coast and east coast) discussed in this chapter.

There are significant national differences in the extent to which climate change has been recognized as a threat to the region's marine environment and fisheries. Of particular relevance are an initial broad vulnerability assessment of the fisheries of the Benguela Current Large Marine Ecosystem (BCLME; including Angola, Namibia and South Africa) in 2011 (De Young *et al.*, 2012) and subsequent development of regionally-appropriate vulnerability frameworks with a specific focus on social and economic vulnerability for use in adaptation planning for Benguela fisheries (FAO, 2013). An overview of possible adaptation options and identification of key research gaps in understanding the vulnerability of the South African marine fisheries sector to climate change was conducted as part of that country's Long-Term Adaptation Scenarios programme (DEA, 2013) and, subsequently, a Draft Climate Change Sector Plan for Agriculture, Forestry and Fisheries has been developed (Government Gazette, Republic of South Africa, 2015). Vulnerability analyses and the identification of adaptation measures to improve resilience of marine fisheries and fishing communities to the impacts of disasters and climate change in the Southwestern Indian Ocean have recently also been initiated (FAO, 2014, 2016).

11.2 WEST COAST

11.2.1 Fisheries of the region

Fisheries of the west coast area are dominated by industrial and semi-industrial sectors with large catches requiring large processing facilities; annual landings of important fisheries resources combined, including small pelagic fish, midwater fish, demersal fish and crustacean species for this area are of the order of 1 million tonnes (Figure 11.2). Additionally, extensive artisanal and/or small-scale fisheries that take much smaller catches but are important for coastal communities are found in Angola and South Africa, but not Namibia. Country-specific descriptions of important fisheries of the west coast area are provided below.

Angolan fisheries

In Angola there is an important industrial trawl fishery over the whole shelf to the north of the country for a wide range of demersal species such as large-eye dentex (*Dentex macrophthalmus*) and other sea breams as well as Benguela hake (*Merluccius polli*), with an average annual catch (1990 to 2015) of these species of just below 17 000 tonnes (Figure 11.2A). Deep water shrimps (*Parapenaeus longirostris* and *Aristeus varidens*) are also taken by this fishery but annual catches are less than 1 000 tonnes (Figure 11.2D). There are also important industrial and semi-industrial fisheries for small pelagic fish such as sardinellas (*Sardinella aurita* and *S. madarensis*) and, in the extreme south, sardine (*Sardinops sagax*), with annual catches of these species averaging 60 000 tonnes but showing an increasing trend in recent years (Figure 11.2B). Similarly, for Cunene and Cape horse mackerel (*Trachurus trecae* and *Trachurus trachurus capensis,* respectively), with average annual catches of the two species (primarily *T. trecae*) around 45 000 tonnes and also showing an increase in recent years (Figure 11.2C). Added to these is an extensive artisanal fishery along the entire coast beyond the arid southern region targeting a wide range of species, which is an extremely important source of employment and food for coastal communities. Small-scale fishing accounts for around 20 percent of annual catches whilst semi-industrial and industrial fishing accounts for the remaining 80 percent.

Namibian fisheries

Off Namibia, there is a major demersal trawl fishery for Cape hakes (*Merluccius capensis* and *M. paradoxus*), monkfish (*Lophius* spp.) and various bycatch species, with annual catches of the two hake species averaging 133 000 tonnes over the period 1990 to 2015 and remaining relatively stable from the mid-1990s (Figure 11.2A). There is also a substantial fishery, the country's largest in terms of landed mass, for adult Cape horse mackerel, with annual catches of this species averaging 287 000 tonnes (albeit with some large variation; Figure 11.2C), which are caught mainly by large midwater trawlers and processed at sea. There are also much smaller fisheries for small pelagic fish, primarily sardine, with recent catches (average annual catch of 52 000 tonnes; Figure 11.2B) substantially reduced compared to historical catches of this species, as well as for rock lobster, small quantities of which (around 200 tonnes per annum; Figure 11.2D) are caught inshore off southern Namibia and processed in Lüderitz almost entirely for export.

South African fisheries

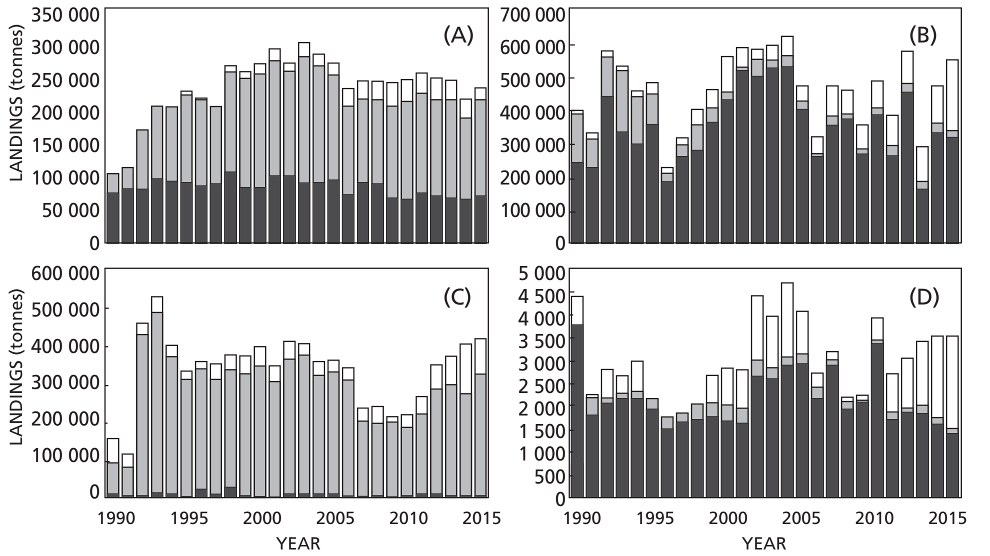
South Africa has an important offshore demersal trawl fishery that is dominated by the two Cape hakes and fishes primarily from the shelf-edge but also across the entire shelf from the Namibian border to Cape Agulhas. Deepwater hake (*M. paradoxus*) comprise the bulk of demersal trawl catches off the west coast, with average annual landings of the two hake species being 133 000 tonnes from 1990 to 2015 (Figure 11.2A).

The fish are processed at sea or ashore with a large proportion of the catch exported as fresh fish or frozen products to Europe. The income from hake is roughly equal to the total gross income from all other fishery sectors in South Africa combined. The South African purse-seine fishery for small pelagic fish targets sardine, anchovy (*Engraulis encrasicolus*) and round herring (*Etrumeus whiteheadi*) and is the largest in terms of volume in South Africa (Figure 11.2C) and second only to the demersal trawl fishery in commercial value. Anchovy and round herring are only caught off the west coast, together with occasional small bycatch of primarily juvenile sardine and horse mackerel, and are reduced to fish meal and oil in large factories in the St. Helena Bay region. Whereas most of the sardine catch is taken off the west coast some are also caught off the south coast (see below), with this species either canned for human consumption or pet food, or frozen as bait. Combined annual catches of sardine, anchovy and round herring off the west coast average 354 000 tonnes over the period 1990 to 2015 (Figure 11.2B), with the bulk of this being anchovy.

Rock lobster is the target of another important fishery on the west coast, where it is an important source of employment for over 4 200 people, who fish with baited hoop nets and traps, laid from small boats close inshore. Annual catches over the period 1990 to 2015 averaged 2 200 tonnes, markedly higher than landings of important crustaceans off Angola or Namibia (Figure 11.2D) but substantially reduced compared to historical peak landings of approximately 10 000 tonnes taken in the mid-twentieth century.

There is also an important and extensive small-scale fishery for line- and net-caught fish along most of the west coast, especially south of the sparsely-populated Namaqualand coast in the north. This fishery consists of a commercial boat-based fishery, a small-scale, beach-based line- and net-fishery, and a recreational fishery, which includes all forms of angling from shore or boats and by divers. These fisheries are mostly labour-intensive, low technology activities, which exploit a large number of species in estuaries and near-shore waters. Important species include snoek (*Thyrsites atun*) and yellowtail (*Seriola lalandi*; both targeted by the commercial line-fishery with annual catches of these two species of the order of 7 000 tonnes over the past decade), mullet *Liza richardsonii*; targeted by the net-fishery with annual catches of around 2 500 tonnes), and a variety of seabreams and scianids (targeted by the recreational fishery). Around 200 small vessels are presently active in the commercial line-fishery off the west coast, and roughly 4 000 more in the recreational sector throughout South Africa. The number of small-scale fishers in South Africa, a significant number of whom operate from the west coast as here defined, has been recently estimated at around 10 000 (C. Smith, DAFF, personal communication).

FIGURE 11.2
Catches of important fisheries species in the west coast region

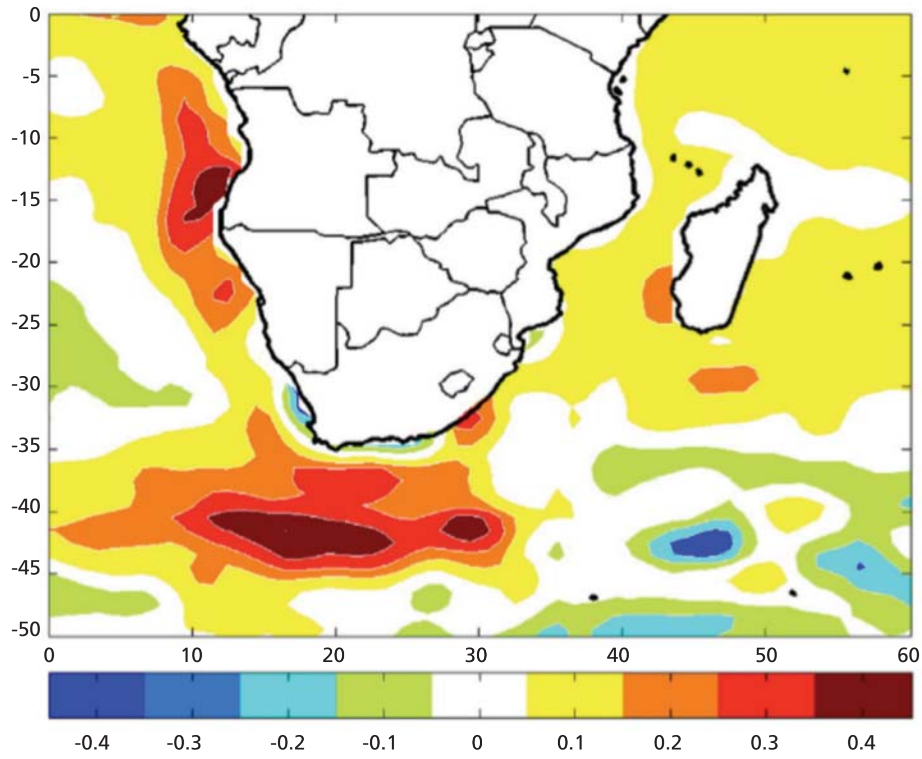


Including annual landings of (A) demersal fish (primarily bigeye dentex but including other seabreams and Benguela hake in Angola, and only Cape hakes in Namibia and South Africa; (B) small pelagic fish (sardinellas in Angola, sardine in Namibia, and anchovy, sardine, and west coast round herring in South Africa); (C) midwater fish (Cunene horse mackerel in Angola and Cape horse mackerel in all three countries); and (D) crustacean (deep water shrimps in Angola, and rock lobster in Namibia and South Africa) species taken off the west coast (i.e. to the west of Cape Agulhas), 1990 to 2015 (data from www.fao.org). In all plots Angola is represented by white histograms, Namibia by grey histograms and South Africa by black histograms. Note that the y-axis of each plot is differently-scaled.

11.2.2 Observed and projected impacts of climate change on the environment

According to satellite imagery, sea surface temperature (SST) off Angola has been increasing over the past three decades, with average rates between 0.23 °C (Jarre *et al.*, 2015) and 0.8 °C (Potts *et al.*, 2014) per decade depending on which satellite data-source is used (Figure 11.3). This is above the global average and southern Angola in particular is recognized as one of 24 ocean warming hotspots (Hobday and Pecl, 2014). This warming is interspersed with warm and cool periods which have generally become more pronounced in the south; especially the cool events (Jarre *et al.*, 2015). These cool events appear to be caused by internal waves of tropical origin rather than an increase of upwelling-favourable winds in the region. There is evidence from satellite imagery of increased phytoplankton production off southern Angola in some years since 2002 (Jarre *et al.*, 2015), but this observation should be treated with caution because of the limitations of satellite imagery as a measure of chlorophyll concentration in southern Angolan waters. Current zooplankton collections off Angola are not consistent enough to provide a coherent time series of trends in zooplankton biomass and community structure, particularly for the subtropical system. A more definite climatic threat is considered to be damage to coastal infrastructure as a result of sea level rise (estimated at about 0.6 mm per year during the 1990s (Hardman-Mountford *et al.*, 2003) aggravated by rising SST, and increased flooding from higher rainfall in the interior.

FIGURE 11.3
Linear trend of 1° x 1° resolution Reynolds SST in °C per decade from 1982 to 2012



Source: Reproduced from Blamey *et al*., 2015, with permission.

High resolution computer simulations of the South Atlantic coupled with multiple oceanic and atmospheric re-analyses have provided clear evidence of a southward shift in the position and intensification in the strength of the Angola/Benguela Front since 1980, related to a southward shift in the position of the South Atlantic subtropical anticyclone (Vizy, Cook and Sun, 2018). Periodic, southward intrusions of warm, saline, nutrient-poor and low oxygen water onto the Namibian shelf and associated with marked southward movement of the Angola/Benguela Front, known as Benguela Niños, have occurred roughly once a decade, most notably in 1994/95 when the intrusion was particularly extensive and protracted, and most recently in 2010/11 (Rouault *et al.*, 2017). These have a marked impact on the environment and fishery resources of the northern and central Namibian coast and species not acclimated to these abnormal conditions may die off or migrate. Both pelagic and demersal fish species showed mortalities and/or southward or offshore displacements associated with the 1994/95 event (Gammelsrod *et al.*, 1998; Hamukuaya, O'Toole and Woodhead, 1998).

In the past three decades, SST off the coast of northern Namibia has increased in all months of the year by between 0.2 °C and 0.5 °C per decade depending on season, but south of about Walvis Bay there has been no general change in SST over this period (Hutchings *et al.*, 2009; Jarre *et al.*, 2015; [Figure 11.3]). Whilst wind patterns off Lüderitz (the centre of the strongest upwelling in the Benguela system) display interannual and decadal-scale variability there appears to have been a general decline in upwelling-favourable winds there between 1990 and 2005 (Hutchings *et al.*, 2009). Lamont *et al.* (2018) reported a significant quadratic trend in total cumulative upwelling (TCU) for the northern Benguela that corroborated previous reports of a recent decline in upwelling in that region, with TCU between 2009 and 2014 less than half the long-term mean.

There have been large seasonal and interannual variations in dissolved oxygen in Namibian shelf waters in the last few decades, but no clear trends are evident, either in the advection of low-oxygen water from the Angola dome area, or in the frequency of localized low-oxygen events caused by the decay of organic matter (Jarre *et al.*, 2015). There is also no unequivocal evidence of major long-term changes in phytoplankton production in Namibian waters, despite the apparent long-term decrease in upwelling-favourable winds and the increase in SST over the northern part of the system. In contrast, there is evidence of a major increase in copepod production and of significant changes in zooplankton community structure since the 1970s (Verheye and Kreiner, 2009). Whereas this had been attributed to increased primary production combined with a reduction in predation following the depletion of pelagic fish stocks, the change in community structure from large to small copepod species may also be associated with ocean warming observed in this region (Jarre *et al.*, 2015). However, the dramatic declines in the abundance of pelagic fish in the 1970s caused by excessive fishing pressure appear to have changed the food web from one dominated by "wasp-waist" pelagic fish such as sardine and anchovy, to a less efficient regime in which jellyfish, and pelagic gobies (*Sufflogobius bibarbatus*), have assumed far greater importance in the ecosystem, substantially altering trophic pathways (Roux *et al.*, 2013).

Satellite imagery has shown that over the past four decades the southern Benguela has cooled from April to August by 0.3 °C to 0.5 °C per decade (Rouault, Pohl and Penven, 2010) suggesting stronger unseasonal upwelling-favourable winds and a poleward shift of the St. Helena Anticyclone. More recent analyses that corrected for a warm bias in previous satellite-derived data have suggested that this cooling is less (0.2 °C per decade) and more restricted than previously thought (Blamey *et al.*, 2015; [Figure 11.3]). Analyses of wind data have indicated that despite inter-decadal variability there has been a tendency toward increased upwelling in the southern Benguela over the past three decades, although the trend is not significant (Lamont *et al.*, 2018). Corresponding ocean colour imagery has revealed large interannual and inter-seasonal variability in surface chlorophyll concentrations during this period, but there is no clear trend suggestive of a long-term change in primary production in the area (Jarre *et al.*, 2015). In contrast, zooplankton collections off St. Helena Bay since the 1950s show an approximately ten-fold increase in copepod abundance, and a pronounced trend towards smaller sizes (Hutchings *et al.*, 2012), as was found in the northern Benguela. However, this appears to have been primarily a result of a reduction in predation by small pelagic fish after the start of the fishery, rather than driven by long-term environmental change. Sampling of copepods off the western Agulhas Bank between 1988 and 2016 has shown a gradual decline in copepod biomass there since 1996 and a long-term decline in the biomass of *Calanus agulhensis*, the dominant large copepod on the Agulhas Bank. As on the west coast these changes are thought to be largely driven by changes in predation pressure by pelagic fish, although they are probably also influenced by environmental variability (DEA, 2016).

11.2.3 Effects of climate change on stocks sustaining the main fisheries

Angolan resources

There is little evidence at present of major responses of Angola's most important marine resources to changes in their environment in recent decades that are strong enough to be used to detect or predict their responses to climate change. While there have been changes in *Sardinella aurita* and *S. madarensis* migration patterns, and pronounced changes in the seasonality and size of catches (Ostrowski, da Silva and Bazik-Sangolay, 2009), no long-term changes in their distribution or stock structure have been documented (Jarre *et al.*, 2015). There has been an increase in the latitudinal range of demersal assemblages, with an overall southward tendency and an expansion into deeper water, but no link has been found between these shifts and changes in bottom temperature, indicating that other environmental factors, such as changes in oxygen concentration on the bottom, and the effects of fishing need to be considered (Yemane *et al.*, 2014). There was also a major shift in the structure of the demersal community and in the biomass of a few species in the mid-2000s, but no obvious environmental or anthropogenic changes at the time that could have driven this apparent regime shift were identified (Kirkman *et al.*, 2015). However, Potts *et al.* (2014) documented a rapid distribution shift southwards from Angola extending into Namibia by the coastal scienid *Argyrosomus coronus*, a species that is heavily targeted by the artisanal and subsistence (and developing recreational) fisheries off Angola (Potts *et al.*, 2009). That distributional shift was attributed to the rapid warming of Angolan coastal waters, and the changed distribution of *A. coronus* appears to have resulted in hybridization of this species with a congener, *A. inodorus*, which is distributed from central to northern Namibia.

Namibian resources

The major changes in Namibia's most important commercial resources in the 1970s and 1980s – i.e. hake, small pelagic fish (sardine and later anchovy) and rock lobster, were clearly primarily caused by overfishing rather than the environment (Boyer and Hampton, 2001; Roux *et al.*, 2013). Since then, the environment has played a far larger role, particularly the major Benguela Niño event in 1994/95, which *inter alia*, severely reduced hake recruitment and probably also halted a modest recovery in the sardine population. Although less conclusive, there is evidence to suggest that the further substantial decline in the rock lobster resource which occurred in the late-1980s/early-1990s was also environmentally induced, in this case by intrusions of low-oxygen water into the fishing grounds (Gammelsrod *et al.*, 1998). The situation at present is that hake have expanded their distribution over a wider depth range, the very reduced sardine population (which is substantially different in structure than prior to the collapse) is now confined largely to areas north of Walvis Bay, while anchovy have all but disappeared from Namibian waters (Boyer and Hampton, 2001). Rock lobster catches appear to have more or less stabilized at a very low level since 1990. The distribution of Cape horse mackerel has shifted southwards, accompanied by changes in overall stock structure and a return to the areas where spawning occurred in the 1970s. Since catches of all these species have been conservatively managed since Namibian independence in 1990, whatever changes in abundance and distribution have occurred since then have most likely been environmentally driven, although changes in population size itself could also have played a role in some instances (Boyer and Hampton, 2001).

It is clear that despite the increases in understanding of the effects of the environment on the Namibian marine ecosystem in recent years, changes in abundance and distribution arising from environmental changes cannot be predicted with sufficient confidence for use in management for any of the above resources. A possible exception is the greater appreciation of the origin and significance to marine life of Benguela Niño events, which may now be predictable to some extent a few months in advance, and be taken into account in management, at least qualitatively. Additionally, continued poleward movement of the Angola/Benguela Front as reported by Vizy, Cook and Sun (2018) may result in a contraction of the suitable habitat of commercially important species in northern Namibia.

South African resources

The west coast fisheries considered here are those regarded as most important in terms of value, employment and/or food security. These are the commercial fisheries for demersal fish, small pelagic fish and west coast rock lobster, and the small-scale line- and net-fisheries for a wide range of species.

Relatively little is known about the effects of environmental factors and behavioural responses on the size of the hake resource, but their longevity, wide geographical range, extensive diurnal vertical migrations, very diverse diet and ability to tolerate relatively low oxygen levels, all suggest that they should be resistant to all but extreme, prolonged environmental perturbations. There is, however, no evidence that major perturbations such as this have in fact been occurring over the hake fishing grounds in South Africa, or that there have been significant changes in abundance or distribution of the species in recent years.

In contrast, there has been a well-documented eastward shift in the distribution of adult anchovy (Roy *et al.*, 2007) and sardine (Coetzee *et al.*, 2008) since the mid- to late-1990s. Anchovy spawners showed an abrupt shift from being located primarily (i.e. more than 50 percent of total biomass) to the west of Cape Agulhas during the 1980s and early 1990s, to being predominantly east of Cape Agulhas in 1996 and virtually every year thereafter. That shift was related to an abrupt cooling of coastal waters east of Cape Agulhas, thought to arise from increased wind-induced coastal upwelling there and which resulted in an increased cross-shelf temperature gradient in that region (Roy *et al.*, 2007). The shift had little impact on the fishery since the bulk of the anchovy catch consists of juvenile fish caught off the west coast, and the shift does not appear to have adversely impacted recruitment. The eastward shift in sardine distribution was more gradual, with more than 70 percent of surveyed biomass being west of Cape Agulhas during the 1980s and early 1990s but falling to less than 25 percent in the mid-2000s (Coetzee *et al.*, 2008). The changed distribution of sardine negatively impacted the fishery, with a progressive eastward shift in the centre of gravity of sardine catches (Fairweather *et al.*, 2006) having an adverse effect on profitability since most of the landing points and processing plants are situated on the west coast. Although the centre of gravity of sardine catches has shifted westwards since 2006 it has remained east of Cape Agulhas and south of Cape Town since 2005, whereas it was west of Cape Agulhas and north of Cape Town before then (Augustyn *et al.*, 2018). The changed sardine distribution is also significantly correlated with the cross-shelf temperature gradient east of Cape Agulhas, suggesting an environmental linkage (Augustyn *et al.*, 2018). However, that relationship is much weaker than for anchovy and the changed distribution is believed to be because of, to some extent, higher fishing pressure on sardine west of Cape Agulhas (Coetzee *et al.*, 2008), which are hypothesized to comprise a different stock to sardine east of Cape Agulhas (van der Lingen *et al.*, 2015). Significant southward and eastward shifts in the annual centre of gravity of round herring catches over the period 1987 to 2012 have also been observed (DAFF, 2014), with catches being furthest to the southeast in 2005 to 2007 but moving westward in recent years, but this shift is substantially smaller than observed for either anchovy or sardine.

There was a well-documented reduction in rock lobster growth rate between the late-1980s and late-1990s (Pollock, Cockroft and Goosen, 1997) accompanied by an increased frequency of fatal “walk-outs” (mass strandings) in the Elands Bay region as a result of episodes of anoxia associated with the decay of harmful algal blooms (Cockcroft, 2001), and, in the 1990s, an eastward shift in distribution co-incident with the eastward shift in the distribution of small pelagic fish (Cockcroft, van Zyl and Hutchings, 2008). All appear to have been environmentally driven, although the mechanisms are not well understood. The eastward migration of rock lobster has already had a severe impact on the fishery and communities on the west coast, with further negative impacts expected if this trend continues. It has also severely affected the near-shore ecosystem on the western Agulhas Bank, for example by the depletion of abalone (*Haliotis midae*) through competition for urchins (their chief prey; Blamey, Branch and Reaugh-Flower, 2010). Fortunately, since the turn of the century the eastward migration of rock lobster appears to have halted, growth rates have increased slightly, and the incidence of walk-outs from harmful algal blooms has returned to pre-1980's levels (Augustyn *et al.*, 2018).

Ortega-Cisneros *et al.* (2018) used an ecosystem model and climate projections to evaluate the effects of fishing, warming, and horizontal and vertical mixing on the southern Benguela (west and south coasts of South Africa) ecosystem. They found that warming had the greatest effect, almost always negative, on the biomass of almost all species including some important fishery resources. Cape hakes showed biomass reductions of the order of 10 percent to 20 percent by 2050 compared to control simulations, but anchovy showed the strongest response to predicted warming of the southern Benguela, with a reduction in biomass of around 50 percent and being more negatively impacted off the west than the south coast. A similar result was reported by Raybaud *et al.* (2017) who used an ecological niche model for European (= Cape) anchovy and a suite of ocean-atmosphere global circulation models driven by IPCC scenarios to evaluate climate change effects on the distribution of this species. Those projections indicated substantial distributional change and a consistent reduction in the probability of occurrence south of 48 °N, with a 40 percent to 50 percent reduction predicted for anchovy off Southern Africa.

11.2.4 Vulnerability and opportunities for the main fisheries and those dependent on them

Angolan fisheries

Angola's national economy was rated as the most vulnerable of 132 countries to climate-induced impacts on fisheries (Allison *et al.* 2009), with vulnerability assessed using measures of exposure to the physical effect of climate change, sensitivity of the ecosystem or economic importance of the fisheries sector, and the level of adaptive capacity to offset these impacts. Fishing is one of the main economic activities in Angola and the country's National Adaptation Programme of Action (NAPA; MoE, 2011) found agriculture and fisheries to be the country's most vulnerable sectors. Whereas the NAPA recognized a lack of data in this regard it identified studying the vulnerability of the fisheries sector to climate change and changes in water currents as one of its main adaptation priorities (FAO, 2013) that was likely to have significant benefits, particularly in terms of rural livelihoods (MoE, 2011).

In the 2011 preliminary vulnerability assessment (De Young *et al.*, 2012), the two Angolan fisheries rated as most vulnerable to climate were the artisanal fishery and the semi-industrial fishery for small pelagic fish; the former because of its sensitivity to local environmental perturbations, socio-economic importance and limited ability to adapt, and the latter because of its apparent sensitivity to larger-scale environmental perturbations, high value in terms of employment and food security, and its relatively low adaptive capacity because of the moderate scale of semi-industrial fishing enterprises in Angola. Despite their greater commercial value, the demersal and industrial pelagic fisheries were rated as somewhat less vulnerable, primarily because of their larger vessels and greater access to capital to introduce adaptive measures. Note that the initial assessment of the vulnerability of Angolan fisheries was very preliminary, and was based on general principles rather than in-depth analyses of the threats to each fishery and of possible adaptation measures, which is yet to be done. FAO (2015a) used participatory and inclusive community-level rapid vulnerability assessments to gather information on local socio-ecological vulnerabilities in relation to environmental and climate change for three fishing communities in Angola, primarily line-fishers fishing from small vessels close to the coast but some also using seine- and gill-nets. Communities reported socio-economic stressors such as a lack of financial resources and no access to credit as most important, followed by declining fish catches attributed to industrial vessels fishing in the artisanal zone, and a lack of government support and infrastructure (e.g. refrigeration facilities) at landing sites. Fishers' perceptions of a changing environment (e.g. increasing sea temperatures and changes in fish species composition) corroborated the scientific findings described above. A related, more definite climatic threat is damage to coastal infrastructure because of sea level rise (estimated at about 0.6 mm per year at present) aggravated by rising SST, and increased flooding from higher rainfall in the interior. The artisanal fishers are clearly the most vulnerable to these effects.

Namibian fisheries

The Namibian fishery rated as the most vulnerable to climate change in the 2011 assessment (De Young *et al.*, 2012) was the demersal trawl fishery, predominantly for hake. This was because of its high economic value, large number of employees and sensitivity to extreme environmental events such as the protracted Benguela Niño which occurred in 1994/95. The vulnerability of the small pelagic fishery was also rated as high because of the high sensitivity of the resource to environmental variations (evidenced, for example, by large interannual variability in biomass estimates), the relatively large number of people directly and indirectly involved in the industry, and its poor ability to adapt, primarily because the industry is constrained by low profit margins and does not have other resources to turn to. Likewise, the vulnerability of the rock lobster fishery was also rated high, being driven by the relatively large number of people in Lüderitz dependent on the fishery, and its poor adaptive capacity because of the small-scale nature of the fishery and the lack of alternative resources to turn to or other sources of employment in the area. In contrast, the horse mackerel fishery was rated as one of the least vulnerable to climate change because of the wide distribution of the resource, its modest socio-economic importance (despite the size of the catch), and the ability of the fleet to adapt to changes in abundance and distribution through the long-range mobility and endurance of the vessels. Rapid vulnerability assessments of two Namibian fishing communities, one of which consists of the collection of mussel shells along the coastline by women for making traditional jewellery and the other of shore-based line-fishers, indicated a lack of financing and adequate equipment, increased costs (e.g. for bait) and low achieved prices, poor organization, and declining (mussel shells) or a reduction in size (line-fishers) of harvested resources as major stressors (FAO, 2015a). Shell-collectors reported that shells are now more brittle than previously, which compromises product quality, and line-fishers reported changing weather patterns and changing seasonal distributions of some fish species.

South African fisheries

The South African marine fishery rated by the 2015 workshop (Augustyn *et al.*, 2018; Hampton *et al.*, 2017) as being most vulnerable to climate change was the small-scale fishery for line- and net-fish, a significant proportion of which are caught on the west coast as here defined. This is because of the fishery's sensitivity to both large-scale and small-scale changes in the environment, the large number of people involved, and the fact that, with the exception of the recreational sector, individuals and communities in this fishery are generally poor, relatively unskilled and socially disadvantaged, resulting in a very limited capacity to adapt to adverse changes (Hampton *et al.*, 2017). Furthermore, they are often severely restricted by legislative and logistical constraints on the species and areas available to them, and since they operate from small boats or from the shore, they are more affected by deteriorating weather conditions than fishers in the larger-scale commercial fisheries. Rapid vulnerability assessments of two communities indicated that climate change and variability, seasonal changes in fish availability, unemployment and poaching, and a lack of government support were the main stressors perceived (FAO, 2015a). Changing seasons, and stronger southeasterly winds in summer and changes in west coast rock lobster distribution were also reported.

The fishery for small pelagic fish on the west coast and western Agulhas Bank was rated as the second-most vulnerable to climate change because of the sensitivity of the resource to environmental perturbations, its commercial value and the large number of people employed in the fishery. The vulnerability to climate change of the fishery for west coast rock lobster was rated as moderately high because of the evident major response to environmental change in the recent past, the relatively high value of the fishery in terms of income and employment, and the comparatively poor ability of fishers to adapt because of the small-scale nature of most of their operations and the scarcity of alternative employment opportunities in the remote areas where many of them operate. Alleviating factors are the fact that it has been shown through laboratory experiments (Knapp *et al.*, 2016) that juvenile and adult rock lobster are well adapted to the highly dynamic upwelling system which they inhabit, and that recovery from all but the most extreme walk-out events in the past has been relatively rapid. It has also been recognized that the eastward shift in distribution has had some benefits to the fishery, and that because of coastal topography, future walk-outs are unlikely to spread beyond the Elands Bay area, where they currently occur.

In contrast to the above fisheries, the demersal trawl fishery as a whole was rated as one of the least vulnerable to climate change at present, despite its high value and relatively large labour force, because of the apparent tolerance of hake to changes in the environment, and the fact that the major part of the fishery is heavily industrialized, with the financial and technical resources to adapt to changes in resource abundance and distribution.

11.2.5 Responses and adaptation options

Angola, Namibia and South Africa are member states of the Benguela Current Commission (BCC) and have signed the Benguela Current Convention, the objective of which is to "promote a coordinated regional approach to the long-term conservation, protection, rehabilitation, enhancement and sustainable use of the BCLME to provide economic, environmental and social benefits" (BCC, 2013). Most recently, the BCC has partnered with the FAO in a project that aims to build resilience and reduce the vulnerability to climate change of marine fisheries and mariculture sectors within the BCLME through strengthening adaptive capacity and implementing participatory strategies. This is to be achieved, *inter alia*, by integrating fisheries climate change considerations into fisheries policies and planning, piloting improved climate-resilient fisheries practices, and capacity building and the promotion of climate-resilient fisheries practices.

Angola

Angola's NAPA (MoE, 2011) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) lists several priority actions pertinent to fisheries, including the need to study vulnerability of this sector to climate change and changing water currents, and to create early warning systems for flooding and storms (FAO, 2013). Activities in the former include establishing models to investigate climate change impacts in the northern Benguela Current ecosystem and coastal fisheries, and developing climate monitoring infrastructure in the latter. However the coordination of climate change adaptation plans and measures in the Angolan marine fisheries sector is still at an early stage.

Adaptation strategies identified in FAO's (2015a) study that were broadly common across all communities investigated included the upgrading of fishing vessels and gear to improve fisher safety, increasing organization at a local level through cooperatives, improving post-harvest infrastructure and marketing, implementing training and capacity building programmes to enhance skills development, developing additional income-generating opportunities such as aquaculture, instituting legal protection for small-scale fishers, and developing community-level participation monitoring and participatory research with government and other institutions. FAO (2015a) emphasize that building adaptive capacity to climate change in small-scale fishing communities is best achieved by enhancing the general resilience of those communities, and recommend developing and strengthening local organizations, rebuilding fisheries through local co-management plans and community-monitoring programmes, developing complementary livelihoods in partnership with local non-governmental organizations and government agencies, and addressing broad socio-economic rights of fisher communities. For Angolan fishing communities specifically, adaptation strategies included limiting the number of industrial vessels, developing early warning systems for extreme weather conditions, improving fisheries compliance, and shifting fishing effort to new locations FAO (2015a).

Namibia

Namibia's national climate change policy promotes integrated fisheries management, integrated coastal zone management for the protection of marine resources, and the strengthening of joint management of shared fish stocks as actions to address climate change impacts on the fisheries sector (FAO, 2013; MET, 2010). Adaptation plans for Namibia's marine fishing sector are also at an early stage at present. Special attention may well be given to the small pelagic and rock lobster fisheries, both of which have poor ability to adapt, the former because the industry is constrained by low profit margins and does not have other resources to turn to, and the latter because of the small-scale nature of the fishery and the lack of alternative resources to turn to or other sources of employment in the area. In addition to the common possible adaptation measures for coastal communities on the west coast listed above for Angola, Namibian shell-harvesters are now using additional materials such as freshwater mussel and ostrich shells for jewellery production, travelling further to harvest shells, and developing local (e.g. tourist) and international markets, whilst line-fishers identified accessing new resources and new fishing areas as possible adaptation options (FAO, 2015a).

South Africa

A number of adaptation measures have been proposed for the highly vulnerable small-scale line- and net-fishery in South Africa as a whole, such as improving detection and capturing ability, targeting new species and making better use of catches (e.g. through developing refrigeration infrastructure at landing sites to improve fish quality), moving to larger, safer vessels and better protecting small boat harbours, improving predictions of distributional changes through development of better bioclimatic models, and providing fishers with better access to weather predictions and other information important to them (Augustyn *et al.*, 2018). There have also been a number of socio-economic initiatives which could facilitate adaptation significantly, the most far-reaching of which, particularly for the small-scale fisheries for line-fish, rock lobster and other resources, is the government's new Policy for the Small Scale Fisheries Sector in South Africa (Government Gazette, Republic of South Africa, 2012), scheduled for full implementation by 2018. This policy acknowledges the threats posed by climate change and contains many elements to improve governance and cooperation between communities and government, and strengthen interaction and cooperation within the communities themselves. As such it could be an effective vehicle for informing them of incipient climate change effects and harnessing their assistance in monitoring climate change effects on the ground, and helping them to adapt to it. Common possible adaptation measures for coastal communities in general are as listed above for

Angola, but South African small-scale fishers also identified declaring exclusive small-scale fisheries zones, changing fishing areas to follow the fish, exploring new fishing areas, and improving marketing as adaptation options (FAO, 2015a). In addition, a novel information and communications technology approach aimed at developing social justice and poverty-alleviation in small-scale fishing communities has recently been pioneered in South Africa through a suite of inter-connected mobile phone applications (known as ABALOBI[1]). Designed for small-scale fisheries governance and following the small-scale fisheries policy and FAO guidelines for securing sustainable small-scale fisheries (FAO, 2015b), the applications enable small-scale fishers to be incorporated into information and resource networks, including fishery monitoring and maritime safety, local development and market opportunities, and will promote traceable seafood production by small-scale fishers.

Suggested ways of adapting to the threats of climate change by the small pelagic fishery include making better use of present resources through product beneficiation (e.g. processing anchovy and round herring for human consumption), developing fisheries for alternative resources such as mesopelagic fish species (an experimental fishery for mesopelagics has been underway since 2011), using larger vessels that are better able to withstand adverse sea conditions and alternative fishing methods (e.g. midwater trawling), and allowing for greater variability in resource abundance and availability in management measures (Augustyn *et al.*, 2018). It has been recognized that the high capital cost of converting to new fishing and processing methods and building new vessels and factories, etc. will be a major constraint, which rights-holders will be reluctant to embark on unless they have secure long-term fishing rights. Consideration of the applicant's ability and willingness to make such investments when allocating long-term rights would be in itself an adaptation measure. The predicted reduction in anchovy biomass as a consequence of ocean warming could have substantial negative socio-economic effects, given the importance of this species to the small pelagic fishery as well as its ecological importance as forage for other commercially exploited species. Strategic fisheries management should plan for these potential changes, including further developing models to provide plausible and robust outcomes to climate change for key fisheries species, considering the combined effects of climate drivers and fishing in fisheries management plans, and implementing management plans that attempt to maintain the resilience of key species and the ecosystem (Ortega-Cisneros *et al.*, 2018).

No specific adaptation measures for the west coast rock lobster fishery have yet been suggested but an aggressive stock-rebuilding strategy and combating the illegal harvesting of this resource is required to promote recovery of the rock lobster population (Augustyn *et al.*, 2018). In addition, a number of adaptation measures suggested for the small-scale line-fishery are likely to be applicable, including moving to larger and more seaworthy vessels and improving small boat harbours. It can also be expected that better understanding of changes in distribution in response to environmental change through further research and improved monitoring will be beneficial in adapting to these changes.

11.3 SOUTH COAST

11.3.1 Fisheries of the region

Several of the species caught in the industrial-scale fisheries off the west coast of South Africa are also targeted off the country's south coast, including Cape hakes, Cape horse mackerel, and sardine. The hake resource on the south coast is exploited by offshore and inshore trawlers, long-liners and (close inshore) hand-liners, with shallow water hake dominating the catch and annual catches of 50 000 tonnes reported over the

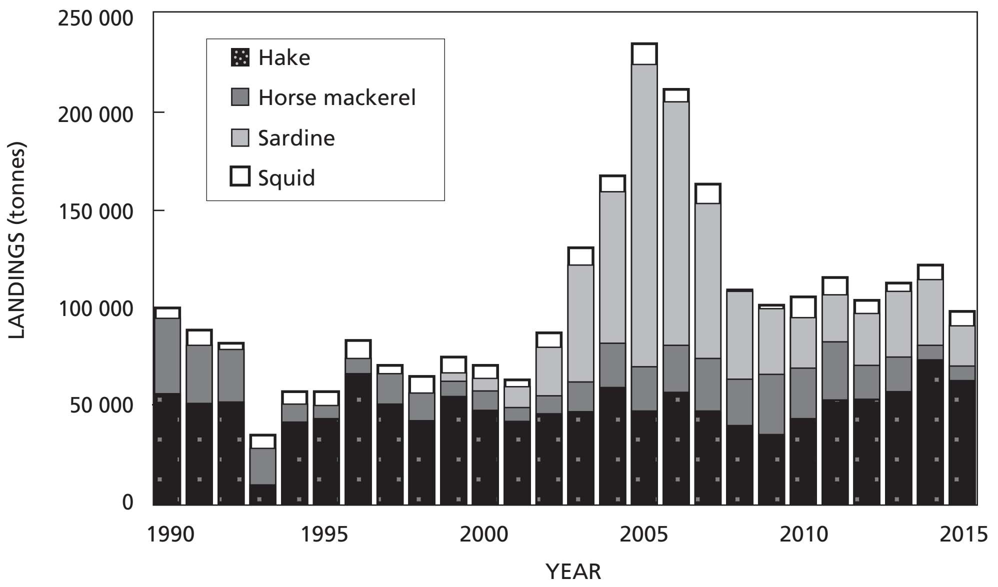
[1] http://abalobi.info/

period 1990 to 2015 (Figure 11.4). Horse mackerel are targeted by midwater trawlers in this area, with annual average landings of this species around 19 000 tonnes, more than double those taken off the west coast. Sardine have only been caught in this area since the late-1980s and whilst annual landings of more than 100 000 tonnes of this species were recorded in the mid-2000s they have declined substantially since (Figure 11.4).

The small-scale line-fishery (already discussed in the context of the west coast) is another important fishery on the South African south coast with around 80 small vessels active; important species in this region include the kob (*Argyrosomus* spp.), geelbek (*Atractoscion aequidens*), carpenter (*Argyrozona argyrozona*) and several seabreams (e.g. *Chrysoblephus* spp.), and average annual catches are of the order of 2 000 tonnes. A dramatic increase in fishing effort and improvements in fishing technology during the 1980s and 1990s resulted in over-exploitation of and massive declines in populations of many line-fish species targeted by the commercial and recreational fisheries, with one species (dusky kob, *Argyrosomus japonicus*) falling to below two percent of pristine levels (DAFF, 2016). Whereas substantial reduction in fishing effort implemented in both sectors in the early-2000s has enabled the partial recovery of some line-fish species, other important species have not recovered and may need more drastic measures to facilitate re-building. There is also a jig fishery for chokka squid, which is caught when aggregating to spawn in summer in inshore areas between approximately 24 °E and Port Elizabeth, with annual catches ranging between 3 000 and 14 000 tonnes (Figure 11.4).

FIGURE 11.4

Catches of important fisheries species in the south coast region, including annual landings of Cape hakes, Cape horse mackerel, sardine, and chokka squid, 1990 to 2015



Source: Data from www.fao.org.

11.3.2 Observed and projected impacts of climate change on the environment

Satellite imagery has shown that since the 1980s the inshore region of the south coast has cooled between April and August by around 0.4 °C per decade (Rouault, Pohl and Penven, 2010), most likely as a result of increased upwelling there. As for the west coast, however, correcting for a warm bias in previous satellite-derived data indicates that this region has not cooled substantially (Blamey *et al.*, 2015; [Figure 11.3]). In contrast, and consistently, despite which satellite data were used, the Agulhas Current has warmed in all months of the year by up to 0.6 °C per decade as a result of increased wind stress curl in the South Indian Ocean, increasing the thermal gradient across the shelf (Rouault, Pohl and Penven, 2010; Blamey *et al.*, 2015; [Figure 11.3]). Hobday and Pecl (2014) examined 50 years of historical global SST data and identified the South African south coast as one of 24 global marine hotspots where the ocean is warming faster than elsewhere. Subsequent simulations have suggested that this hotspot will experience further changes in circulation patterns, a 3 °C increase in SST, decreased pH, a shallowing of the upper mixed layer and declining primary production (Popova *et al.*, 2016).

Analyses of wind data have shown a significant increase in upwelling-favourable winds on the Agulhas Bank over the period 1979 to 2014, particularly after 2007 (Lamont *et al.*, 2018), and sea level rise in this region is of the order of 1.5 mm per year (Mather, Garland and Stretch, 2009). There have also been substantial changes in river inflow, as a result of changes in rainfall over the interior (Augustyn *et al.*, 2018), which have significantly affected estuarine and near-shore environments there. As observed off the South African west coast, there has been a long-term decline in copepod abundance off the south coast over the period 1988 to 2011, accompanied by an increase in the relative proportion of small calanoid copepods (DEA, 2016).

11.3.3 Effects of climate change on stocks sustaining the main fisheries

The incidence of harmful algal blooms on the South African south coast may be increasing as a consequence of climate change, with several unprecedented blooms occurring there over the past decade. The spatial extent of these HABs coincided with near-shore aggregations and wash-ups of sardine, and sardine within the bloom area were in markedly poorer condition than sardine elsewhere, but the blooms did not appear to have a deleterious impact on either anchovy or round herring (van der Lingen *et al.*, 2016). This reduction in sardine condition is likely to have negative implications for spawning success and subsequent recruitment given that clupeoid reproductive output is to some extent dependent on stored energy. Additionally, sardine catches off the south coast in general and off Port Elizabeth in particular have declined markedly since the first of these extensive HABs was observed off the south coast in 2011 (DAFF, 2016).

The distribution of some 30 estuarine and marine subtropical line-fish species on the east coast has expanded into the warm-cool transition zone on the south coast (Augustyn *et al.*, 2018) which suggests a common environmental cause, and such changes are predicted to continue (James, Whitfield and Harrison, 2016). Some of these species are of importance to the small-scale fishery, e.g. spotted grunter *Pomadasys commersonni* which has established a permanent breeding population on the south coast where it only occurred seasonally and did not spawn there previously (Augustyn *et al.*, 2018). Water temperature is a major driver of these distributional shifts but changes in circulation patterns and production on the shelf, and reduced run-off from rivers, with which catch rates of many line-fish species on the east coast have been found to be correlated (see below) are also likely causes. Rainfall on the south coast is projected to decrease under climate change (Engelbrecht, McGregor and Engelbrecht, 2009), which may limit production and food availability in estuarine and the near-shore zones (Potts, Götz and James, 2015). Increasing sea levels are anticipated to influence coastal fish species through the loss of intertidal areas which act as important nursery areas for both resident and migratory species, with likely negative impacts on their recruitment (Potts, Götz and James, 2015).

In the chokka squid fishery, there have been large interannual variations in catch despite strict management measures, which suggests that the resource is highly sensitive to environmental drivers. Hypotheses include increases in turbidity adversely affecting spawning behaviour, direct effects of temperature on the growth of all life history stages, and indirect effects such as the effect of temperature changes further offshore on the production of copepods, which are the main prey of para-larvae (Augustyn *et al.*, 2018). Surprisingly, the simulations by Ortega-Cisneros *et al.* (2018) referred to above indicated that cephalopod biomass would increase under predicted warming, but the low model skill in simulating the biomass of this group in preliminary analyses likely led to an overestimate of its resilience. Those simulations indicated a reduction in horse mackerel biomass of around 30 percent by 2050 arising from the impact of warming.

11.3.4 Vulnerability and opportunities for the main fisheries and those dependent on them

The factors which make the small-scale line-fishery on the west coast the most vulnerable of the fisheries there apply equally, if not more so, to this fishery on the south coast. In particular, increasing winds will likely have a serious negative impact on fishing operations, given that many line-fishers use small, displacement hull vessels, which are launched from a slipway and hence are particularly dependent on atmospheric conditions for fishing, and wind strength is a highly significant predictor of the proportion of boats that attempt to fish (Augustyn *et al.*, 2018). Aggravating factors are the greater volume (and therefore greater variability) in river inflow in this region, and the more pronounced changes in temperature because of the more direct influence of the Agulhas Current on the south coast ecosystem. A south coast fishing community for which a rapid vulnerability assessment was conducted listed overfishing, poor adherence to regulations and price control by fish buyers as the most important stressors, and noted changes in wind patterns (FAO, 2015a). Access to finance was seen as the most critical need for small-scale line-fishers, who also identified the need for participatory management and research, in addition to the other adaptation options listed in the sections on the west coast above.

The vulnerability to climate change of the inshore chokka squid fishery has been rated as moderately high (Hampton *et al.*, 2017). This is because of its apparent sensitivity to environmental effects, the comparatively high value of the catch, and its socio-economic importance to coastal communities. The vulnerability is alleviated somewhat by the fact that stock dynamics have been studied since the 1990s, and the industry is relatively well capitalized, organized and managed, all of which should make the fishery more adaptable in the long-term than most in South Africa. Factors contributing to the vulnerability of the small pelagic fishery off the west coast also apply in the main to the sardine fishery off the south coast.

11.3.5 Responses and adaptation

The climate change adaptations that have been suggested for the small-scale line-fishery on the west coast should in general apply equally well to that on the south coast, perhaps with a greater emphasis on measures to improve safety because of the greater threat of increasing frequency and severity of storms on this coast, and this applies both to fishing vessels and harbours. As on the west coast, the government's incipient implementation of the small-scale fisheries policy could facilitate and provide powerful incentives for cooperative climate change adaptation initiatives in this fishery.

Adaptation measures that have been considered (and in some cases initiated) in the inshore jig fishery for chokka squid are to improve vessel safety and sea-going ability; strengthen harbour defences (with benefits also for the small-scale line-fishery) and improve disaster responses against an anticipated increase in storms; encourage diversification, and to introduce insurance schemes and cooperatives to cushion fishers against a severe downturn in catches (Augustyn *et al.*, 2018). Note, however, that despite its apparent ability to adapt in the long-term, the industry currently has very limited ability to adapt to short-term fluctuations in catch, evidenced for example, by the extreme hardship suffered by fishers and their dependents in 2013, when catches dropped unexpectedly to less than half those of the previous year (Augustyn *et al.*, 2018).

Adaptation options for the sardine fishery include targeting anchovy using alternative fishing methods such as midwater trawling off the south coast, where they occur in abundance but are not presently caught, and processing it for human consumption.

11.4 EAST COAST

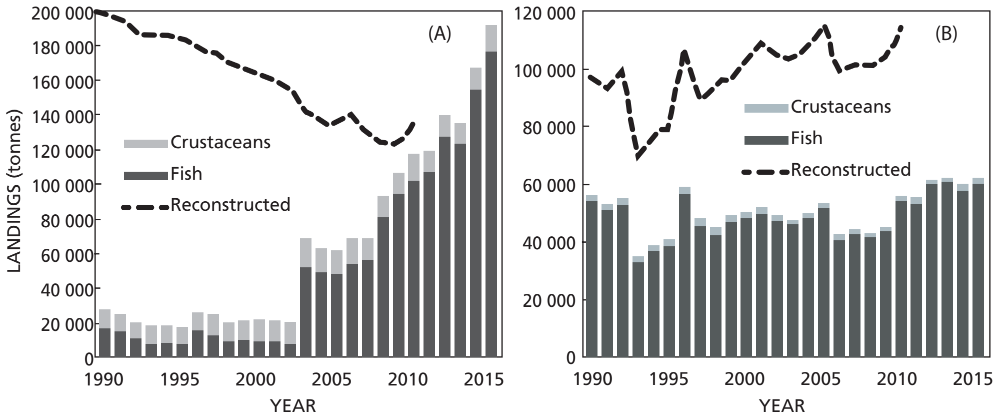
11.4.1 Fisheries of the region

South African fisheries
The most important fisheries here are the shore and small-boat based fisheries for a wide range of line-fish along the Eastern Cape and Kwazulu-Natal coasts. Many of these species are the same as those caught inshore on the south coast, especially along the Eastern Cape coast, and landings of the commercial and recreational boat-based fisheries off the South African east coast are around 1 200 tonnes per annum (Augustyn *et al.*, 2018). Shallow-water prawns (principally *Fenneropenaeus indicus*) and deep-water prawns (*Haliporoides triarthus* and others) are targeted where the shelf widens into the Tugela Bank north of Durban. Catches of deep-water species have fluctuated between 50 and 200 tonnes per annum with a slight increasing trend over the past 25 years. In contrast, catches by the shallow-water fishery have been persistently low for the past decade (DAFF, 2016). Sardine that undertake an annual winter migration from the south coast into KwaZulu-Natal waters during winter (the so-called "sardine run") are harvested by a small, seasonal beach-seine fishery, annual catches of which have not exceeded 700 tonnes (van der Lingen, Coetzee and Hutchings, 2010). The sardine run also supports a recreational fishing and eco-tourism industry whose value in terms of revenue far exceeds that of the small catch from beach-seining (Hutchings *et al.*, 2010). Combined landings of South African fisheries in this region are typically less than 3 000 tonnes per annum (S. Lamberth, DAFF, personal communication).

Mozambican and Tanzanian fisheries
By far the most important fisheries in Mozambique and the United Republic of Tanzania in terms of landings, employment and food security are the artisanal fisheries along the entire coastline for an extremely diverse range of small species including sardinellas (e.g. *Sardinella gibbosa*), anchovies (e.g. *Thryssa vitrirostris*), lethrinids (emperor fish *Lethrinus* spp.) and other fishes that are taken from the beach, estuaries and coastal wetlands, or are caught close inshore, mostly from row or sail boats (Bultel *et al.*, 2015; Doherty *et al.*, 2015). In Mozambique, increasing numbers of people are turning to small-scale fishing in response to decreasing agricultural productivity arising from recent droughts (Benkenstein, 2013). In both countries there are also relatively small semi-industrial and industrial fisheries from larger vessels, which fish for larger fish and penaeid prawns (e.g. *Fenneropenaues indicus*) in deeper water (e.g. the Sofala Bank off Mozambique) and that were initiated in the 1960s.

Reconstruction of marine catches off both Mozambique and the United Republic of Tanzania has been undertaken to account for substantial under-reporting of artisanal catches in both countries and the inclusion of discards by Mozambique's industrial fishery, and reconstructed catches were 6.2 and 1.7 times greater than reported to the FAO for Mozambique and the United Republic of Tanzania, respectively, over the period 1950 to 2005 (Jacquet *et al.*, 2010).

FIGURE 11.5
Annual landings of marine fishes and crustaceans (principally shrimps)



(A) Mozambique and (B) the United Republic of Tanzania from the east coast region, 1990 to 2015, showing annual total country landings as reported to the FAO (histograms; data from www.fao.org) and reconstructed catches (dashed lines) as reported by Doherty *et al*. (2015) for Mozambique and Bultel *et al*. (2015) for the United Republic of Tanzania.

Mozambique's estimated annual marine fishery catches (reconstructed) declined from 200 000 tonnes to around 130 000 tonnes between 1990 and 2010, but FAO-reported catches are now more representative of reconstructed catches and have increased to 180 000 tonnes during the past five years (Figure 11.5A). The United Republic of Tanzania's annual marine fishery catches (reconstructed) have shown a slight increase from mostly below 100 000 tonnes during the 1990s to mostly above 100 000 tonnes in the subsequent decade but there is still a substantial difference (of the order of 45 000 tonnes) between estimated reconstructed catches and those reported to the FAO (Figure 11.5B).

11.4.2 Observed and projected impacts of climate change on the environment

There is satellite evidence that since the 1980s, shelf waters along the South African east coast have warmed throughout the year by between 0.2 °C and 0.5 °C per decade on average, particularly off the Eastern Cape coastline (Lloyd *et al.*, 2012; Rouault, Penven and Pohl, 2009; Rouault, Pohl and Penven, 2010; [Figure 11.3]). The Agulhas Current has become warmer in recent decades, attributed to increased trade winds and a poleward shift in the westerly wind belt in the South Indian Ocean (Rouault, Penven and Pohl, 2009), and there has also been an intensification of mesoscale variability resulting in substantial changes in meanders of the Agulhas Current on its shoreward side (Backeberg, Penven and Rouault, 2012). A recent increase in the frequency and intensity of tropical cyclones originating in the South Indian Ocean has also been reported (Mavume *et al.*, 2009). These, in conjunction with marked changes in rainfall in the interior in recent years, have markedly affected river flow along the KwaZulu-Natal coast in particular (Lamberth, Drapeau and Branch, 2009). Ship-based monitoring programmes off the South African east coast have not to date been comprehensive enough to enable the detection or prediction of long-term trends in variables such as oxygen concentration, phyto- and zooplankton production and ocean acidity in this region.

Similar changes in the marine environment have been observed off Mozambique and the United Republic of Tanzania. Sea surface temperatures along the African east coast have risen over the past 60 years with warming most intense off Mozambique and the United Republic of Tanzania (Lough, 2012). Whereas Mather, Garland and

Stretch (2009) reported that sea level in this region has risen at a rate of almost 3 mm per year between 1967 and 2006, Han *et al.* (2010) identified a distinct spatial pattern in Indian Ocean sea levels since the 1960s, with the south tropical Indian Ocean off the United Republic of Tanzania (but not off Mozambique) showing a substantial decrease in sea level whereas this had increased elsewhere. These trends, together with increases in tropical cyclones, storm surges and flooding that are aggravated by increasingly unpredictable heavy rainfall over the land, will likely impact coastal habitats, resources and infrastructure markedly, impacting the livelihoods of the many fishers along the coast and their dependents. Particular threats in these countries are coral bleaching (McClanahan *et al.*, 2007) and a general decrease in coral cover and changing coral communities (McClanahan *et al.*, 2014), as well as the effect of sea level rise, increased sedimentation and other impacts such as overharvesting and clearing for agricultural use or coastal development on mangrove forests, which extend over large sections of the coast and coverage of which has declined by 20 percent to 30 percent over the past few decades (Lugendo, 2015).

11.4.3 Effects of climate change on stocks sustaining the main fisheries

South African fisheries

The previously noted poleward movement of some 30 estuarine and marine species on the east coast, apparently in response to increases in temperature, changes in circulation patterns and in particular decreases in river inflow, has resulted in severely reduced catches of some of the exploited line-fish species there (Augustyn *et al.*, 2018). Predicted changes in precipitation and freshwater abstraction suggest that catches are likely to continue declining. Similarly, ocean warming off Kwazulu-Natal has resulted in a change in the species composition of reef fish, with the relative proportion of temperate species decreasing and that of tropical species increasing (Lloyd *et al.*, 2012). There has also been a decline in the abundance of other co-habiting lightly- or unexploited species, suggesting a common environmental driver. In addition to temperature-induced changes in distribution, impacts on fish physiology are also anticipated, with growth rates and reproductive scope likely to decline once critical temperature thresholds are reached (Potts, Götz and James, 2015). The reduced river inflow, arising from reductions in rainfall, aggravated by an increase in water abstraction and other agricultural practices, has caused river mouth closures and a reduction in the deposition of sediment in the near-shore zone, affecting species that utilise estuaries as breeding and nursery areas (Augustyn *et al.*, 2015), or those that rely on nutrients from sediments for growth, such as the shallow-water prawns, which have now become scarce in inshore waters, almost collapsing the trawl fishery there. In addition, there appears to have been a recent reduction in the occurrence and/or magnitude of the sardine run in the past decade (van der Lingen, 2015). This could well be primarily a result of the increase in water temperatures on the east coast shelf and an associated weakening in the circulation processes that favour the migration, but may also be because of increased fishing pressure on sardine on the south coast.

Mozambican and Tanzanian fisheries

Artisanal catches in Mozambique have declined significantly in the past decade or so (Doherty *et al.*, 2015) and critical fisheries resources there are considered over-exploited (Blythe, Murray and Flaherty, 2014). These declines have been attributed both to human factors such as overfishing and destructive fishing practices such as dynamiting (Blythe, Murray and Flaherty, 2014; Yusuf *et al.*, 2015), and to climate disturbances (McClanahan and Muthiga, 2017).

The destruction or degradation of fish spawning and nursery grounds and feeding areas is considered to be the main impact of climate change on Tanzanian fisheries (DoE, 2012), with coral reef bleaching and a reduction in mangrove cover obvious examples. Coral reefs are complex ecosystems with a high faunal diversity and are important to both fisheries and tourism in East Africa, and climate change is considered the greatest threat to coral reefs, principally from rising SST and ocean acidification (Obura, 2015). Coral bleaching has led to substantial damage to coral reefs and changes in these habitats are one of the factors most likely to impact resident fishes in this region (Potts, Götz and James, 2015). However coral reefs appear to have the capacity to adapt to changing temperatures more quickly than previously thought (Baker *et al.*, 2004), and Hughes *et al.* (2003) suggested that coral reefs will change their species composition rather than disappear, with likely changes in the associated fish fauna towards more generalist species (Jones *et al.*, 2004). McClanahan and Muthiga (2017) reported that the environmental and biodiversity portfolio characteristics necessary to promote coral species adaptation and persistence during rapid climate change exist in northern Mozambique. However, low fisheries compliance and widespread migratory fishing that reduced fish diversity and biomass on the reefs resulted in negative impacts on coral reef community life-history characteristics, emphasizing the need for increased management restrictions and compliance in order to sustain these climate-adaptive centers.

Similarly, mangrove forests are preferred nursery habitats for many species, including several fishes and the commercially important shrimp species, and the continued decline of mangrove cover will likely reduce recruitment of these species with deleterious effects on both the small-scale and the semi-industrial prawn fisheries. Other negative effects of mangrove forest loss include decreased estuarine biodiversity and shoreline protection from extreme weather events (Lugendo, 2015), and increased sedimentation and erosion, which have negative impacts on seaweed farming conducted in adjacent, shallow intertidal areas (Quinn *et al.*, 2017). As off the South African east coast, changing rainfall patterns will impact estuarine and near-shore areas in Mozambique and the United Republic of Tanzania, with low rainfall resulting in the closure of estuaries, which also serve as important breeding grounds for shrimps and small pelagic fishes that support small-scale fisheries (Benkenstein, 2013).

11.4.4 Vulnerability and opportunities for the main fisheries and those dependent on them

South African fisheries

The evidently strong response to environmental forcing of fish targeted by the line- and net-fisheries along the South African east coast, together with the socio-economic importance of these fisheries, and (with the exception of the recreational sector), the very low adaptive ability for a variety of social reasons, were major considerations in the small-scale line-fishery as a whole being rated as the marine fishery most vulnerable to climate change in South Africa (Hampton *et al.*, 2017).

Mozambican and Tanzanian fisheries

The national economies of Mozambique were ranked as the eighth and the United Republic of Tanzania the 31st most vulnerable to climate-change driven impacts on fisheries by Allison *et al.* (2009). However, unlike in the agriculture sectors in these countries, which have received much more attention because of their greater contribution to the GDP in both, there have not yet been any comprehensive vulnerability assessments for the marine fisheries sectors of these countries. Mozambique's National Climate Change Adaptation and Mitigation Strategy (MICOA, 2012) identifies fishing as particularly vulnerable to climate change, primarily as a consequence of rising seawater temperatures and changes in the distribution and availability of fish stocks. Similarly, the United Republic of Tanzania's NAPA (DoE, 2007) considered the coastal and marine resources of that country to be highly vulnerable to climate change because of their substantial role in economic and social development, primarily because of increases in seawater temperature and sea levels which would negatively impact coastal resources and infrastructure. Cinner *et al.* (2012) reported that the United Republic of Tanzania's coral reef fisheries were the second-most vulnerable to climate change impacts (coral bleaching) of five Western Indian Ocean countries (Kenya, Madagascar, Mauritius, Seychelles and the United Republic of Tanzania), primarily because of high sensitivity of these ecosystems coupled with low adaptive capacity. Anderson and Samoilys (2016) attempted to assess the vulnerability to climate change of the Tanzanian fishery for small pelagic fish, and reported that inadequate fisheries data represents a serious challenge to understanding the sensitivity of this resource to climate change, which limits the tracking of (and subsequent adaptation to) climate change impacts, and insufficient social data make it difficult to assess the fishers' adaptive potential. From the large number of people involved, their generally poor circumstances, their heavy and increasing dependence on fishing for their subsistence, and their vulnerability to damage to coastal infrastructure, there can be little doubt that the artisanal fishers in both countries are those most vulnerable to climate change. Those most exposed in terms of their geographical location are likely to be most threatened.

11.4.5 Responses and adaptation

South Africa

The adaptation measures that have been suggested for the South African small-scale line-fisheries in general, are applicable to the east coast as well, particularly those aimed at improving safety and operability in response to the threat of increasingly severe weather perturbations from the South Indian Ocean. Because of the changing species base caused by environmentally-driven emigration and immigration of certain species, measures to target alternative species and/or make better use of catches through infrastructure development, would also seem to be of particular importance. It is hoped that, as on the west and south coasts, improved coordination and communication between fishers, and between small-scale fishing communities and government, espoused by the South African small-scale fisheries policy, will be effective in increasing awareness of climate change among these fishers, and in assisting them to adapt to it.

Mozambique and the United Republic of Tanzania

Neither Mozambique nor the United Republic of Tanzania have yet developed specific national plans for increasing the resilience of their marine fisheries to climate change. However, both countries have recognized the need to do so and have made some progress towards doing so (see below). Both countries have opted to concentrate on raising awareness of climate change among small-scale fishing communities, and are moving towards rights-based local resource management and participatory fisheries management as primary adaptation measures. Some of the adaptation initiatives for small-scale fisheries elsewhere in the region (particularly in the artisanal fishery in Angola, which faces similar challenges in many respects) could well apply to the East African artisanal fisheries as well. Both Mozambique and the United Republic of Tanzania are participants in the Southwest Indian Ocean Fisheries Governance and Shared Growth Programme (known as the SWIOFish programme[2]) of the World Bank/Global Environmental Facility, which aims to enhance regional collaboration in fisheries research and management, improve governance of priority fisheries including

[2] http://projects.worldbank.org/P132123/south-west-indian-ocean-fisheries-governance-shared-growth?lang=en

developing fisheries resilience to climate change, and increasing economic benefits from priority fisheries.

Mozambique's National Climate Change Adaptation and Mitigation Strategy (MICOA, 2012) identified increasing water temperatures, sea level rise and increasing tropical cyclones as the major climate change impacts on its fisheries sector. Increasing the resilience of the fisheries sector to these impacts is to be achieved by promoting aquaculture as a response to decreasing fish stocks and increasing demand; regenerating mangroves and implementing protective measures for sea grass, corals, and other important areas for fish spawning and feeding; improving information quality to and skills of small-scale fisheries; and reinforcing control and management measures for fisheries to facilitate stock renewal and maintenance. Coastal zones, fisheries and tourism combined comprise one of the ten thematic areas to be addressed by the Centre for the Management of Climate Change Knowledge through the collection and dissemination of relevant knowledge, conducting vulnerability studies, contributing to the formulation and monitoring of climate change policies and strategies, and meeting research needs (MICOA, 2012).

Mozambique has adopted a participatory fisheries management approach by establishing a country-wide, community-level organizational system that brings together fisheries community councils and government extension workers to cooperate on a variety of issues, including climate change impacts on fisheries, and which link into the national governance system (FAO, 2014). Important actions to strengthen resilience in fisheries include the development of flexible, climate-adaptive fisheries policies able to react quickly to changing environmental conditions, investigating the socio-economic impacts of climate change, and harmonizing climate change and disaster management response policies between capture fisheries and aquaculture (FAO, 2014). The development of early warning systems for extreme weather (cyclones) using simple technology (flag/traffic light system and/or cellphones) is presently being piloted by Mozambique's Ministries of Fisheries and of Meteorology.

Coastal communities in Mozambique have adapted to declining catches in different ways and depending on their investment levels (Blythe, Murray and Flaherty, 2014); specialized fishers with a relatively high investment in fishing gear adapt by intensifying their fishing efforts whereas poorer fishers with less investment adapt by livelihood diversification into non-fishery sectors. In both groups adaptation is facilitated by fishers' groups, occupational pride and family networks, and inhibited by limited assets, competition over declining resources and poverty. Adaptation is thus a heterogeneous process influenced by multiple factors, hence understanding the complexity of fishers' responses to changes is critical for fostering adaptive capacity in coastal communities (Blythe, Murray and Flaherty, 2014).

Strategic objectives for fisheries outlined in the United Republic of Tanzania's national climate change strategy (DoE, 2012) include increasing the protection and conservation of aquatic ecosystems (e.g. mangroves), exploring alternative and/or diversified livelihoods for fishing communities, and promoting environmentally friendly adaptive technologies in fish catching, processing and storage. These will be achieved by improved monitoring of fisheries habitats and species, enhancing the protection of aquatic systems, facilitating the development and/or enhancement of integrated data management systems within the fisheries sector, and supporting alternative livelihood initiatives for fishing communities including the promotion of aquaculture. Measures to protect mangrove forests through the establishment of conservation areas and replanting in deforested areas have been included in an integrated coastal area management programme developed for Zanzibar. Whereas protected areas do seem to reduce exploitation pressure on mangroves, the effectiveness of the integrated coastal area management programme to conserve mangroves in the face of apparent increasing exploitation remains unclear (Quinn *et al.*, 2017).

The majority of communities in coastal areas in the United Republic of Tanzania depend on fishing as a dominant economic activity (Sigalla, 2014) with some also utilizing mangroves for firewood and timber, as well as being engaged in farming. In some communities, declining catches, destructive fishing practices and illegal mangrove cutting have been addressed through participatory management between communities and local District Councils, as in Mozambique. These included the delineation of collaborative management areas and the development of specific management plans for each, including area closures, monitoring and enforcement, and have resulted in significant declines in dynamite fishing and the recovery of coastal resources (Verheij, Makoloweka and Kalombo, 2004). Other communities have responded to their increased awareness of mangrove forest loss by introducing protection and rotational harvesting schemes (Quinn *et al.*, 2017). Despite some success, however, Mwaipopo *et al.* (2011) point out that coastal community-based organizations in the United Republic of Tanzania operate in a dynamic environment with changing social, economic and political contexts that impact on their activities, and that a lack (in most cases) of a legal mandate for such organizations severely constrains their capacity to engage in sustainable natural resource use practices. In other communities, declining fish catches were primarily seen as an effect of increased fishing effort and not an impact of climate change, and adaptation and coping strategies were focused on farming operations and alternative livelihoods that did not include fishing (Mbwambo *et al.*, 2012).

A similar pattern of adaptation strategies to those observed in Mozambique coastal communities (Blythe, Murray and Flaherty, 2014) was reported by Cinner *et al.* (2011) for Tanzanian communities; fishers that would employ amplifying responses (such as increasing fishing effort) in the face of declining catches had greater economic wealth, whereas those that would adopt dampening responses (such as reducing fishing effort) tended to have alternative livelihood options. The characteristic that fishers having higher levels of infrastructure development and economic vitality are less ready to exit a declining fishery compared to those with alternative livelihood options and lower catch value appears to be a general phenomenon in Western Indian Ocean fishing communities (Daw *et al.*, 2012).

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Chapter 12: Climate change impacts, vulnerabilities and adaptations: Western Indian Ocean marine fisheries

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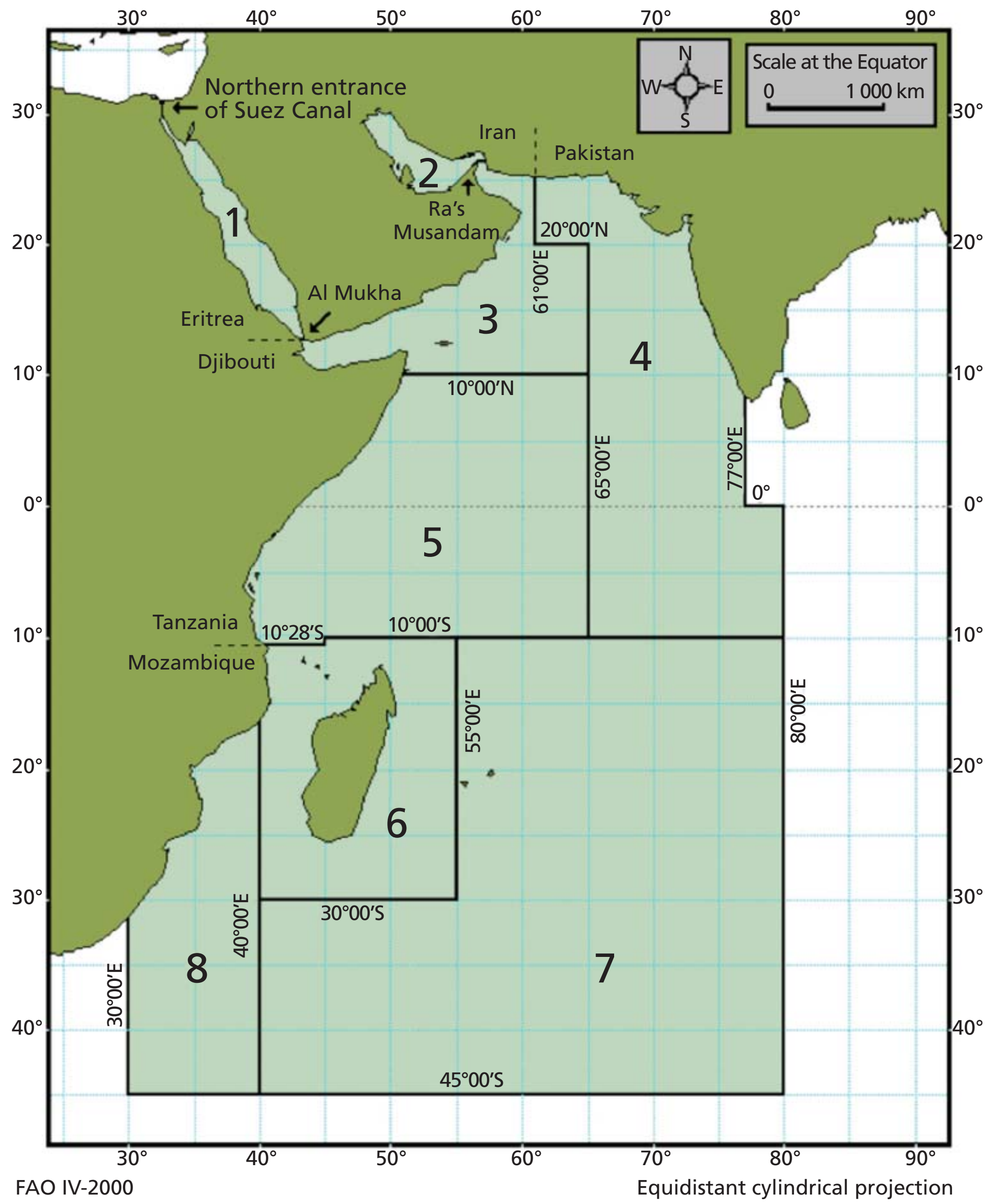
KEY MESSAGES

- The economies of many countries and small island developing states (SIDS) around and in the Western Indian Ocean (WIO) are strongly dependent on large-scale commercial industrial tuna fisheries and small-scale coastal fisheries.
- Climate change has already had observable impacts on fisheries throughout the WIO. Mounting evidence indicates that climate change is causing tuna species to shift spatial distributions and range, and is expected to have knock-on effects on coral reef fisheries in the WIO.
- Warmer habitats with declining productivity, increased human pressure on less resilient coastal ecosystems, and major changes in distribution of large pelagic species will induce strong social and economic impacts in the WIO.
- As a response to changing spatial distribution, the mobile industrial fleets targeting tuna and billfish would relocate outside the WIO. For locally operated domestic fleets in the WIO, innovation in fishing techniques and gears will be a requirement to adapt and mitigate the impact of evolving habitat.
- Whenever catch or effort allocation systems are in place for migrating species, they should be adjusted periodically to account for the spatial patterns of target species.
- Monitoring, information dissemination and awareness of vulnerabilities to climate change in the WIO are currently weak and should be strengthened through community-level vulnerability assessments, integrated monitoring programmes that are effective and feasible with existing capacities, complemented by implementation of an ecosystem approach to fisheries (EAF).
- Existing adaptive measures that could benefit the sector in the WIO include 1) developing and implementing fishery-specific adaptive management plans, 2) implementation, or strengthening, of effective systems of marine protected areas (MPAs), 3) implementation of an EAF, the *FAO Code of Conduct for Responsible Fisheries and Voluntary guidelines on small-scale fisheries* and 4) a sustainable, inclusive blue economy approach.
- Partnerships at the local, regional and international levels will be key to achieving capacity development for effective management of marine and coastal fisheries, and building adaptive capacity and resilience to climate change in the WIO region.

FIGURE 12.1
Western Indian Ocean FAO major fishing area 51 and subareas (FAO, 2004)



12.1 FISHERIES OF THE REGION

The Western Indian Ocean (WIO, FAO major fishing area 51; FAO, 2004) extends from eastern South Africa in the south to India and the Arabian Gulf in the north. The present chapter deals only with the subareas 51.5, 51.6, 51.7 and 51.8 (Figure 12.1), which include ten countries: Comoros, Kenya, Madagascar, Mauritius and the dependent Rodrigues, Mozambique, Seychelles, Somalia, South Africa, the United Republic of Tanzania and the French dependent territory of Réunion (France). The region has a mainland coast that extends over 11 000 km (with over 3 000 km in Somalia) and a coastal population of over 69 million within the 100 km coastal strip (Obura *et al.*, 2017a).

These countries are highly diverse and include SIDS whose people and cultures are profoundly influenced by their large ocean territories, and continental countries whose economies are only partially dependent on the sea. The countries vary in their reliance on agriculture, fisheries, tourism, service industries and banking, and in their cultures, religions and histories. However, they all share one ocean, and this ocean realm is increasingly seen as a new frontier for development, as a basis for economic growth and to lift lower-income countries out of poverty (Obura *et al.*, 2017a).

The WIO region is characterized by high diversity in both species and ecosystems and it is the world's second richest marine biodiversity hotspot (Obura, 2012; Veron *et al.*, 2015). There is also diversity in its people and in their uses of marine resources. A great number of people live at or close to the edge of the ocean (Obura *et al.*, 2017a), and many of them rely on marine resources for food and employment. For example, in Mozambique, where there are 90 000 fishers, it is estimated that 50 percent of the population's protein intake comes from fish (FAO, 2016a). The importance of the ocean and in particular of fisheries to the people of the WIO region cannot be overstated.

The fisheries sector generates nine percent of the gross marine product in this region (Obura *et al.*, 2017a). Of this total, 87 percent is from large-scale commercial and industrial or semi-industrial fisheries, of which tuna is the most important source of national revenue (Marsac, 2017). Artisanal or small-scale fisheries are undertaken by fishing households with small amounts of capital and access to simple gear that can be used from the shore or small boats. Fishing gear includes sticks, spears or harpoons, nets (cast, drag, mosquito, seine and gillnets), hand- and long-lines with hooks, and several trap types (Fulanda *et al.*, 2009). Boats include traditional dugouts and small craft constructed of planks and propelled by sail, as well as some more modern boats with outboard engines and larger dhows with lateens and inboard engines for fishing further offshore (Munga *et al.*, 2014).

Small-scale fisheries account for most of the catch by volume. A study from Madagascar shows that small-scale fisheries were responsible for 72 percent of total fisheries landings (Le Manach *et al.*, 2012). These fisheries are critical in supporting livelihoods, food and income security, particularly for the coastal poor. For the SIDS in particular, fisheries rank high in historical and cultural importance, as well as in their contribution to national economies. For example, 30 percent of gross domestic product in the Seychelles comes from industrial fisheries (Groeneveld, 2016).

The world's second largest tuna fishery occurs in the Indian Ocean, providing significant economic benefits for countries and fishing communities. The tuna catch in the Indian Ocean is worth USD 2.3 billion per year, representing 20 percent to 24 percent of the world tuna supply. Of this, 70 percent to 80 percent, around 850 000 tonnes valued at over USD 1.3 billion, is caught in the WIO (Obura *et al.*, 2017a).

The Indian Ocean Tuna Commission (IOTC)[1] is the intergovernmental regional fishery management organization, established under the framework of the Food and Agriculture Organization (FAO), with a mandate to manage tuna and tuna-like species in the Indian Ocean. While IOTC has the responsibility for the management of tuna resources, other regional organizations or agreements contribute to fisheries governance, such as the Southwest Indian Ocean Fisheries Commission (SWIOFC)[2], the South Indian Ocean Fisheries Agreement (SIOFA)[3], the Southern African Development Community (SADC)[4], the New Partnership for Africa's Development (NEPAD)[5] and the *Commission de l'Océan Indien* (COI)[6]. Kenya, Mozambique and

[1] http://www.iotc.org/
[2] http://www.fao.org/fishery/rfb/swiofc/en
[3] http://www.siofa.org/
[4] http://www.sadc.int/
[5] http://www.nepad.org/
[6] http://www.commissionoceanindien.org/accueil/

the United Republic of Tanzania are developing a set of minimum terms and conditions to provide a collective approach to granting fishing access for highly migratory and shared fish stocks under the 2003 Maputo Declaration (Maputo Declaration, 2003).

While skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obesus*) and albacore (*Thunnus alalunga*) tuna stocks are still estimated by the IOTC to be in a healthy state, others like the yellowfin tuna (*Thunnus albacares*), are considered to be overfished (IOTC, 2016). The Commission's scientific committee predicts that if immediate steps are not taken, there is a high risk of severe depletion of the yellowfin stock within just five years. At the 20th Session of the IOTC in 2016, governments adopted harvest control rules for skipjack tuna and steps to reduce catches of yellowfin tuna (IOTC, 2016).

This chapter addresses the vulnerability of marine fisheries in the WIO to climate change. It summarizes the observed and projected changes to the physical, chemical, biological, and ecological features and fish habitats in the region; how these changes are likely to affect fish stocks; implications for economic development, food security and livelihoods; and the priority adaptations needed to minimize the threats and maximize the opportunities.

12.2 OBSERVED AND PROJECTED EFFECTS OF CLIMATE CHANGE ON MARINE ENVIRONMENTS RELEVANT TO FISHERIES

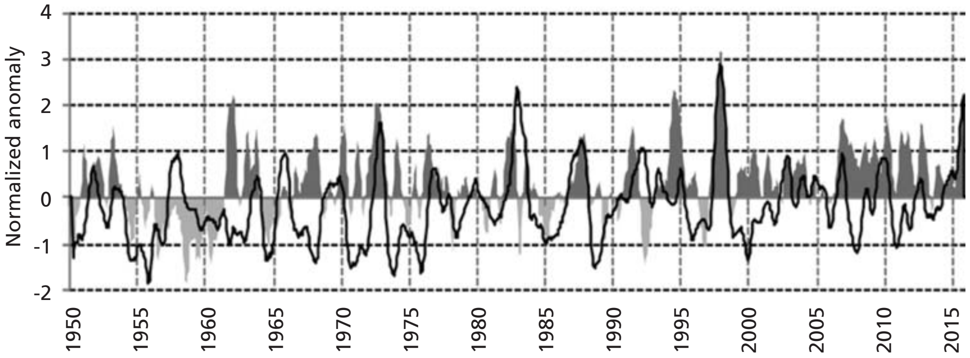
12.2.1 Effects on physical and chemical features of the ocean

Climate change is expected to affect the marine environment substantially by modifying the physical and chemical properties of seawater, including temperature, salinity, currents, vertical stratification and oxygen concentration (Gruber, 2011), with important consequences for the primary production of the global ocean (Steinacher *et al.*, 2010).

In the WIO, increasing warming has been observed for more than a century, at a rate faster than any other region of tropical oceans (Hoegh-Guldberg *et al.*, 2014; Roxy *et al.*, 2014). The sea surface temperatures (SST) in the WIO increased by 0.60 °C between 1950 and 2009 (high confidence; p-value ≤0.05; Hoegh-Guldberg *et al.*, 2014). Trends in SST and sea surface salinity (SSS) vary with location along the East African coastline, with faster rates at higher latitudes. The WIO is an evaporation-dominated region with elevated salinity up to 0.2 psu (Durack and Wijffels, 2010) and there is high confidence that the observed trends in SSS will continue as average global temperature increases (Durack and Wijffels, 2010).

Roxy *et al.* (2014) using observations and global coupled ocean–atmosphere model simulations showed compelling evidence that, besides a direct contribution from greenhouse warming, the long-term warming trend over the WIO during summer is highly dependent on the asymmetry in the El Niño–Southern Oscillation (ENSO) teleconnection, and the positive SST skewness associated with ENSO during recent decades. The extreme positive Indian Ocean Dipole (pIOD) event that occurred in 1997/98 was highly correlated with ENSO and coincided with an outstanding El Niño event. Other intense warming episodes in the WIO (1982/83, 2015/16) were also associated with El Niño events (Figure 12.2; Marsac, 2017). The frequency of extreme pIOD events are projected to increase by a factor of almost three, from one event every 17.3 years over the twentieth century to one event every 6.3 years over the twenty-first century under scenario of representative concentration pathway (RCP8.5) (Cai *et al.*, 2014).

FIGURE 12.2
Dipole mode and El Niño events, 1950 to 2015



The dipole mode index shown in grey shading and El Niño sea surface temperature anomalies (black line). Series have been normalized and smoothed using a five–month running mean. Adapted from Marsac, 2017.

Long-term ocean acidification trends are clearly evident over the past several decades in open ocean time series and hydrographic survey data, and the trends are consistent with the increase in atmospheric carbon dioxide (CO_2; Dore *et al.*, 2009). Surface ocean pH is estimated to have dropped from a mean of 8.2 at pre-industrial CO_2 levels to a current mean of 8.1, or by about 0.1 pH units, and further increases in atmospheric CO_2 are virtually certain to lead to further acidification of the ocean and change its carbonate chemistry. Nearly doubling atmospheric CO_2 (as in the scenario for RCP4.5; Bopp *et al.*, 2013) would decrease ocean pH by another 0.1 pH units and decrease carbonate ion concentrations by approximately 100 µmol/kg in tropical oceans from the present-day average of 250 µmol/kg (high confidence). Projected changes for the open ocean by 2100 range from a pH change of -0.14 pH units under RCP2.6 (421 ppm CO_2, +1 °C, 22 percent reduction of carbonate ion concentration) to a pH change of -0.43 pH units under RCP8.5 (936 ppm CO_2, +3.7 °C, 56 percent reduction of carbonate ion concentration) (Hoegh-Guldberg *et al.*, 2014).

Interestingly, sea surface pH in the WIO is projected to decrease by 0.1 while subsurface dissolved oxygen (between 200 m and 600 m depth) is projected to increase by 25 mmol/m^3 by 2090 to 2099 under the RCP2.6 scenario (see Figure 6 in Bopp *et al.*, 2013). Two stressors are projected to hit extremes under the RCP8.5 scenario (see Figure 14 in Bopp *et al.*, 2013). First, in the northern WIO, SST in 2090 to 2099 will exceed the global threshold of 3.64 °C. Second, the integrated net primary production in the Equatorial WIO during the same decade will decrease by significantly more than its annual global threshold value of -79.8 gC/m^2. See Figure 14 of Bopp *et al.* (2013) for details of computation of global thresholds.

Over the last five decades, dissolved oxygen has decreased at a rate of 20 to 30mol/m^2 per decade (about five percent of the global change in dissolved oxygen) in the WIO (see Figure 1b and extended data Table 1 of Schmidtko, Stramma and Visbeck, 2017; also see Breitburg *et al.*, 2018), and is consistent with that expected from higher ocean temperatures increasing stratification. There is high agreement among modelling studies that oxygen concentrations will continue to decrease in most parts of the WIO and its coasts because of the effect of increased temperature on oxygen solubility, microbial respiration rates, ocean ventilation, and ocean stratification (Andrews *et al.*, 2013; Breitburg *et al.*, 2018), with implications for nutrient and carbon cycling, ocean productivity, marine habitats, and ecosystem structure.

The Indian Ocean warming and the associated wind changes are having a strong impact on the Indian Ocean currents. Rahul and Gnanaseelan (2016) showed the existence of coupled feedback between Indian Ocean warming trends and circulation changes. The mean westerly winds over the equatorial Indian Ocean have strengthened in recent years (1958 to 2015; Gnanaseelan, Roxy and Deshpande, 2017). In the WIO, the observed strengthening of the Southern Hemisphere westerlies has been linked to possible increasing of Agulhas leakage (AL) in modelling studies of Durgadoo *et al.*, 2013 and Loveday *et al.*, 2014. However, the current itself does not seem to have strengthened (Beal and Elipot, 2016; Yang *et al.*, 2016), but rather it has been getting wider (Beal and Elipot, 2016). This has an important implication for global climate change, suggesting that intensifying winds over this region may be increasing the turbulence of the current, rather than increasing its flow rate. In the long term, simulations suggest that the AL is expected to strengthen (Biastoch *et al.*, 2015) as a result of continued strengthening of the westerlies.

While the mean global and Indian Ocean sea levels have risen during the past decades, the sea level has decreased substantially in parts of the western equatorial Indian Ocean near Zanzibar, a pattern that is driven by changing surface winds associated with enhanced convergence in the near-equatorial region coming from both north–south and east–west overturning atmospheric circulation cells, which are partly attributable to the warming caused by raising of the atmospheric greenhouse gases (see Figure 4 of Han *et al.*, 2010). This contrasting finding to the global sea level rise needs to be monitored carefully in the near future (Hinkel, Brown and Exner, 2012). The Seychelles-Chagos Thermocline Ridge region (SCTR; Vialard *et al.*, 2009), which extends from the Somali Coast across the Indian Ocean within the latitude band (5 °S to 15 °S) is a relatively shallow thermocline, has a thin mixed layer (approximately 30m), and is a very productive upwelling region. While the SST is rising, the thermocline has been shoaling (becoming shallower) westward (Alory, Wijffels and Meyers, 2007) since 1960 in the SCTR. How future global warming may affect the SCTR and its impacts on patterns of weather variability, marine biogeochemistry and fisheries is uncertain (Hood *et al.*, 2018).

12.2.2 Effects on biological and ecological features of marine environments

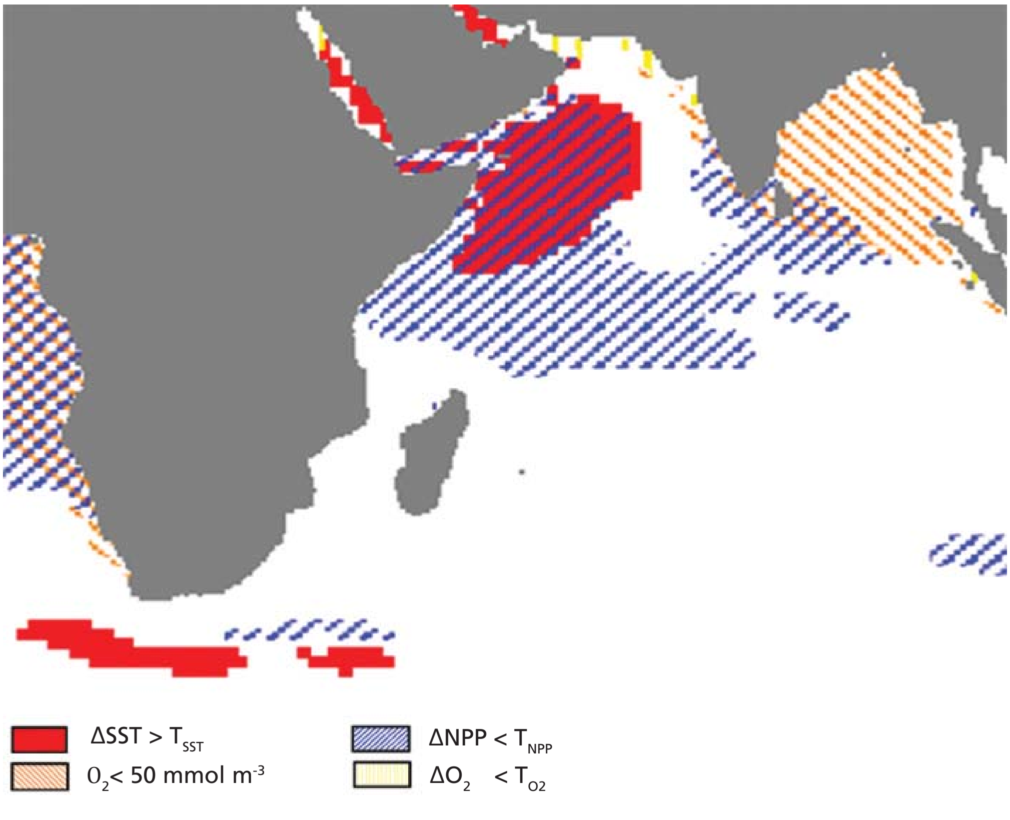
Oceanic food webs

The rapid ocean warming described in Section 12.2.1 has already resulted in increased surface stratification over the Indian Ocean. Re-assessing the coupling between SST and chlorophyll with observations and simulations in the WIO, Roxy *et al.* (2016) found a negative trend in surface chlorophyll, by 30 percent in the observations and 20 percent in the simulations over the past six decades. The main reason for the decline in phytoplankton is attributed to enhanced stratification of the ocean water column as a result of rapid warming, which suppresses upwelling of nutrients from subsurface layers and reduces the primary productivity.

Future climate projected changes in net primary productivity (NPP) in the Indian Ocean show that similar to other oceans, there is a great spatial heterogeneity. However, in the WIO changes in NPP show a strong decrease. The average annual loss is around -120 gC/m^2 (for the highest CO_2 scenario) and -40 gC/m^2 (for the high mitigation scenario) by 2100, representing a decrease of 50 percent and 20 percent of the actual production respectively (Figure 6 in Bopp *et al.*, 2013). These changes can potentially weaken marine food webs through reduced energy flow to higher trophic levels and a shift towards a more detritus-based system, leading to food web simplification and altered producer–consumer dynamics, both of which have important implications for the structuring of marine communities (Ullah *et al.*, 2018). WIO primary productivity could also be reduced as a result of ocean acidification (Cooley *et al.*, 2009). Increased acidity in the ocean may cause dramatic changes to phytoplankton (Dutkiewicz *et al.*, 2015), especially those with calcareous shells such as coccolithophores (like *Emiliania huxleyi*) as well as macroalgae with similar structures, such as *Halimeda* spp.

Downward trends in primary production over the WIO can be detrimental to the marine food webs and the fishing industry, especially the tuna fishing industry. Large-scale distribution of the dominant species of tunas is associated with phytoplankton availability and abundance (Lee, Chen and Tzeng, 2005). Any changes to primary productivity will likely put additional stress on fisheries resources in this region where oxygen depletion, acidification and overfishing have already impacted the resources (Obura *et al.*, 2017a). However, in order to fully understand the totality of the ecosystem response to changing stratification, careful data gathering will be needed. It is, however, definitive that the WIO is warming, and Climate Model Intercomparison Project version 5 (CMIP5) future simulations project a further decline in marine primary productivity in the coming decades (Bopp *et al.*, 2013; Figure 12.3). The Indian Ocean may thus need to be monitored more closely to see if it is acting as an early indicator of physical–biological interactions in a warming world (Roxy *et al.*, 2016).

FIGURE 12.3
Change in multiple stressor intensity in 2090 to 2099 relative to 1990 to 1999 under the RCP8.5 scenario



Change in multiple stressor intensity in 2090 to 2099 relative to 1990 to 1999 under the RCP8.5 scenario. Red indicates where sea surface warming exceeds +3.5 °C, hatched yellow indicates where sub-surface (200–600 m) oxygen concentrations decrease by more than 20 µmol/m^3, and hatched blue indicates where vertically integrated annual NPP decreases by more than 100 gC/m^2. In addition, hatched orange indicates present-day simulated low-oxygen (<50 mmol/m^3) in sub-surface (200 m to 600 m) waters. Adapted from Figure 14 in Bopp *et al.*, 2013.

Coastal fish habitats

Coral reefs and their surrounding ecosystems, including mangroves and seagrass beds that provide important fish habitat and support coastal fisheries in the WIO region are already facing unprecedented stress from warming and rising seas, acidification and storms (Obura *et al.*, 2017a). Steep declines in coral reef health resulted from major coral bleaching events in 1998 (25 percent loss) (high confidence; Ateweberhan *et al.*, 2011; Hoegh-Guldberg *et al.*, 2014) and 2016 (ten percent loss). This is the main finding from the latest Global Coral Reef Monitoring Network regional report on the state of coral reefs of the WIO (Obura *et al.*, 2017b). Subsequent recovery from these increases in mortality of coral reefs has been variable between Indian Ocean subregions. For example, around the central Indian Ocean islands (Maldives, Seychelles, Chagos and Lakshadweep) recovery has been fairly slow (13 percent by 2001 to 2005) while Southern India and Sri Lanka are showing much higher rates (achieving a mean coral cover of 37 percent by 2001 to 2005, Ateweberhan *et al.*, 2011).

Similar impacts, although apparently less severe, have occurred in mangroves and seagrass meadows, although these are less well documented than for coral reefs (Lugendo, 2015). However, many of the consequences of the deterioration of these key productive habitats from the combined impacts of local use and climate change are not only the negative impacts on coral reefs, mangroves and seagrass bed communities themselves, but also most likely the decreases in their ecosystem services, such as their function as a nursery for fish species: this translates into shrinking adult fish populations and declining fish catches (Diop *et al.*, 2016).

The consequences of projected sea temperatures on the frequency of coral bleaching and mortality within the WIO region are outlined in Hoegh-Guldberg *et al.* (2014). As with other regions dominated by coral reefs, mass coral bleaching and mortality becomes an annual risk under all RCP emission scenarios, with mass mortality events forecast to begin to occur every one to two years by 2100 (virtually certain; Hoegh-Guldberg *et al.*, 2014; van Hooidonk *et al.*, 2016).

Coral-dominated reef ecosystems (areas with more than 30 percent coral cover) are very likely to disappear under these circumstances by the mid part of this century (van Hooidonk, Maynard and Planes, 2013). Even lower greenhouse gas emission scenarios (such as RCP4.5) are likely to drive the elimination of most warm-water coral reefs by 2040 to 2050 (Hoegh-Guldberg *et al.*, 2017).

12.3 OBSERVED AND PROJECTED EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING PELAGIC AND DEMERSAL FISHERIES

12.3.1 Effects on distribution, abundance, seasonality and fisheries production

Tuna and other large pelagic fish

Variations in population abundance and distribution of pelagic tuna species have been observed to be clearly linked to large-scale climate phenomena such as ENSO in the Pacific Ocean (Lehodey *et al.*, 1997; Torres-Orozco *et al.*, 2006) and the North Atlantic Oscillation in the Atlantic Ocean (Lan *et al.*, 2011).

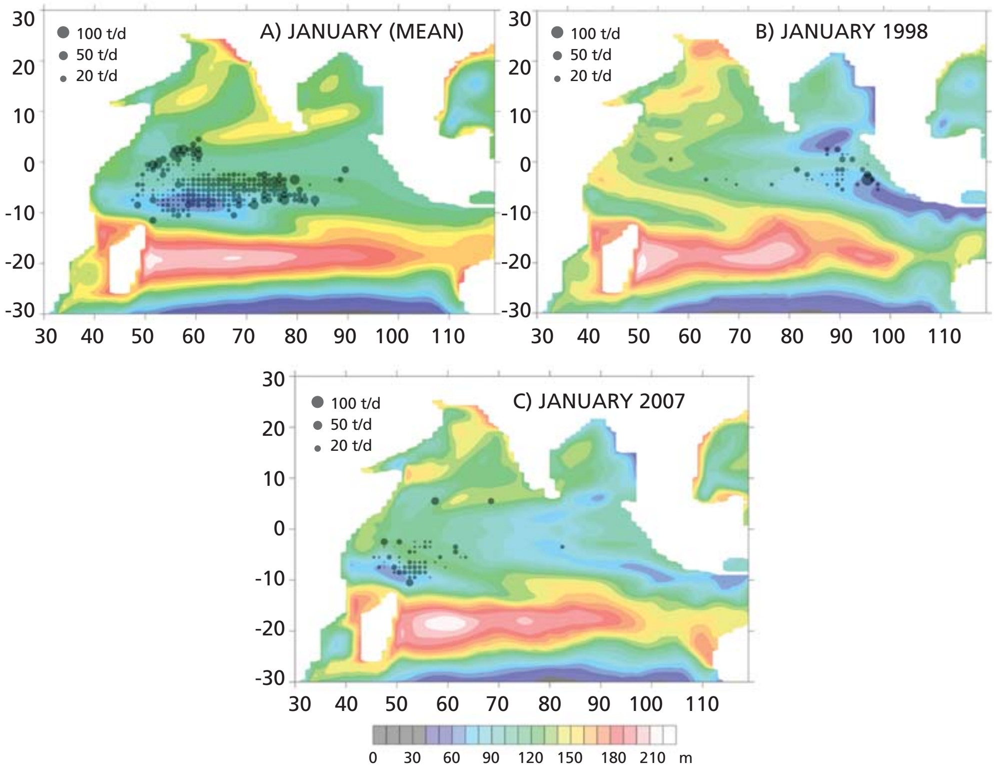
Similarly to the Pacific and Atlantic, variability in the distribution and catch rates of tuna species have also been observed in association with the Indian Ocean Dipole (IOD), a basin-scale pattern of sea surface and subsurface temperatures that affects climate in the Indian Ocean (Lan *et al.*, 2012; Marsac, 2008), and with El Niño events (Kumar, Pillai and Manjusha, 2014; see Section 12.2.1). Lan, Evans and Lee (2013) found that catch per unit effort (CPUE) of yellowfin tuna was observed to be negatively correlated to the IOD with a periodicity centred around four years. During positive IOD events, SSTs were relatively higher, NPP was lower, CPUE decreased and catch distributions were restricted to the northern and western margins of the WIO. During negative IOD events, lower SSTs and higher NPP were associated with increasing CPUE, particularly in the Arabian Sea and seas surrounding Madagascar, and catches expanded into central regions of the WIO.

The anomalously high sea temperatures of 1997/98, the result of one of the strongest ENSO events in the last century acting in phase with a positive IOD event (Section 12.2.1), caused dramatic temperature and wind stress anomalies in the equatorial Indian

Ocean (Murtugudde, McCleary and Busalachhi, 2000). This warming event, leading to a deepening of the mixed layer in the west and a shoaling in the east, coincided with anomalously low primary production in the WIO and a major shift in tuna stocks (Figure 12.4, high confidence; Marsac, 2017; Menard *et al.*, 2007; Robinson *et al.*, 2010). Fishing grounds in the WIO were deserted and purse-seine tuna fishing fleets underwent a massive shift toward the eastern basin, which was unprecedented for the tuna fishery (Figure 1 in Marsac and Le Blanc, 1999).

As a result of these changes, many countries throughout the Indian Ocean lost significant tuna-related revenue (Robinson *et al.*, 2010). Many vessels operated from Asian ports (notably Phuket, Thailand), and landings and vessel activity in Port Victoria, Seychelles, decreased substantially, resulting in negative economic impacts for the fishing industry (Payet, 2005). In 2007, tuna fishing revenue was again reduced by strong surface warming and deepening of the mixed layer, and associated with a modest reduction in primary productivity in the west. These trends highlight the overall vulnerability of tuna fishing countries in the Indian Ocean to climate variability, a situation similar to that in the other major oceans of the world.

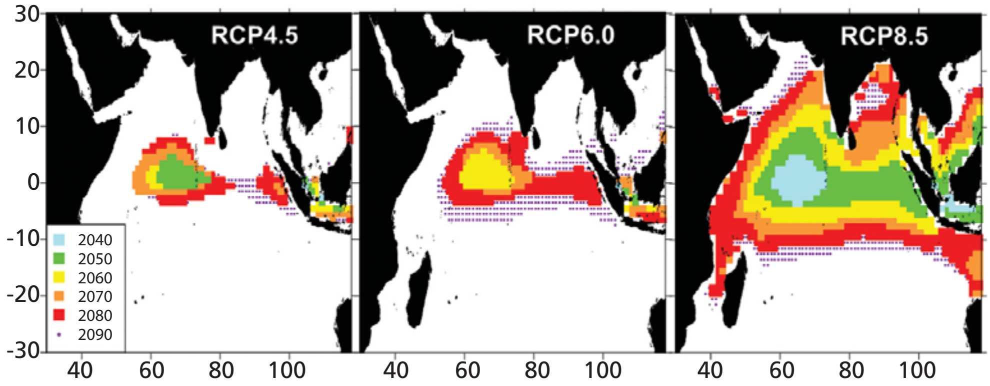
FIGURE 12.4
Purse seine CPUE (tonnes/day) on free swimming schools in January (circles) and 20 °C isothermal depth (m, colour shaded)



Data sources: purse seine catch and effort data are available freely on the IOTC website (http://www.iotc.org/data/datasets); the 20 °C isothermal depth is calculated by interpolation between consecutive depth levels from the Global Ocean Data Assimilation System (GODAS) model outputs of the National Centers for Environmental Prediction (NCEP) (http://www.cpc.noaa.gov/products/GODAS/).
A) Climatological 20 °C isothermal depth in January (1980 to 2005) and average CPUE for 1991 to 2002. Fishing days: 970. CPUE: 8.5 tonnes/day; B) 20 °C isothermal depth and CPUE in January 1998. Fishing days: 1 260. CPUE: 2.0 tonnes/day; C) 20 °C isothermal depth and CPUE in January 2007. Fishing days: 1 367. CPUE: 2.8 tonnes/day. Adapted from Marsac, 2017.

Projections obtained using the Apex Predators ECOSystem Model (APECOSM-E) forced by the Institute Pierre-Simon Laplace Climate (IPSL-CM5) Earth System Model along the last generation of climate change scenarios, highlight the degradation of habitat in equatorial surface water, and project a considerable decrease of skipjack tuna population abundance toward the end of the century (Dueri *et al.*, 2014; Figure 12.5). The model projects deterioration of skipjack habitat in most tropical waters and an improvement of habitat at higher latitudes, and these changes are most pronounced under RCP4.5, RCP6.0 and RCP8.5 emission scenarios. The habitat changes are driven largely by ocean warming, followed by food density changes. The model projections also show an increase of skipjack biomass between 2010 and 2050, followed by a marked decrease between 2050 and 2095 under the "business-as-usual" scenario (RCP8.5). Spawning rates are consistent with population trends, showing that spawning depends primarily on the adult biomass. On the other hand, growth rates display very smooth temporal changes, suggesting that the ability of skipjack to keep high metabolic rates in the changing environment is generally effective.

FIGURE 12.5
Expansion of unsuitable thermal habitats (>31 °C) for the different IPCC scenarios: RCP8.5, RCP6.0 and RCP4.5



Source: Adapted from Dueri *et al.*, 2014.

The projected large-scale redistribution of tropical tuna populations would induce spatial shifts for purse seine fishing. Longline fishing would be less affected as this gear can better mitigate changes by setting hooks in deeper layers (Marsac, 2017). Given the projected long-term degradation of tuna populations and associated fisheries, adaptation strategies must be devised. For example, the Seychelles tuna fishery system would require adaptation to offset the loss caused by a possible decline of purse seine fishing activity in the West Indian Ocean.

Coastal demersal fish and invertebrates

Climate change is expected to have a variety of knock-on effects for coastal fish habitats, demersal fish stocks and invertebrates in the WIO. During the last two decades, the WIO experienced two major warming events that devastated the health of coral reefs and their fish communities. In 1998, one of the hottest years and the strongest El Niño recorded and the strongly positive IOD that decimated tuna catches in the west, also devastated coral reefs in this region. Many locations suffered mortality of 50 percent to 90 percent of corals, and the region experienced the worst impact from this event anywhere in the world (Obura *et al.*, 2002; Spencer *et al.*, 2000, Wilkinson, 2000). The Seychelles and Kenya suffered the greatest mortality of corals (90 percent in the Seychelles) in 1998, but since then have shown recovery of corals. South Africa has shown slight increases in coral cover since monitoring started. The other countries (Comoros, Réunion [France], Madagascar, Mauritius, Mozambique and the United Republic of Tanzania) have all shown a progressive decline in overall cover since monitoring began in each country (Obura *et al.*, 2017b). Severe impacts on fish species were observed: 62 percent of fish species declined in abundance within three years after a loss of more than ten percent of coral cover (Wilson *et al.*, 2006). Following the major bleaching event of 1998, minor bleaching events have been reported in the region, revealing a worrying trend of reduced intervals between larger events and rising temperatures. Then, in 2016 another major bleaching event occurred, which severely impacted coral communities across the IndoPacific (e.g. Hughes *et al.*, 2017).

In the Maldives, the recovery post-1998 occurred within about 10–12 years (Pisapia *et al.*, 2016), a trend replicated at other remote Indian Ocean sites (e.g. Chagos; Sheppard, Harris and Sheppard, 2008). In other areas of the Indian Ocean, recovery trajectories post-1998 were more divergent, with some reefs recovering successfully and others undergoing phase shifts to states with lower coral cover and diminished carbonate budgets (Graham *et al.*, 2015).

Coral bleaching can drive large-scale mortality on even well-managed and geographically isolated reefs (Perry and Morgan, 2017a), and particularly affects those species and genera that typically dominate shallow reef habitats (e.g. Acroporids; Baker, Glynn and Riegl, 2008; Pratchett *et al.*, 2013). A recent study shows that accompanying these coral cover and rugosity declines have been major changes in the relative abundance of both individual coral genera and parrotfish (*Scaridae*) (Perry and Morgan, 2017b). Research by Pratchett *et al.* (2011) looking at four primary functional groups (corallivores, herbivores, planktivores and carnivores), showed that corallivores, for example, displayed a strong trend towards decreased abundance with loss of coral (see also Obura *et al.*, 2017b), while carnivores showed a range of responses, both positive and negative. Overall, more species showed a reduced abundance than an increased abundance.

Coral reefs in the WIO seem to have shifted from a pre-1998 state to a post-1998 state with 25 percent lower coral cover and 2.5 times more algae abundance. For almost two decades, coral and algal covers have been equivalent, which may be an early indicator that at the regional scale, reefs are approaching a threshold, beyond which they may become dominated by algae, or by other non-hard coral invertebrates. This could be exacerbated by the fish communities also shifting from more complex to simpler trophic webs in which herbivory and detritivory by small-sized fish are dominant processes. Exactly what the implications of these regional trends in coral and algal cover and fish community structure are likely to be is difficult to predict (Obura *et al.*, 2017b).

At least in the near future, the major threat to these resources is going to be indirect, from the loss of habitat and ecosystem function of coral reefs resulting from reduced calcification and periodic coral bleaching, a phenomenon that is predicted by some researchers to increase in frequency in the future (FAO, 2016b). There are also potential threats to recruitment, with eggs and larval fish likely to be vulnerable to lower pH levels. Acidification may also constrain growth rates, which in turn may affect fertility or possibly cause sub-lethal physiological effects.

The recovery of benthic and fish populations can vary greatly. Healthy coral populations may recover within 15 years, although over twice as long may be necessary in compromised communities. Fish populations could take 10 to 50 years or more to recover, depending on the key species and impacts, although recovery would be contingent on improvements in fisheries management (Obura *et al.*, 2017a).

12.3.2 Comparative effects of non-climate stressors

As described in Section 12.2, climate change will potentially cause changes to the water temperature, salinity and pH of oceans and to primary productivity over the next decades.

At the same time, degradation of key habitats or fish nursery areas along the coast through destructive anthropogenic practices such as the use of dynamite (Wells, 2009), coral trampling, aquaculture, destructive gear, coral extraction, snorkelling (trampling, habitat disturbance, anchorage), land use (sedimentation and run off), unplanned development, changes in land use and freshwater impoundments, erode the biological systems on which ecological sustainability relies. These non-climatic stressors are reducing coastal demersal fish stocks, destroying their habitats, and impacting livelihoods in this region (Brander, 2007).

The status of key target tuna species in the WIO is assessed as generally good, with only yellowfin tuna subject to overfishing (IOTC, 2017). Fisheries management capacity in the WIO, along with action at the regional level through IOTC, provides the basis for sustainable tuna fisheries management, but improvements in fisheries management, monitoring, control, surveillance and the functioning of regional institutions are all required to maintain healthy levels of tuna stocks. The potential increases in vessel numbers in the coming years, resulting from both coastal state fleet development and an expected return from other parts of the Indian Ocean by some vessels to the WIO, together with illegal, unreported and unregulated fishing practices, and marine pollution such as offshore dumping of waste (UNEP, 2009), could threaten stock status of both target and non-target species unless carefully monitored and controlled.

Human populations in WIO states continue to grow (see Section 12.6), with a concurrent increase in their dependence on food extracted from the ocean. It is difficult to see how the spectre of "too many fishers, too few fish" can be avoided without successful interventions to reduce fishing pressure and mitigate impacts of coastal development on marine resources (Groeneveld, 2016).

12.4 IMPLICATIONS FOR ECONOMIC DEVELOPMENT, FOOD SECURITY AND LIVELIHOODS

12.4.1 Economic development

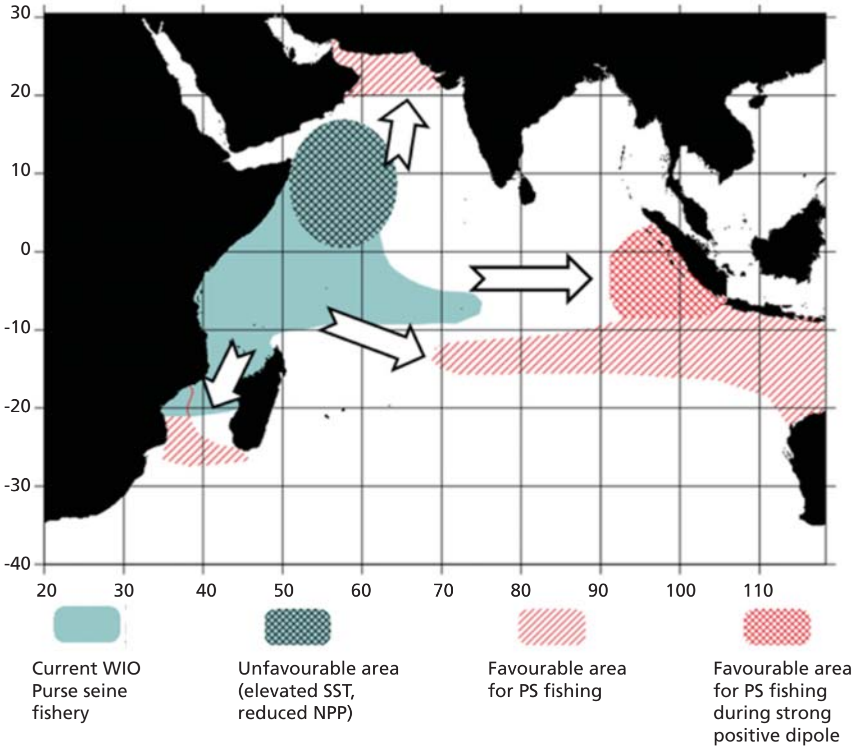
Concerns about the socio-economic impacts of observed and projected climate change have been high on the research agendas of scientists for the last several decades.

Studies have shown that another major spatial shift of the tuna fishing fleets similar to the one that was observed during the 1997/98 El Nino event in the WIO, would have a devastating impact on SIDS that have developed economies that are strongly dependent on tuna fisheries. The analysis conducted by Robinson *et al.* (2010), revealed that the direct, indirect and induced economic effects of the tuna industry expenditures benefiting the Seychelles economy declined in 1998 by 58 percent, 26 percent and 35 percent respectively (mean decline: 42 percent), compared with a yearly growth trend of 19 percent, 3 percent and 5 percent (mean annual increase: ten percent) for the same effects during the period 1992 to 2004, respectively. Thus, the anomalous year 1998 caused a significant dip in the long term growth of the sector which started to recover in 1999.

Based on the projections for the purse seine fishery conducted by Marsac (2017) for the worst case scenario of greenhouse gas emissions by 2100 (Figure 12.6), the potential fishing grounds in the region would shift well outside the core of the current WIO fishery, to the North Arabian Sea, South Mozambique Channel, Southeast Indian Ocean and off Sumatra (during strong positive dipole events) in the second half of the century. The longline fishery would not be as affected as the purse seine fishery and the WIO and Seychelles EEZ could remain potential longline fishing grounds under conditions in which deep longlining is performed. Under the high mitigation scenario (RCP2.6), the changes in tuna habitat would not be significant and purse seiners could continue to operate in the same areas as today. Whatever the scenario, the potential decline in catch rates in the WIO cannot be estimated throughout the twenty-first century, because reliable quantitative models able to project abundance trends in relation to the changing climate conditions are not yet available (Marsac, 2017).

FIGURE 12.6

Synoptic sketch of possible spatial shifts of the purse seine fleets operating for tropical tuna in the Western Indian Ocean by 2100, under the highest CO_2 scenario (RCP8.5)



The main shift would occur towards the Southeast Indian Ocean, and would result in a relocation of the purse seine fishing effort. The Mozambique Channel would remain partly suitable for purse seine fishing and a new area would extend to the southern tip of Madagascar. This sketch is purely qualitative, resulting from an expert system-based analysis combining the projected change of stressors (temperature, dissolved oxygen, net primary production), tuna habitat suitability and operational requirements of purse seine with regards to the environment. Note that the wind at the sea surface is not accounted for in this qualitative analysis.
Adapted from Marsac, 2017.

Twenty years after it occurred, coral reefs of the WIO are still recovering from the major El Niño climate event of 1997/98 (Obura *et al.*, 2017b, see also Section 12.3.1). The repeated El Niño events in 2016 combined with increased human pressure and local threats prevent the recovery of coral reefs to their pre-1998 state. Similar impacts, although apparently less severe, have occurred in mangroves and seagrass beds, although these are less well documented than for coral reefs (Lugendo, 2015).

The ongoing loss of productive habitat will likely result in diminished fish catches for coastal communities and reduced protection from storms and rising seas, putting coastal communities in peril. This will reduce the adaptive capacity and resilience of communities to cope with varied natural, social and economic challenges. Collectively these impacts can lead to a "socio-ecological trap" from which resource-users may not be able to escape without significant assistance and better stewardship of their resources (Cinner, 2011). Strong leadership from local to national levels is needed to mitigate the impact of climate change and adapt to projected climate change (see Section 12.6).

12.4.2 Food security and livelihoods

The SIDS depend heavily on seafood, which can account for up to 90 percent of their animal protein intake (FAO, 2016a).

In the Maldives, tuna is the most essential resource for food security and supports livelihoods of the islands' communities. It is also the single most important export commodity, earning about USD 140 million in 2014 (Ahusan *et al.*, 2017). In Comoros, fishing is only artisanal and provides 55 percent of the employment in the agricultural sector and 21 percent of its added value. However, seafood production does not cover the national demand (Soilihi, 2017). Madagascar is affected by persistent food insecurity that affects 65 percent of the population (Black-Michaud *et al.*, 2009). Fishing is the largest foreign exchange revenue in Madagascar but the pelagic fisheries potential is considered under-exploited by local fleets. Artisanal and traditional fishing account for 70 percent of capture fisheries (MRHP, 2015). This sector has a larger socio-economic importance than the industrial component, which represents only 2 300 jobs out of the 100 000 jobs directly related to the marine fisheries. Considering the indirect jobs and the spill-over in coastal communities, it is estimated that sea fishing provides livelihoods to nearly a million people.

Tuna in Seychelles is essentially harvested by locally-based small longliners, and foreign-owned and licensed industrial longliners and purse seiners. The catches of these fleets supply the export market. Canned tuna accounts for 90 percent of total national export value and a large proportion of the purse seine catches are processed by locally-based canning factories. The main target of the artisanal fishery is the demersal fish caught on the plateaus, which are mostly sold on the local market, whereas a small proportion (ten percent) is exported fresh on ice. Overall, the fisheries are a vital source of income, employment, food security and foreign exchange in the country. Although fish products in the Seychelles are less important than in the Maldives in terms of food security (60 kg/yr per capita vs 144 kg/yr), the socio-economic importance of the sector in the former country is indisputable: direct and indirect employment in fisheries and related sectors was estimated to be 5 000 to 6 000 people in 2014, representing around ten percent of total formal employment in the country (SFA, 2014).

As stated in the previous section, the loss of coral reef biodiversity and ecological function has severe consequences for countries in and bordering the WIO. Coral reef-associated fisheries sustain the livelihoods, food security and protein intake of many small-scale fishers in the region. Further, coral reefs are the primary asset for the coastal tourism sector, providing coastal protection, recreation areas and seafood estimated at USD 18.1 billion annually (Obura *et al.*, 2017a). In the Maldives, reef fishes are eaten by tourists and used as bait for fishers supplying tuna, the staple food for the region and main export (Wells and Edwards, 1989). Tackling climate change is a global challenge, but countries in the region must take urgent local action to protect reef health. This includes reversing the rise in those threats under their control, such as destructive fishing and pollution, and taking a proactive approach to improve reef condition and identify reef-specific management actions and options.

12.4.3 Consequences for fisheries management

Tuna ignore EEZ borders as they migrate throughout the ocean basins, thus their stocks must be managed by regional organizations. The IOTC gathers 31 countries, 16 of which are developing coastal states. The Commission is faced with somewhat conflicting goals, such as putting in place measures that ensure sustainable fish stocks through catch limits, and at the same time allowing fleet development plans for developing coastal states. There are ongoing discussions at the IOTC to establish a quota allocation system for the main targeted species, however no final agreement has been reached so far. Several developing coastal states want to ensure that their legitimate development aspirations and food security concerns are accommodated in the allocation system. Other parties would like to ensure that only member states without major compliance issues be eligible for a total allowable catch allocation. Within this context, one major issue is the lack of capacity from many developing states to monitor their catches and comply with the mandatory statistics that are the basis for stock assessment. Similar weaknesses exist in the understanding of management procedures used by the IOTC and their application by member states. Therefore, capacity building programmes on those matters must be pursued with those countries in need.

Tuna stock assessment in the Indian Ocean does not explicitly incorporate environmental variability, and the models used lack an ecosystem perspective. Environmental indicators and ecosystem considerations (e.g. in relation to success of recruitment, catchability, fleet movements or the multi-species nature of tuna fishing) appear in the management advice in an external and qualitative manner only. The projections of the probability of being in a desirable (or undesirable) state under various catch scenarios (so-called Kobe-2 matrix) is a worthy approach that can inform the managers when a management measure has to be taken based on catch reductions. However, it does not account for changes in the carrying capacity of the ecosystem at interannual or decadal scales, when more frequent extreme events are likely to occur with climate change. Environmental variability (in a wide sense) could be better formalized in stock analyses and projections by using ecosystem models to complement the existing set of assessment models. Eventually, the allocation of effort and catch between fishing states that may be implemented in the Indian Ocean, will need to be adjusted periodically to account for changes in the distribution of tuna stocks.

The recovery of benthic and fish populations can take years (Section 12.3), and recovery would be contingent on improvements in fisheries management. Countries in the region must take urgent action to protect reef health. Local and regional stakeholders need to give greater credence to the challenges posed by climate change and climate variability and, as stated in the previous section, take action to reverse the rise in those threats under their control, such as destructive fishing and pollution, as well as taking a proactive approach to improve reef conditions and identify reef-specific management actions and options (Obura *et al.*, 2017a). Appropriate response strategies may not require radical changes in current approaches to management, but rather more effective implementation of existing and proposed arrangements.

12.5 VULNERABILITY

12.5.1 Synthesis of vulnerability/opportunities of the main fisheries and dependent economies and communities

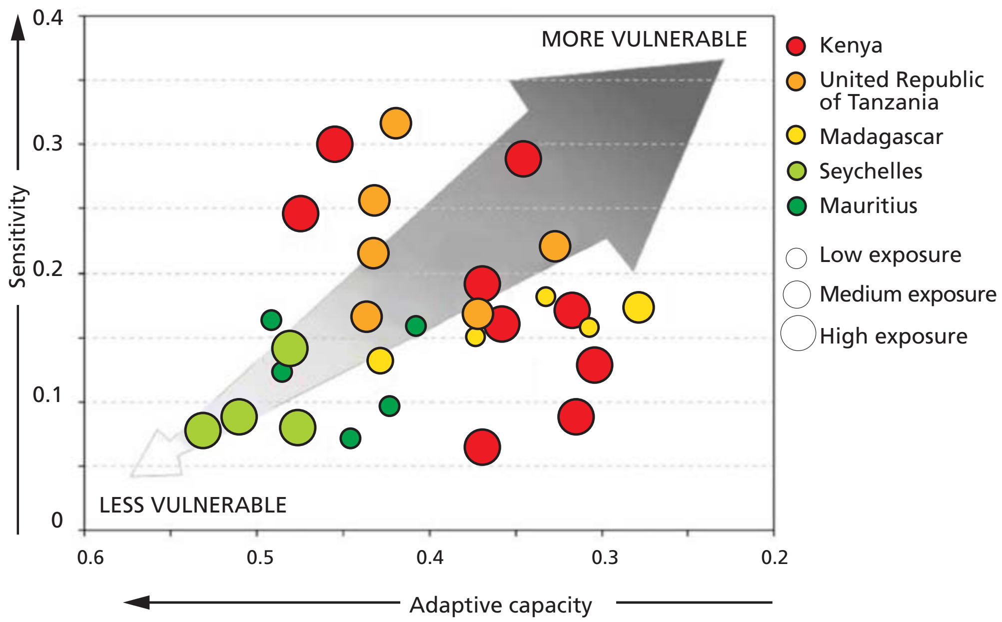
Projected changes in the oceanic parameters that are directly related to biological cycles are likely to produce physiological stresses that will impair the productivity of marine organisms. The magnitude of the impacts will differ depending on the ability of species to move and to relocate to more appropriate habitats. Coral reef fisheries will likely be the most affected and this will impact severely the livelihoods of coastal communities as these fisheries represent a significant part of their subsistence. Large pelagic fish such as tuna and billfish will probably change their movement patterns and may dwell in deeper layers, thus making surface gears less efficient. Such ecological changes will force the pelagic fleets to redeploy to other areas and to adapt their fishing techniques, which is manageable for the wealthy fishing companies. By contrast, locally-operated artisanal or semi-industrial fishing fleets could be severely affected unless they can innovate and adapt their gears to the changing habitat conditions (e.g. fishing deeper).

In the case of tuna fisheries, the Seychelles is a good case study to illustrate the vulnerability of a SIDS to a warmer and less productive ocean environment. As stated earlier (Section 12.4.1), because of the probable relocation after 2050, due to climate change, of the core purse seine fishing zones to the north, east and south of the Indian Ocean, well outside the Seychelles EEZ, Port Victoria would become a less attractive tuna hub than it is today. Other ports such as Port Louis (Mauritius), Colombo (Sri Lanka) and Phuket (Thailand) would then be better located for the unloading and transshipping operations of the oceanic purse seine fleets. However, opportunities could be created to mitigate such negative economic impacts. For instance, the strategy could be to target deep-dwelling tunas (large yellowfin, bigeye and albacore) in the Seychelles EEZ and beyond, with the locally-operated semi-industrial longline fleet (which was made up of 29 vessels in 2016).

The projections show that oxygen levels will increase at depth in the WIO, which is an unusual situation compared to most of the areas in the Indian Ocean. This region could then become a new ecological niche for deep-dwelling tunas that may congregate in the region. Such a situation could sustain tuna production in Seychelles by local operators. Furthermore, a better value for the raw tuna landed in Port Victoria should be sought. The fish should be handled and stored with great care onboard the vessels, and transformed to maximize the economic value (loins, smoked fillets or derived-products such as fish oil for dietary complements, etc.). Such a strategy should be developed by local entrepreneurs and well-trained workers to sustain local employment.

Small-scale reef fisheries across the WIO are highly vulnerable to climate change because of the degradation of the fish habitat structure (coral reefs) as a result of climate change and ocean acidification (IPCC, 2014). As warming trends continue, the frequency and severity of bleaching episodes are predicted to increase in this region and potentially could lead to declines in marine fish production and compromise the livelihoods of fisheries dependent communities. Cinner (2011) examined three dimensions of vulnerability (exposure, sensitivity and adaptive capacity) of 29 coastal communities across five Western Indian Ocean countries to the impacts of coral bleaching on fishery returns: they found that key sources of vulnerability differ considerably within and between the five countries. Kenya had the highest overall vulnerability, followed by the United Republic of Tanzania, Madagascar, Seychelles, and Mauritius (Figure 12.7). At the site level, they found that Sahamalaza in Madagascar had the highest vulnerability, but seven of the ten most vulnerable sites were in Kenya.

FIGURE 12.7
Plot of the vulnerability of coastal communities to the impacts of coral bleaching on fisheries



Adaptive capacity (x-axis; note values reversed so high adaptive capacity is on the left) is plotted against sensitivity (y-axis,) such that more vulnerable communities are in the top right of the graph and less vulnerable communities in the bottom left. These two dimensions of vulnerability can be modified by policy and development. The third dimension of vulnerability, exposure, is represented as the size of the bubble (larger = more exposure). To aid in visualization, exposure values were represented as the lowest, middle, and highest third rather than scaled to actual site values. Colours represent a gradient of vulnerability based on the country's mean vulnerability score from least vulnerable (green) to most vulnerable (red): Dark green = Mauritius, light green = Seychelles, yellow = Madagascar, Orange = United Republic of Tanzania, Red = Kenya. Adapted from Cinner *et al.*, 2012.

The WIO island states are also highly exposed to adverse natural events. Recent risk analysis by the World Bank (2017) in South WIO island states (Comoros, Madagascar, Mauritius, Seychelles and Zanzibar) revealed that tropical cyclones and extreme non-tropical cyclone rainfall are the main drivers of disaster risk in these island states.

This analysis also shows an increasing trend in the frequency and intensity of extreme weather related events across the entire South WIO region, and the exacerbating effects of climate variability and change pose additional challenges to the financial and fiscal sustainability of the region's governments. These governments are confronted with increasing contingent liabilities resulting from the potential materialization of external shocks, particularly those triggered by weather and climate-related hazards.

This work further concluded that development of a regional framework for natural disaster risk financing, as well as comprehensive national disaster risk financing and insurance strategies could help protect the countries' development and social gains.

12.5.2 Assisting communities to assess their vulnerability

Approaches such as the community-level vulnerability assessment that incorporates both ecological and socio-economic dimensions of vulnerability have already been tested in the WIO region (Cinner *et al.*, 2013; FAO, 2016b), and the widely adopted Intergovernmental Panel on Climate Change (IPCC) vulnerability assessment framework (Schneider *et al.*, 2007) is available to assist fisheries communities in the WIO to assess their vulnerability to climate change. Assessments are carried out on the basis of environmental, social and economic indicators that have been selected to summarize the key elements of the complex system of climate-ecosystem-social-economical interactions. It is essential to ensure those indicators can be monitored among the different communities, which means they have to be tailored to the existing human capacity without compromising their significance and usefulness for taking action if needed. These approaches, complemented by the FAO *Ecosystem approach to fisheries* (Garcia *et al.*, 2003; http://www.fao.org/fishery/eaf-net/toolbox/en) could help raise awareness, identify vulnerabilities and develop practical policy actions that could be used to target and guide interventions to reduce vulnerability at varying spatial and temporal scales.

12.6 ADAPTATIONS

12.6.1 Existing and recommended adaptations

The fisheries sector is critical to reducing hunger and improving nutrition in coastal societies in the WIO. Therefore, there is an urgent need for countries to take immediate and strategic action to build more resilient and secure food provision from the sea in order to minimize the impacts of climate change.

Existing adaptive measures to ensure long-term sustainability of fisheries in the WIO region include developing and implementing fishery-specific management plans that address the dynamics of the target species and of fishery stakeholders. In the case of small-scale fisheries, implementation of local co-management approaches that are grounded in community-based resource management principles could build adequate capacity, and where applicable, ensure equitable sharing of benefits from offshore industrial fisheries. For example, artisanal fishers in Mozambique and the United Republic of Tanzania are embracing this adaptation approach and they are becoming more involved in local resource management initiatives, as is being done for small-scale fishing communities in South Africa in terms of a new, incipient small-scale fisheries policy (Obura *et al.*, 2017a).

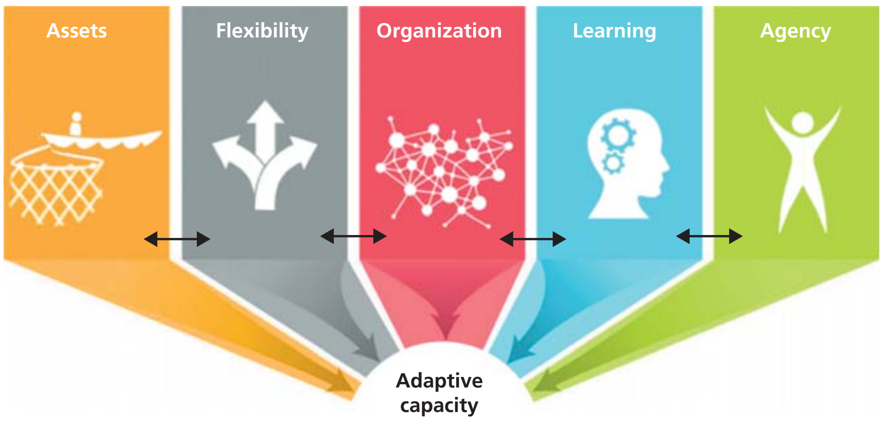
Other measures, such as designing and implementing MPAs could also support sustainable fisheries production by protecting key habitats and fish species, and strengthening connectivity and recruitment. In the United Republic of Tanzania for example, closures to fishing were observed to have a positive impact on reef recovery (McClanahan *et al.*, 2009). Setting up systems of adaptive management of fishing capacities, using climatic and environmental warning systems (especially for extreme events) would also make the WIO region more resilient to climate change (Rakotobe, Holmes and Ralison, 2012).

FAO's *Ecosystem approach to fisheries* (Garcia *et al.*, 2003), *Code of conduct for responsible fisheries* (FAO, 1995) and *Voluntary guidelines on small-scale fisheries* (FAO, 2015) incorporate approaches and measures that can strengthen the fisheries sector, and ensure sustainability and building resilience to climate change. The good news is that most countries in the WIO already recognize these in their national policies and legislation, but more efforts are needed to implement them.

To build adaptive capacity to climate change in tropical coastal communities, Cinner *et al.* (2018) based on lessons from hundreds of research and development projects, highlight five key measures, these include (Figure 12.8):

1. Ensuring that people have the assets to draw upon in times of need.
2. Providing the flexibility to change. Having some flexibility can enable people to minimize losses or even take advantage of climate-related change. For example, fishers might need to change fishing grounds or target new species.
3. Learning about climate change and adaptation options. People need to learn about new techniques and strategies that can help them cope with changing circumstances.
4. Investing in social relationships. The formal and informal relationships that people have with each other and their communities can help them deal with change by providing social support and access to both knowledge and resources.
5. Empowering people to have a say in what happens to them, ensuring the ability to determine what is right for them.

FIGURE 12.8
Five domains of adaptive capacity to climate change: assets, flexibility, social organization, learning, and agency



The five domains are interlinked; feedbacks and interactions can occur among any of the domains, not just the neighbouring ones graphically represented by connecting arrows. Adapted from Cinner *et al.*, 2018.

For example, coastal societies in the WIO that are experiencing a shift in the ranges of important fish species (Sumaila *et al.*, 2011), might draw upon financial assets (savings or credit) to purchase bigger boats and freezers to store fish during longer journeys, in order to fish further afield. Likewise, people who fish might adapt to altered compositions of fish assemblages by purchasing new fishing gear that selectively targets the species that have increased in abundance (Cinner *et al.*, 2013). In respect of IOTC resolutions on fleet development plans for member states, the Seychelles government, for example, has expanded its domestic semi-industrial longline fleet (from 11 in 2015 to 29 vessels in 2016) to create more jobs and increase the participation of the country in the tuna fishery (Marsac, 2017). This may be seen as an adaptation to the projected decline (after 2050) in surface schools harvested by purse seiners. Limiting access to distant water longline fleets in the Seychelles EEZ could be an additional measure to maximize the tuna capital for the domestic longline fleet.

However, trade-offs must be considered when designing interventions to enhance adaptation capacity. Building assets as indicated by Cinner *et al.* (2018) might have a negative effect on fish stocks and coastal ecosystems and thereby increase vulnerability of coastal communities to climate change. It may also benefit the wealthy more than the poor, and therefore exacerbate socio-economic inequalities, or in some cases lead to increased pressures on the environment. For example, in the United Republic of Tanzania, fishers who were more likely to intensify fishing effort in response to lower catches (thereby increasing exploitation) were those who had assets, but lacked flexibility to change livelihood strategies. Wealthier fishers were thus more likely to catalyse a "social-ecological trap" (Cinner, 2011), whereby lower yields increased fishing exploitation, which in turn further decreased yields. While in some situations trade-offs are inevitable, adaptation to climate change should not aggravate existing problems and should help long-term commitments to reverse social-ecological degradation.

It is worth indicating that there is no one adaptive approach that fits all. Trade-offs between approaches and models need to be considered when building adaptive capacity for the fisheries sector. For example, one other way to mitigate the short-term impact of climate change and depleted or shifted stocks in a region is to establish a networked understanding between these coastal countries (and their communities) and develop a collaborative agreement, so that higher abundance regions in a particular boom-year could share their productivity with the low-abundance regions in their bust-year and vice-versa over a longer period of time.

The challenges for the national economies in the WIO region to meet their need for jobs and food need to be recognized as the population is projected to grow to 306 million by 2030 (an increase of nearly 50 percent), and quadruple to 818 million by 2100 (Gerland *et al.*, 2014). This will require new, innovative ways for investment and new forms of and opportunities for employment need to be explored. In this context, the emerging concept of the blue economy has gained a great deal of prominence since 2012 as a mechanism for realising sustainable growth centred on an ocean-based economy (Ababouch, 2014; Obura, 2018). The blue economy vision is based on a number of principles: economic efficiency, sustainability, social equity, good governance, resilience, research and innovation, and partnerships. Well-agreed and nationally-tailored marine spatial planning is an essential tool to better share opportunities and benefits among communities, and on the other hand, to mitigate adverse conditions and trends.

For SIDS in the WIO, in particular, the concept of the blue economy presents itself as a promising avenue for economic diversification and growth embedded in the fundamental principles of environmental sustainability. WIO countries are now taking steps in this direction. Several countries have adopted blue economy (Mauritius, Seychelles, and South Africa) and green economy (Mozambique, Kenya) principles as national priorities. Kenya, Madagascar, the United Republic of Tanzania and Mozambique have also developed legislation strengthening community participation and empowerment in natural resource governance (Obura, 2017a). A commitment to putting inclusive, people-centred approaches at the heart of these policies is needed. These will help individual countries to pursue the policies and interventions required to attain the Sustainable Development Goals.

12.6.2 Capacity development and enabling environment

Capacity development (CD) in marine and coastal fisheries of the WIO region is a very important activity, given the present growing and projected pressures on marine resources from overfishing and climate change (UNEP, 2015). However, CD ambitions and approaches need to match the different realities of WIO states, economies and societies. CD in the context of this chapter reflects peoples' capacity to process new information about climate change, adaptation options, and ways to live with, and manage, uncertainty. CD can occur within and across multiple organizational, spatial, and temporal scales. For example, in response to climate change, fishers may have to learn about new fishing grounds, gears, weather patterns, technologies, species, and in some cases, new ways of making a living (Badjeck *et al.*, 2010).

Provision of access to critical information, such as market prices and weather forecasts, is central to building capacity in coastal fishing communities. For example, early warning systems can help fishers to assess potential risks, reduce lost or unproductive fishing days, and ultimately reduce deaths. Likewise, seasonal forecasts of fish distribution and abundance for pelagic species can help fishers to adapt to spatial and temporal shifts. For example, seasonal forecasts of the spatial distribution of southern bluefin tuna in the Great Australian Bight have been used to support the strategic planning of fisheries in this region for nearly a decade (Eveson *et al.*, 2015). Within fisheries management, questions around the productivity (and thus quotas and sustainability) of a fish stock typically gather substantial attention and energy, both from the scientific community and the public. However, the distribution of the resource in both time and space ultimately sets the framework within which fisheries operate and is thus a second issue of critical importance to both fishers and managers.

Developing capacity to adapt to climate change often requires coordination in provision of resources, collaboration and communication across multiple sectors and organizational boundaries. It is a prior condition that adaptations must be designed and delivered in such a manner that they are acceptable to the communities that they are intended to benefit. Prevailing incentives and capabilities to do this may be limited unless driven strongly from the top. Therefore, ambitions should be scaled accordingly. It may be useful to seek sufficient policy coherence; and then to focus CD efforts mostly on what individual organizations have to deliver in this bigger picture. Incentives for organizational performance are shaped by the strength of the formal and informal voice of citizens, users, media, and the checks and balances of organizations. Looking for means to strengthen those voices that would pressure for more equitable or better service delivery can be an important way of making the environment more enabling for CD.

CD also requires investment in building networks that allow people to share experiences of ecological knowledge and surprises from other locations and other knowledge systems (for example, expert, local and indigenous). Such networks have not only facilitated CD, but also empowered people to develop novel adaptation strategies (Cinner *et al.*, 2018). For example, locally managed marine areas networks connect and share experiences among coastal communities across the Indo-Pacific, blending scientific and local ecological knowledge systems to implement a range of community-based fisheries management strategies.

The Western Indian Ocean Marine Science Association (WIOMSA) CD programme[7] is a good example of an organized network in the WIO. The objectives of WIOMSA's CD programme are focused on research, technical and managerial capacity as well as the professionalism of experts dealing with coastal and marine issues, to make them capable of meeting the existing and future challenges of coastal and marine management in the WIO region and beyond. Such initiatives should be encouraged and supported

[7] http://www.wiomsa.org

to help WIO communities to strengthen their capabilities to reduce potential adverse impacts of climate change.

It is critical to stimulate research capacity especially among SIDS and Indian Ocean rim nations by promoting training courses to develop multidisciplinary science skills, workshops, summer schools and a programme of personnel exchange among these countries and with the other countries in the developing and developed world. In fact, under the International Indian Ocean Expedition-2 (IIOE-2) programme, many countries are developing multi-national programmes to engage Indian Ocean scientists and associated institutions from developed and developing countries that are planning to undertake science activities in the region (Hood *et al.*, 2016).

Some examples of potential training, education and outreach activities that should be proposed and undertaken in the near-term could include:

- Creating online workshops and courses for educators in the WIO region that are designed to reach K-12 educators as well as other interested participants, such as university students and faculty, policymakers, civil society, non-governmental organizations and industry representatives.
- Developing environmental "report cards" of the WIO for communication and education. Environmental report cards synthesize data from scientists and volunteers and convert it into an image-rich format that is easily accessible to a wide audience and that can be used to inspire real change.
- Formulating ocean literacy principles for the WIO and creating a guide for the WIO based on the current ocean literacy guide[8].
- Developing curricula for schools and teachers that include educational resources, highlighting past and present climate-related research findings (including projections for the future), that could be posted online and used by teachers in their classrooms or other educational settings.
- Fostering participatory approaches (such as "citizen science") where the communities that are directly exposed to stresses contribute to the data gathering process and engage with scientists and managers by framing the most stringent societal issues. Overall, this contributes to create a well-informed and transparent decision-making process, and facilitates acceptability by communities and other stakeholders.
- Connecting experts with the education, industry and governmental policy-making communities through transdisciplinary educational/training programmes and science communication methods that engage these stakeholders within a societally responsive framework.

The Intergovernmental Oceanographic Commission committee on International Oceanographic Data and Information Exchange (IODE) has established a network of regional training centres, several of which are located in the Indian Ocean region (Kenya, Mozambique, India and Malaysia) that could be very useful for capacity building in WIO countries and SIDS. For example, the IODE Ocean Teacher Global Academy is another IODE training platform that can be leveraged by these countries at the regional level.

Finally, to achieve CD objectives and build adaptive capacity, partnerships at the local, regional and international levels will be a key to face the challenges of climate change. Cooperative action among countries can be coordinated through regional and intergovernmental institutions in the WIO, with a focus on more effective engagement across sectors (Obura, 2017a). For example, setting up regimes for the governance of shared marine living resources is a priority (UNEP, 2012), needing engagement with the relevant management and economic institutions, such as regional fisheries management organisations, as well as across countries and non-state actors. To implement such partnerships, countries need to put in place policies and legislation that

[8] http://oceanliteracy.wp2.coexploration.org/

support complex negotiations among actors. Initiating smaller-scale actions for trials will likely deliver greater success than overly ambitious projects (Obura *et al.*, 2017a).

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Chapter 13: Climate change impacts, vulnerabilities and adaptations: Southern Asian fisheries in the Arabian Sea, Bay of Bengal and East Indian Ocean

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KEY MESSAGES

- Pakistan, India, Bangladesh, Myanmar and Maldives are among the countries most affected by climate change and weather events.
- There is strong socio-economic pressure from population growth, presence of dams and irrigation needs, heavy metal and waste pollution, habitat modification and destruction, illegal fishing, and insufficient infrastructure, skills credit and welfare.
- Inland fisheries captures are high and interlinked with the marine environment in countries where fisheries are important for employment, exports and income generation.
- Artisanal and subsistence fisheries are important in the region; however, the number of artisanal boats is decreasing probably as a result of over-exploitation and overcapacity.
- Marine maximum potential productivity is likely to decrease in those regions because of climate change, but that potential is not being achieved at present because of overfishing. This suggests that climate change impacts on specific fisheries can be partly mitigated by improving fisheries management.
- In many countries, government institutions have long-term plans that recognize the likely impacts of climate change. With limited resources, they are trying to establish and enforce fisheries management measures which can increase the resilience of communities to climate change.
- A lack of resources and scientific knowledge is often addressed through internationally funded cooperative research and support programmes that encourage ecosystem- and community-based approaches and science-driven management advice.
- International fisheries safety and sustainability certifications are a successful driver of change and have the potential to improve infrastructure, people training, commodity values, diversify markets and support the ecological sustainability of the activities of associated industries.
- Increased economic stability of fishers and associated industries through easy and low-cost access to insurance, welfare, credits and minimum wages is being promoted through government and non-government agencies; however, they can only reach a very small number of the people whose livelihoods are impacted by climate change.

13.1 FISHERIES OF THE REGION

13.1.1 Sensitivity and dependency of fisheries communities and livelihoods to climate change

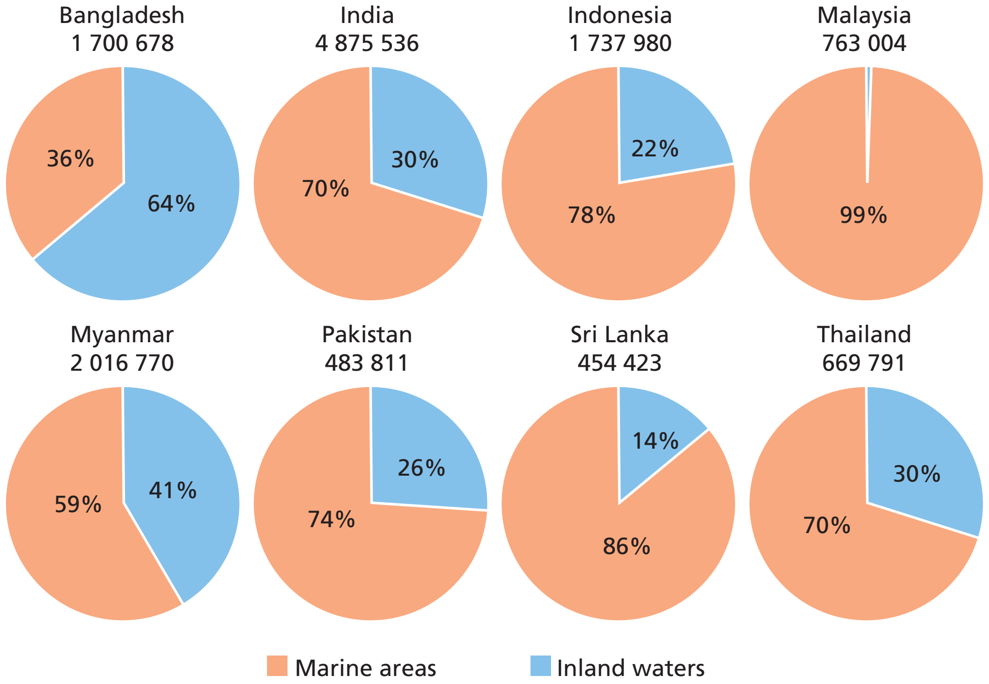
The South and Southeast Asian (SA) countries in the Arabian Sea, Bay of Bengal and East Indian Ocean consist of the following: Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Pakistan, Sri Lanka and Thailand. These countries share similarities in their fisheries environment and socio-economics and this chapter, through examples taken from different countries, presents an overview of current and projected impacts of climate change in the region and the responses of countries to these changes and their impacts on marine fisheries. Maldives is also addressed in Chapter 12 on the Western Indian Ocean. Most SA countries fall in the region of heavy rainfall in the monsoon belt. As a result, they have many rivers, frequent floods and river bank erosion in delta regions. These factors contribute to a variety of ecosystems of high biodiversity and natural capital richness such as mangroves, wetlands and coral reefs (Tittensor *et al.*, 2010), but also to their vulnerability and the vulnerability of associated communities to climate change (Allison *et al.*, 2009; Barange *et al.*, 2014; Hossain *et al.*, 2018). Deltas (e.g. Ganges–Brahmaputra–Meghna delta in Bangladesh and India, Mahanadi delta in India, Indus delta in Pakistan and Ayeyarwady delta in Myanmar) are areas with fertile soils that contribute to maintaining the mangrove forests, which provide protection for the coast from erosion and sea level rise, while also providing refuge for young fish and serving as an important carbon sink (Salik *et al.*, 2015). During dry seasons, the water stored in wetlands is discharged slowly towards nearby habitats, helping to regulate the water levels and, during monsoons, wetlands such as marshes and ponds, store large amounts of water, reducing the pressure of flooding (NICRA-CIFRI, 2016). Coral reefs form some of the most diverse and sensitive ecosystems at a distance from deltas and other freshwater influxes (Heron *et al.*, 2016).

Bangladesh, Pakistan and Maldives are among the national economies most vulnerable to future impacts of climate change on fisheries and aquaculture (Allison *et al.*, 2009; Blasiak *et al.*, 2017). Bangladesh used to be ranked first among countries vulnerable to climate change (Ahmed, Diffenbaugh and Hertel, 2009) but research and development programmes might subsequently have contributed to reducing its vulnerability to sixth position (Kreft, Eckstein and Melchior, 2016). Four SA countries are among the ten countries considered to be most affected by climate change and weather events during the last two decades (Kreft, Eckstein and Melchior, 2016): Myanmar (second), Bangladesh (sixth), Pakistan (seventh) and India. In 2014 and 2015, India was placed fourth and tenth respectively in this ranking because of floods caused by unseasonal rainfall and it suffered from one of the deadliest heatwaves in world history, followed by a much weaker monsoon than normal. In general, poorer developing countries are hit much harder than more developed countries and these results further emphasize the vulnerability of developing countries to climatic risks, even though the absolute monetary losses may be much higher in more developed countries. The Maldives is composed of low islands that face the prospect of submergence during the twenty-first century (Nicholls and Cazenave, 2010). Sri Lanka is vulnerable to tsunami, which destroyed 65 percent of its fishing fleet in 2005 (De Silva and Yamoa, 2007).

13.1.2 Basic information on value of fisheries and its socio-economics: some examples

The relative contributions of marine and inland fisheries differ across the region, as illustrated by the examples presented here. The proportion of inland catches is larger than marine catches in Bangladesh (Figure 13.1). SA countries are rich in brackish water species (e.g. hilsa shad [*Tenualosa ilisha*], prawns) which have life cycles in both marine water and rivers. Widely distributed species are likely to be impacted by climate change and are among the top fished species in SA countries (hilsa shad, Indian oil sardine [*Sardinella longiceps*], Bombay duck [*Harpadon nehereus*], Indian mackerel [*Rastrelliger kanagurta*], Indian salmon [*Eleutheronema tetradactylum*], small tunas [e.g. skipjack tuna], other mackerels [*Auxis* spp. and *Decapterus* spp.], and squids). These species have high economic and cultural value (e.g. hilsa shad in Bangladesh and Myanmar; ILO, 2015; Fernandes *et al.*, 2016a). Bombay duck, gobies, anchovies, bivalves, drums, croakers and shrimps are likely consumed by the poorest people (Ullah *et al.*, 2014; Fernandes *et al.*, 2016a).

FIGURE 13.1
Examples of the average total national catch (metric tonnes) and the percentage contributions to those catches of wild captured fish from inland and marine waters for 2010 to 2016 (aquaculture is excluded)



Source: FAO Fisheries and Aquaculture statistics.

Fishing is an important socio-economic activity in SA countries. Fish products are a substantial source of animal protein (up to 50 percent to 80 percent in Bangladesh, Pakistan and Sri Lanka) and contribute up to four percent of the gross domestic product in Bangladesh, Indonesia, Pakistan and Sri Lanka (Ali *et al.*, 2015; Bogard *et al.*, 2015; Dey *et al.*, 2008; DoFB, 2016; FRSS, 2017; Harkes *et al.*, 2015; Mruthyunjaya *et al.*, 2004; De Silva and Yamoa, 2007) and reaches 44 percent of coastal communities' GDP in Sri Lanka (Sarathchandra *et al.*, 2018). Fisheries and related industries are also an important source of employment in SA countries, e.g. seven to eight percent of the working population in Bangladesh and Indonesia, and particularly in rural areas (DoFB, 2016; Kathun, 2004; Hoegh-Guldberg *et al.*, 2009; Pakissan, 2017; SIDATIK, 2015). While full-time fishers are common in all countries (e.g. approximately 65 percent of all fishers in India, but only about 16 percent in Myanmar), it is often a part-time or occasional activity, sometimes involving children (Ali *et al.*, 2015; DAHDF, 2014; ILO, 2015).

Fisheries are also an important source of foreign income and, for example, India fishery products (shrimps, prawns, ribbon fish [*Trichiurus lepturus*], oil sardine and mackerel) represent about 13 percent of the total agricultural exports (Shinoj *et al.*, 2009). Hilsa is the top exported marine fish species of Myanmar and Bangladesh. Myanmar exports mainly to China, Thailand, Malaysia, Singapore, Japan, Bangladesh and the EU (ILO, 2015), while Bangladesh exports frozen seafood products to more than 50 countries, including Belgium, United Kingdom of Great Britain and Northern Ireland, the Netherlands, Germany, the United States of America , China, France, the Russian Federation, Japan and Saudi Arabia. In Pakistan, about 35 percent of the fish and fishery products are exported to EU, Japan, the United States of America , China, Saudi Arabia, the United Arab Emirates, Malaysia, the Republic of Korea, China, Hong Kong SAR, Sri Lanka and Singapore (Pakissan, 2017).

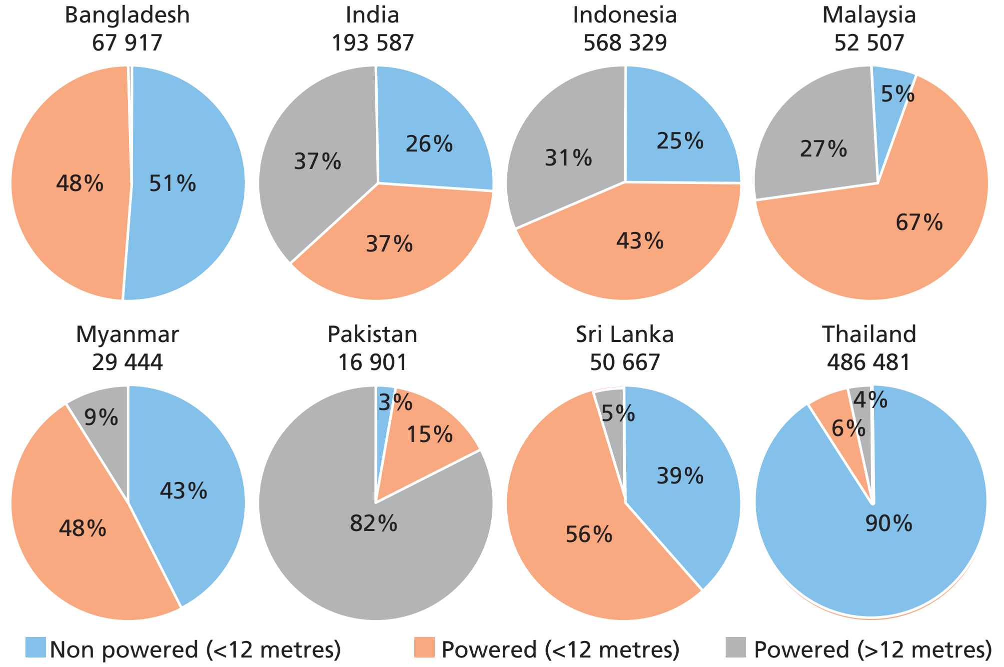
13.1.3 Basics of the structure and management of the fisheries of the region: some examples

Fisheries structure

Industrial and artisanal are the two main fisheries sectors in the SA countries (Vivekanandan, 2011) and illustrated in Figure 13.2. Artisanal fisheries involve the use of small mechanized and non-mechanized vessels, as well as nets deployed from the banks of rivers and coastal shores. Indonesia has an important tuna longline and purse seine fleet in the East Indian Ocean. Despite the general prevalence of artisanal and subsistence fisheries, there has been a trend in the last ten years of a decline in the number of small vessels and an increase in larger vessels that fish offshore. For example, in Myanmar the number of small fishing boats decreased by 15 percent in 2013 compared to 2009 figures, while locally owned offshore vessels increased by 45 percent (ILO, 2015). The reason could be high overfishing in nearshore waters driven by increases in the coastal populations (Fernandes *et al.*, 2016a). Large motorized and industrial fisheries often concentrate in one or a few ports in SA countries, for example in Myeik Township (Tanintharyi Region) and Yangon in Myanmar (ILO, 2015), Chittagong in Bangladesh (Hossain and Hasan, 2017), and Karachi harbour in Pakistan (Pakissan *et al.*, 2017).

FIGURE 13.2

Examples of the total numbers and percentage contributions of different types of registered vessels for some SA countries



Source: FAO Fisheries and Aquaculture statistics for year 2016 (except for Thailand where only 2015 statistics are available, and Indonesia). Since FAO fleet statistics for Indonesia have not been updated since 2011, we used DGCF (2015). PBS (2012) shows a larger proportion of small, non powered vessels (53 percent of the total) in Pakistan. Vessels data include all the country's fisheries, not only fisheries taking place in the East Indian Ocean region.

Fisheries management

The SA countries are developing fisheries management measures to increase the resilience of the sector to climate change despite limited capacity for implementation and enforcement. Some examples of recent developments in management measures include:

- *Limits to fishing gear.* The Myanmar government increased the mesh size for prawn trawl nets and finfish trawl nets (ILO, 2015) and various devices to reduce by-catch have been introduced. In shoreline areas (from five to ten kilometres) trawling and other forms of mechanized fishing are not permitted in India (FFCI, 2015).
- *Licensing schemes and seasonal closures.* In Myanmar (ILO, 2015), licenses for the monsoon fishing season have been cut by 25 percent and the length of season has been reduced from 90 days to 45 days. Foreign fishing vessels have been banned and the operations of large fishing companies reduced by 35 percent from April to August. India has undertaken licensing prohibitions on certain fishing gear or sizes and has established closed seasons and areas such as a "monsoon fishing ban" (FFCI, 2015).
- *Protection of nursery grounds.* Bangladesh banned the catching, possession, transport and trading of juvenile hilsa (jatka) between 1 November and 31 May every year, established hilsa sanctuaries, and introduced a ten day fishing ban in major spawning grounds.
- *Encourage alternative livelihoods.* In Bangladesh, hilsa fishers were provided with food-grains to live with and to start alternative activities (FRSS, 2017).
- *Limiting fish aggregating devices (FADs).* As an example, in 2014 Indonesia introduced around 12 new laws for management of the ever-increasing number of FADs in that country.
- *Introduction of monitoring and control tools.* For example, Thailand has introduced a vessel monitoring system (VMS) and logbooks, and every entry and exit to port of fishing vessels must be reported (DoFT, 2015).

13.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT RELEVANT TO FISHERIES

13.2.1 Physical and chemical

SA countries are very sensitive to cyclones, floods, droughts, rainfall, sea level rise and changes in temperature and salinity because they have long and highly populated coastlines (Das *et al.*, 2016; Hossain *et al.*, 2018). For example, Sri Lanka has experienced major floods and droughts in the last decade and rainfall variability is expected to increase (Esham *et al.*, 2018). Cyclones and hurricanes of categories 3, 4 and 5 are strongly influenced by sea surface temperatures (Ahmed, Occhipinti-Ambrogi and Muir, 2013; Knutson and Tuleya, 2004; Webster *et al.*, 2005). These countries' responses to cyclones have reduced the resulting deaths, however, economic losses are still large. For example, in 2007 Cyclone Sidr affected the livelihoods of around 8.9 million people and economic losses were estimated at USD 1.67 billion (Ahmed, Occhipinti-Ambrogi and Muir, 2013). The frequency of droughts has recently increased in Bangladesh (Habiba, Takeuchi and Shaw, 2010). In addition, sea level rise and glacier melting in the Himalayas are foreseen consequences of global warming that are likely to increase the problems of inundations in Bangladesh as two-thirds of the country is less than five metres above sea level (Ahmed, Occhipinti-Ambrogi and Muir, 2013): sea level rise in the Bay of Bengal will result in intrusion of saline water approximately 50 km further inland in Bangladesh than at present (Jakobsen *et al.*, 2005). Coastal zones of Thailand have experienced increases of sea level at the rate of 3 mm to 10.5 mm per year in the last two decades (Panpeng and Ahmad, 2017). In the Indus delta in Pakistan, an increase in mean annual air temperature of 1.47 °C between 1951 and 2010 and a mean annual decrease of 78.4 mm in precipitation over the same period has been estimated (Salik *et al.*, 2015), with projections showing that the annual temperature could rise by another 1.15 °C by 2040 and up to 4.19 °C by the end of the century (Salik *et al.*, 2015). Sea surface temperature has increased by 0.2 °C to 0.3 °C along the Indian coast in the last 45 years, and it is projected to increase by 2.0 °C to 3.5 °C by the end of the century (Vivekanandan, 2011; Vivekanandan, Hermes and O'Brien, 2016). During the southwest monsoon, wind speeds and coastal upwelling have strengthened, resulting in higher concentrations of chlorophyll along the Kerala coast (Vivekanandan, 2011). The IPCC (2014) report provides an estimate of 4 °C increase in the ocean heat content in the Indian Ocean between 1960 and 2010. The Arabian Sea and Bay of Bengal are forecast to be among the marine areas with highest increases in temperature and precipitation by the end of century, with forecasts of increases of 4 °C and 40 percent precipitation under the high emission scenario for these two areas. The IPCC (2014) report also states that oxygen minimum zones are progressively expanding in the Indian Ocean.

13.2.2 Biological and ecological

There is only sparse specific literature looking at future scenarios in SA countries and regions (e.g. Bay of Bengal and Arabian Sea). Most literature is composed of global studies that have assessed that SA countries are among the countries more dependent on fisheries and more likely to be impacted by climate change. For example, 90 percent of inland fisheries occur in Africa and Asia (Cochrane *et al.*, 2009), where temperature increases are expected to exceed the global annual mean warming (Christensen *et al.*, 2007). Coral bleaching is likely to be an annual event in the future and reefs could soon start to decline and become only a remnant in the Indian seas between 2050 and 2060 (Vivekanandan, 2011). Mangroves in tropical regions are sensitive to global warming, which impacts the extent and composition of mangroves (Vivekanandan, 2011). The occurrence of harmful algal blooms seems to have become more frequent, intense and widespread and to cause considerable mortality of fish in the Arabian Sea and the Bay of Bengal (do Rosário Gomes *et al.*, 2014; Martin and Shaji, 2015; Vivekanandan, 2011). There is a relationship between the increasing surface temperature and the incidence of infectious diseases (e.g. dengue; Paul and Tham, 2015) and this has became a major public health issue in Sri Lanka (Sirisena and Noordeen, 2014).

13.3 EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING THE MAIN FISHERIES

13.3.1 Distribution, abundance, seasonality and fisheries production

Bioclimate envelope approaches have predicted a 30 percent to 70 percent increase in fish catch potential in high latitudes and a 40 percent drop in the tropics (Cheung *et al.*, 2010; Chapter 4). In a more recent study (Barange *et al.*, 2014), climate change was predicted to decrease total productive potential in South and Southeast Asia, driven by a temperature increase of approximately 2 °C by 2050, despite increased primary production by small phytoplankton. Oxygen concentrations might decrease in many areas of the ocean and vertical shifts in oxygen depth distribution will potentially influence tunas and food webs in the Arabian Sea and the Bay of Bengal (Mislan *et al.*, 2017). While these studies do not agree on the magnitude of change, given that they consider different numbers of drivers and uncertainties (Payne *et al.*, 2016), there is much agreement on areas of impact and direction of this impact and key drivers (temperature, acidification and hypoxia). A regional study forecast large decreases in potential catch of two key commercial species (hilsa shad and Bombay duck) in the Bay of Bengal (Fernandes *et al.*, 2016a). However, this study also showed that if the existing high overfishing is reduced to a sustainable level, then climate change impacts can be partly mitigated. It has been reported that the small pelagics such as the oil sardine and Indian mackerel have extended their distributional boundary to northern and eastern latitudes, contributing to fisheries in the last two decades (Vivekanandan, 2011). The threadfin breams have been found to have shifted the timing of their spawning towards cooler months off Chennai (Vivekanandan, 2011). Oil sardine and Indian mackerel could benefit from increased temperature (Salim, Shridhar and Fernandez, 2017). However, local benefits resulting from changes in the distribution of species driven by climate change could be only temporal (Fernandes *et al.*, 2017). Shellfish species can be the most impacted by changes in temperature and pH (Fernandes *et al.*, 2017; Queirós *et al.*, 2015) and fish species could see their average size reduced (Queirós *et al.*, 2018), while changes in the seasonality of species such as threadfin bream are also expected (Salim, Shridhar and Fernandez, 2017). Exotic carp species, tilapia, pangas and koi, considered invasive species, expanded massively in Bangladesh, which could have been driven by climate change (FRSS, 2017).

13.3.2 Other non-climate stressors

Non-climate stressors can exacerbate impacts from climate change. Population growth and socio-economic drivers are highly likely to be a higher short-term source of stress to the environment and the livelihoods depending on it than climate change. Several of these stresses are highlighted in this (general) and the next section (fisheries specific).

Pollution

Heavy metal pollution affects ecosystem biodiversity through reproductive impairment and increased incidence of diseases (Kibria *et al.*, 2016b; Wu *et al.*, 2007). Invertebrates and fish accumulate metals from the environment, which can pose risks to humans through seafood consumption (Kibria *et al.*, 2016a). Agricultural, domestic and industrial wastes directly discharged into rivers are the main causes of metal pollution in Chittagong, Bangladesh (Kibria *et al.*, 2016a). Schmidt, Krauth and Wagner (2017) estimated that 95 percent of plastic polluting the world's oceans comes from just ten rivers including the Ganges (India and Bangladesh), Brantas (Indonesia) and Indus (Pakistan).

Dams

Impacts such as lower river flows because of the presence of dams and increased evaporation as a result of climate change are exacerbated by the construction of dams and increased demand for irrigation water (Cruz *et al.*, 2007; Salik *et al.*, 2015). Large dams may adversely affect small-scale fisheries downstream (Hallwass *et al.*, 2013; Chapter 19), particularly in the nursery areas of specific key species (Bhaumik, 2015).

Habitat modification and destruction

Unsustainable practices include coral mining, anchoring in reef areas and destructive fishing methods, such as cyanide fishing, dynamite fishing and the use of fine mesh nets (Burke *et al.*, 2011). Nowadays, 93 percent of Indonesia's coral reefs are at risk from these threats (Burke *et al.*, 2011). The Indus Delta in Pakistan hosts 97 percent of the country's total mangrove forests, which have suffered a 70 percent reduction associated with cutting for fuel wood and clearing land for agriculture, housing and industrial uses (Abbas *et al.*, 2013; Zaheer *et al.*, 2012). Similarly, Indonesia and Sri Lanka have lost 40 percent to 50 percent of their mangroves in the last three decades as a result of aquaculture development (Harkes *et al.*, 2015; Murdiyarso *et al.*, 2015).

13.3.3 Additional stress from fishing and post-harvest operations

Shrimp post-larval collection for aquaculture

The 80 hatcheries in Bangladesh can provide only 30 percent of the demand (Ahmed, Occhipinti-Ambrogi and Muir, 2013) and therefore farming of prawn (*Macrobrachium rosenbergii*) and shrimps (*Penaeus monodon* and *Metapenaeus* spp.) remains largely dependent on the capture of wild postlarvae (Ahmed *et al.*, 2013; Hossain and Hasan, 2017) in Bangladesh and Myanmar.

Overfishing and overcapacity

In many areas, fishing has become unrewarding as the catch per unit effort is extremely low, but poor fishers still try to catch whatever they can and thus contribute to destroying the natural resource (Ferrol-Schulte *et al.*, 2015; FRSS, 2017; ILO, 2015; Vivekanandan, 2011). The catch rate of elasmobranchs in coastal and shelf waters off India appears to be declining because of overfishing (Croll *et al.*, 2016). The export market has likely driven increased fishing effort and technological innovation leading to increased harvest and declines in local populations of Mobula species in Indonesia (Dewar, 2002; Heinrichs *et al.*, 2011). Overfishing in Malaysia might have been exacerbated by capacity-enhancing subsidies with capacity at 135 percent to 200 percent of the level needed to harvest the maximum sustainable yield (MSY; Ali *et al.*, 2015). Hilsa shad has been fished at two to three times MSY levels in Bangladesh (Fernandes *et al.*, 2016a). India also experiences overfishing in species such as Bombay duck and Indian mackerel (Fernandes *et al.*, 2016b). The Bay of Bengal Large Marine Ecosystem (BOBLME) project estimated that, for Myanmar, current catches are twice MSY levels (BOBLME, 2010). Thailand stock assessments report that current fishing effort is between 5 percent and 33 percent greater than MSY levels, depending on the species and regions (Derrick *et al.*, 2017).

Illegal, unreported and unregulated activities

Illegal, unreported and unregulated (IUU) fishing and piracy contributes to overfishing and insecurity in the sector. It remains a pervasive problem in the Asian region and its clandestine and illegal nature makes IUU fishing difficult to detect and deter (BOBLME, 2015; FAO, 2016). In Bangladesh, coercion of fishers by boat owners and captains and lack of enforcement of fishing regulations and maritime laws have been identified as barriers to adaptation (Islam *et al.*, 2014).

Lack of skills, education and infrastructure

Low levels of education, skills and climate literacy are acknowledged in SA countries as a limitation to adapting to climate change (Ahmed, Occhipinti-Ambrogi and Muir, 2013; ILO, 2015; Salik *et al.*, 2015; Vivekanandan, 2011). Lack of leadership has also been identified as a limitation to adaptation in Thailand (Bennett *et al.*, 2014). The lack of infrastructure constrains ice use for preserving catches, the cost of which represents 54 percent of the total costs for vessels (fuel only eight percent) in Myanmar (ILO, 2015).

Lack of economic stability

Credit services flow from the individual players who are at the top of the value chain to other actors, and fishers are trying to escape what becomes a "sweet prison" by avoiding loans so that they can search for options to get a better price for their catch (ILO, 2015). This problem could be exacerbated by a lack of finance and risk management literacy among those dependent on fisheries for their livelihoods (Ahsan, 2011). Corruption and inequitable distribution of wealth have been listed as factors that may constrain the ability of Thai to adapt (Bennett *et al.*, 2014).

Gambling and crime

Gambling and crime could be a new problem in some cities with high concentrations of fisheries activity, which have experienced rapid development such as Cox's Bazar, in Bangladesh (Lincoln, 2014).

13.4 RESPONSES (ADAPTATION)

Sustainable management of international fisheries has been estimated to have the potential to increase global fisheries production by ten percent (Cheung *et al.*, 2017), which could also translate into an additional increase of the value of fish products at local scales (Bundy *et al.*, 2017; Coll *et al.*, 2013). There are many options available for adaptation in fisheries, many of which benefit or provide an advantage to small-scale fishers and fish farmers (Miller *et al.*, 2018). These include actions that increase the resilience and adaptive capacity of communities and ecosystems, particularly by reducing other stresses such as social (poverty, inequality) and environmental stresses (overfishing, habitat destruction, pollution) (Cheung *et al.*, 2010; IPCC, 2007). Development agencies, regional fisheries management organizations (e.g. Indian Ocean Tuna Commission) and regional fisheries bodies (e.g. Bay of Bengal Programme–Intergovernmental Organization and the Southeast Asian Fisheries Development Center) as well as other regional organizations (e.g. Indian Ocean Commission, Regional Organisation for Protection of the Marine Environment, Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden, and South Asia Cooperative Environment Programme) can direct efforts to document, understand and apply proven successful adaptation mechanisms. For example, the Asia-Pacific Fishery Commission has carried out consultative workshops on climate change and fisheries with assessments and recommendations (FAO, 2011a; Sriskanthan and Funge-Smith, 2011). In considering adaptation approaches, it should be recognized that traditional management systems may support sustainable livelihoods, but they may also reinforce the social positions of those who oversee them, at the expense of less privileged members of the community. This can hinder equitable development (Neiland, Madakan and Béné, 2005).

13.4.1 Migration of people

Migration is a socially embedded process, which is perceived as arising from low adaptive capacity of the individuals or the communities coping with stressful changes (Adger, 1999, 2003; Brooks, Adger and Kelly, 2005). However, considering the broader perspective of migration, it can be established that migrations enhance the adaptive capacity of any community to cope with climate change (Barnett and Webber, 2010; Hossain *et al.*, 2018). Seasonal migration to locations where fish are available are common in fisheries, particularly small-scale or artisanal fisheries. This phenomenon can be exacerbated and complicated by the need to follow changes in geographical distribution of fish species because of climate change. A one metre rise in sea level could displace an additional 17 million people in Bangladesh, who will then act as "climate refugees" (Hossain *et al.*, 2012). Cyclones have also had a high impact in coastal communities, which can exacerbate migration (Hossain *et al.*, 2018). Deltas and low-elevation coastal zones are known for significant urbanization trends and land use change (e.g. Meyer *et al.*, 2016) and associated high movement of people, mainly for economic reasons (e.g. Foresight, 2011).

13.4.2 Community-based adaptation

An adaptation plan must be in line with the community's needs, abilities and interests. This requires that the community must be included in the planning, which will empower them by enabling them to posit their own ideas (Grafton, 2010; Shaffril, Samah and D'Silva, 2017). This empowerment can be based on local property rights-based approaches (Allison and Ellis, 2001; Costello and Kaffine, 2010). Fishers' sense of belonging to their place of residence has been identified as leading to strong cooperative behaviour and social reciprocity in Malaysia and Pakistan, which has the effect of strengthening social relationships as an adaptation measure (Salik *et al.*, 2015; Shaffril, Samah and D'Silva, 2017). All the SA countries are developing the needed community collaboration and organizations for community-based fisheries management although at different scales and with different intensities. An important element is the existence of fishers' and industrial associations such as Fish Farmers Development Agencies in India (DAHDF, 2014) or Myanmar Fisheries Federation (ILO, 2015). An ecosystem approach to fisheries (EAF) at local scales should protect and restore fish recruitment and key habitats, explore livelihoods diversification and improve co-management systems (Table 2 in FAO, 2012). EAF strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about nature and human components of ecosystems and their interactions to apply an integrated approach to fisheries that considers the impacts of fishing on the environment and other sectors, and at the same time considers the impacts of other sectoral influences (including climate change) on fisheries (Garcia *et al.*, 2003; Heenan *et al.*, 2015).

13.4.3 National climate change policies and long-term action plans

The need for policy that considers climate change has been acknowledged within SA countries. Malaysia and Myanmar (Shaffril, Samah and D'Silva, 2017) emphasize enhanced coordination and the adoption of systematic and targeted education and awareness on climate change for non-governmental and community-based organizations. Malaysia and Indonesia have adopted EAF as a national guiding principle in their policies and planning. Pakistan is developing localized action plans such as the National Climate Change Policy of 2013 and the Framework for Implementation of Climate Change Policy for the period of 2014 to 2030 (Salik *et al.*, 2015). India has several ongoing policy plans (DAHDF, 2014; Salim, Shridhar and Fernandez, 2017) that include: 1) Climate Change Action Programme; 2) National Action Plan on Climate Change 2008; 3) Indian Network for Climate Change Assessment; and 4) Twelfth Five-Year Plan and Climate Change. In Bangladesh end of century planning is under development considering outcomes from the ESPA-DELTA research project. Indonesia is also developing a National Climate Change Adaptation Plan. Sri Lanka has developed the National Climate Change Policy and the National Climate Change Adaptation Strategy (Marambe *et al.*, 2015).

13.4.4 Food safety and sustainability certifications

Change in the industry driven by certification requirements might have the effect of increasing the catch values, thereby mitigating potential catch volume reductions arising from climate change. Certifications are opening international markets, which account for 75 percent of the global fish trade (EU, Japan, and the USA) for SA countries. China is growing in importance as an importing country and aims to improve quality of fish imports, requiring that all Myanmar marine-product exports to China must be subjected to inspection to ensure that they match the same import regulations as imposed by the EU (ILO, 2015). Bangladesh's export success is because of the export of quality shrimp and introducing sanitary and hazard control procedures and traceability regulations according to the requirements of the EU and the United States of America (FRSS, 2017) after overcoming many problems to meet international food safety and quality standards (BBS, 2001; Golub and Varma, 2014). An importers' ban forced the local industry to act by investing to upgrade plant infrastructure, train employees and audit sanitary facilities (Cato *et al.*, 2003). The government, together with external donors, also invested in laboratory upgrades and employee training to meet the requirements of sanitary and hazard control standards (Dey *et al.*, 2010). Indonesian companies are also working on getting international sustainability certifications to avoid losing European, American and Japanese markets. Thailand receiving a "yellow card" status from the EU has triggered a fishing vessels survey and the development of monitoring tools (VMS and logbooks) and landings control (Derrick *et al.*, 2017).

13.4.5 Alternative and diversified livelihoods

Recent work has started to assess the adaptive capacity of fisheries management to confront climate change (Leith *et al.*, 2014; Melnychuk, Banobi and Hilborn, 2014), and has identified economic resilience attributes for a given fishery (van Putten *et al.*, 2013), livelihood diversification options (Leith *et al.*, 2014) and the role of cooperation in addressing equity concerns as economic instruments for resource management (Pascual *et al.*, 2014). The increase in types of fishing gears in Myanmar is a strategy of fishers to cope with declining catch (ILO, 2015), despite a growing awareness by government that it can further aggravate overfishing. The Force of Nature Aid Foundation, a non-profit agency in Malaysia, has demonstrated the importance of skills diversification as one of the ways to empower communities (Shaffril, Samah and D'Silva, 2017). One example of such mechanisms is the diversification of livelihood systems, such as switching between farming and fishing in response to seasonal and interannual variation in fish availability. However, it must be considered that fishers are strongly attached to their work (Shaffril, Samah and D'Silva, 2017). For example, communities in Thailand have been quite varied in their capacity to adapt to alternative non-fisheries livelihoods (Bennett *et al.*, 2014). However, the promotion of non-fishing, non-environment-related income-producing activities should be intensified among small-scale fishers, which would reduce their dependence on the sea and diversify their income (Shaffril, Samah and D'Silva, 2017). As the financial dependence of their families on small-scale fishers is typically very high (Shaffril *et al.*, 2013), it would be advantageous to offer such alternative skills not only to small-scale fishers, but also to their families. Training efforts in Myanmar led to 40 fishery training courses in aquaculture, fisheries management, English and computer literacy, and market access requirements during 2013 to 2014 (ILO, 2015). Cultivating aquatic algae in India for food and pharmaceutical purposes and for production of biodiesel is an alternative livelihood that has been a positive response to climate change (Vivekanandan, 2011).

On industrialized continents such as Europe, North America, and Australia, recreational fisheries can represent the primary fisheries sector in inland waters (Christensen *et al.*, 2007). Recreational fisheries provide substantial additional value because they can also boost other tourism industries (Cooke *et al.*, 2016; Paukert *et al.*, 2017). Even in emerging economies, inland recreational fisheries are expanding as a result of angling tourism and increasing domestic participation (India, Gupta *et al.*, 2015; Malaysia, Teh and Teh, 2014). A lack of scientific knowledge on the basic biology of sport fish species, targeting of threatened species, and the absence of region- or species-specific angling regulations for recreational fisheries are identified as the challenges associated with this sector in India. Moreover, governance structures need to be strengthened, as multiple agencies are currently assuming some responsibility for recreational fishing, but none is tasked explicitly with its sustainable development and management (Gupta *et al.*, 2015).

13.4.6 Socio-economic stability: insurances, welfare, credits and minimum wage

Many small-scale fishers face risks each time they operate their fishing routine because of the lack of safety-at-sea training and adequate equipment, which hinders their capacity to adapt to changes as result of climate change. The National Fisherman's Association of Malaysia has introduced an affordable insurance protection scheme (Shaffril *et al.*, 2013), while India has the National Scheme of Welfare of Fishermen (DAHDF, 2014). Less than 20 percent of the total population have access to formal financial services in Myanmar and Bangladesh, with lower rates in rural areas (ILO, 2015; Jahan, Ahsan and Farque, 2017). The United Nations Development Programme Human Development Initiative has contributed to the development of microfinance operations in Myanmar and an increasing access of small-scale fishers to finance with low or zero interest rates (Shaffril *et al.*, 2017). The FAO Regional Fisheries Livelihoods Project has facilitated micro-finance services in some SA countries (ILO, 2015). Peer savings networks are usually comprised of people from similar social networks, financial strata, and occupation (ILO, 2015). Low wages and insecurity resulting in high employee turnover is leading some companies to offer long-term employee recognition programmes and meal and transportation subsidies as well as training programmes (ILO, 2015). In Thailand, Bennett *et al.*, (2014) identified the importance for fishers' adaptation of access to credit, social bonding, equity, access to land and local ownership, suitability of sites for tourism, and hiring of local labourers.

13.4.7 Marine protected areas, ecological restoration and spatial planning

Establishment of marine protected areas can be an effective tool for conserving fish stocks, biodiversity and increasing fish production (FAO, 2011b; Hilborn, *et al.*, 2004; Lubchenco *et al.*, 2003). They have been promoted as a solution to fisheries collapses in some instances, because of their potential positive spill over effects, for some species, for adjacent fisheries with potentially substantial benefits for artisanal fisheries (Costello and Polasky, 2008; Lester *et al.*, 2009; White *et al.*, 2008). Series of linked marine reserves have been proposed as a logical response to protect shifting species ranges arising from climate change (Hannah, 2008; Jones, Qiu and De Santo, 2013). Bangladesh has established more than 500 fish sanctuaries throughout the country (FRSS, 2017) including the Saint Martin Island, the Sundarbans (mangrove forest) and a marine reserve (covering 698 km^2) in the Bay of Bengal to protect and preserve the breeding grounds of marine flora and fauna. It has also developed a MPA policy framework (BOBLME and IUCN, 2014).

Ecological restoration has been practised as a means of rehabilitating ecosystems and habitats that have been degraded or impaired through human use or other causes, such as climate change, with evidence of increased biodiversity and improved ecosystem function, but has been expensive and of limited coverage (Timpane-Padgham, Beechie and Klinger, 2017). Marine spatial planning is a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives (Ehler and Douvere, 2009; Muñoz *et al.*, 2017; Sale *et al.*, 2014). Novel approaches can use ecosystem models to consider socio-economic activities as well as climate scenarios in areas with sparse biological data using methodologies that have been tested in rich data areas (Queirós *et al.*, 2016), aided by improved data collection and geographical information systems (DAHDF, 2014). All these can be, with effective and participatory planning, examples of win-win adaptation measures (Grafton, 2010).

13.4.8 International research and collaboration programmes

Projections of fish distribution, abundance and catches need to be developed for planning better management adaptations (Vivekanandan, 2011). Lack of data (e.g. oceanographic surveys) and scientific knowledge is a constraint to this aim (Maung-Saw-Htoo-Thaw *et al.*, 2017). However, it is starting to change with initiatives such as the 2nd International Indian Ocean Expedition (IIOE-2), a five-year programme of oceanographic research that started in the Indian Ocean in 2015. Several international scientific research programmes are also addressing those needs. BOBLME[1] in the Bay of Bengal (Maldives, India, Sri Lanka, Bangladesh, Myanmar, Thailand, Indonesia

1 http://www.boblme.org/

and Malaysia) aims to improve the lives of the coastal populations through improved regional management of the Bay of Bengal environment and its fisheries. The EAF-Nansen Project[2] in Myanmar aims to strengthen regional and country specific efforts to reduce poverty and create conditions to achieve food security through development of sustainable fisheries management regimes, and specifically through the application of the ecosystem approach to fisheries in several developing countries in all regions of the world. ESPA-DELTA[3] in Bangladesh aims to provide policymakers with the knowledge and tools to enable them to evaluate the effects of policy decisions on the poorest people's livelihoods using the latest state-of-art ecosystem models and scenarios (climate and socio-economic). DECCMA[4] in India, Bangladesh and Ghana aims to analyse the impacts of climate change and other environmental drivers across contrasting deltas in Africa and Asia as well as the processes of migration as an adaptation strategy, also considering the gender dimension. USAID Indonesia Marine and Climate Support developed the Indonesia Fisheries Information System (I-Fish), a tool for Coastal Habitats (I-CATCH), which aims to help in enacting 25 new laws and regulations around fisheries and marine resource management. This project also trained 2 225 government personnel on marine affairs management. These and other initiatives provide valuable support for increasing knowledge and informing planning and decision-making.

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[2] http://www.fao.org/in-action/eaf-nansen/en

[3] http://www.espadelta.net/

[4] http://www.deccma.com

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Chapter 14: Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries

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KEY MESSAGES

- Continued CO_2 (and other greenhouse gas) emissions are very likely to affect the outcomes of regional and national plans to maintain or improve socio-economic benefits derived from industrial tuna fisheries and small-scale, coastal fisheries.
- Global warming is likely to affect food webs supporting tropical tuna species, and very likely to cause changes in distribution and abundance of tuna by 2050 under the RCP8.5 emissions scenario.
- Redistribution of tropical tuna is very likely to affect licence revenues from purse-seine fishing, and shift more fishing into high seas areas.
- Harvest strategies for tropical tuna will very likely need to account for changes in distribution and abundance resulting from climate change.
- Priority adaptations to maintain the economic benefits of industrial tuna fisheries will need to focus on interventions to maintain licence revenues, and ensure delivery of fish to local canneries.
- Global warming, extreme events, and ocean acidification are very likely to damage coral reefs and other habitats underpinning small-scale, coastal fisheries for demersal fish and invertebrates.
- Changes to coral reefs and other fish habitats, and the direct effects of CO_2 emissions on fish and invertebrates, are likely to reduce harvests from small-scale, coastal fisheries by up to 20 percent by 2050, and by up to 50 percent by 2100, under the RCP8.5 emissions scenario.
- Climate change is very likely to increase uncertainty in replenishment of coastal fish stocks, requiring a more conservative community-based ecosystem approach to fisheries management.

- Priority adaptations to maintain the benefits of coastal fisheries involve minimizing the gap between sustainable harvests and the fish needed for food security, and filling the gap mainly by increasing access to tuna for small-scale fishers.

14.1 INTRODUCTION

This chapter applies an end-to-end, climate-to-fish-to-fisheries, approach (Bell *et al*., 2013; Bell, Johnson and Hobday, eds., 2011) to assess the vulnerability of the region's plans to secure and increase the socio-economic benefits from fisheries to climate change and ocean acidification. It begins by summarising the observed and projected changes to the physical and chemical features of the Western and Central Pacific Ocean (WCPO), and how these changes are expected to alter fish habitats. For each of the main types of fisheries in the WCPO, the chapter then explains how the direct and indirect effects of continued carbon dioxide (CO_2) emissions are likely to affect the distribution and abundance of fish stocks; the implications for economic development, government revenue, food security and livelihoods; and the adaptations needed to minimize the threats and maximize opportunities.

The analyses presented here are based on global and regional modelling approaches that use the representative concentration pathways (RCPs) from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), or emission scenarios from the IPCC Fourth Assessment Report (AR4). The likelihood and confidence ratings for the key messages have been attributed using the IPCC method.

14.1.1 Fisheries of the region

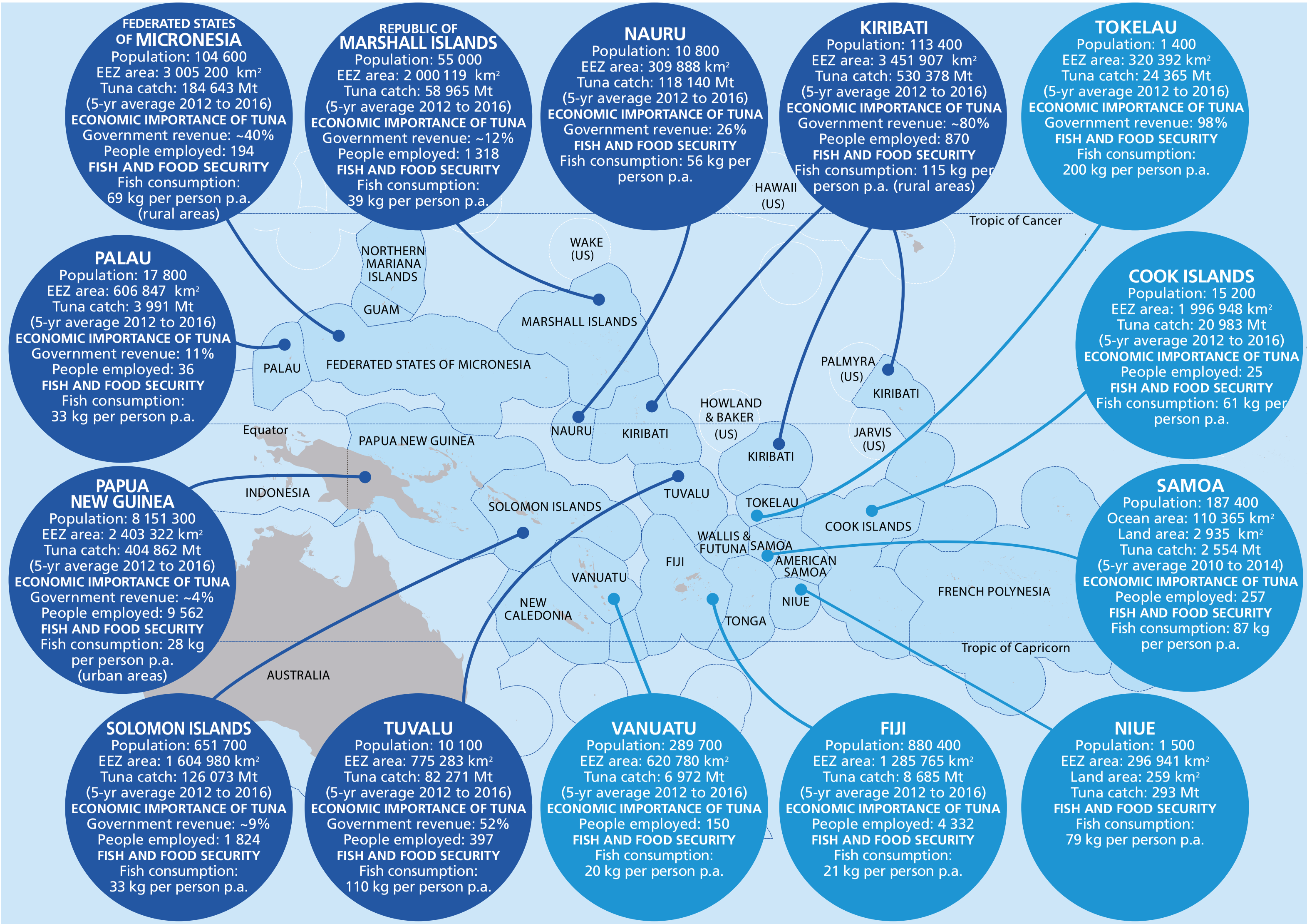
The Western and Central Pacific Ocean[1] supports major industrial tuna fisheries and a variety of small-scale, coastal fisheries. The region's industrial tuna fisheries are the largest in the world, and make substantial contributions to government revenue, gross domestic product (GDP) and employment in several Pacific Island countries and territories (PICTs; Gillett, 2016; Williams, Terawasi and Reid, 2017; Figure 14.1). The industrial surface fishery targets skipjack tuna (*Katsuwonus pelamis*) and juvenile yellowfin tuna (*Thunnus albacares*) using purse-seine and pole-and-line fishing methods to supply canneries in the Pacific, Asia and Europe. The industrial longline fishery targets mature bigeye tuna (*Thunnus obesus*) and yellowfin tuna for the sashimi trade and other high-value markets, and South Pacific albacore (*Thunnus alalunga*) for canning. Around 60 percent of the tuna catch from the WCPO convention area is taken from the exclusive economic zones (EEZs) of PICTs (Williams, Terawasi and Reid, 2017). Industrial tuna fisheries also capture smaller quantities of other large pelagic fish.

Small-scale, coastal fisheries underpin fish consumption and livelihoods in most Pacific Island communities (Figure 14.1; Bell, Johnson and Hobday, eds., 2011; Gillett, 2016). These fisheries target mainly demersal fish and invertebrates associated with coral reefs, mangroves and seagrasses, and increasingly tuna and other large pelagic fish in nearshore waters (Bell *et al*., 2018; Bell, Johnson and Hobday, eds., 2011; Johnson *et al*., 2017).

[1] Defined for the purposes of this chapter as the area 25 °N to 25 °S and 130 °E to 130 °W, including Northeastern Australia.

FIGURE 14.1

Key features of selected PICTs and the contributions of fisheries to government revenue, employment and food security



Dark blue circles denote countries that are the Parties to the Nauru Agreement.

Source: Pacific Community and Conservation International.

14.1.2 Strategic plans and management arrangements

Given the great significance of fisheries to Pacific Island people, a concerted effort has been made by PICTs to understand the key drivers of the sector, and to develop strategic plans to secure and increase the socio-economic benefits derived from marine resources. These efforts culminated in the *Regional Roadmap for Sustainable Pacific Fisheries*[2], endorsed by Pacific Island leaders. The Roadmap is designed to 1) optimize the benefits of tuna resources for economic development, government revenue and employment; 2) ensure that growing human populations have enough fish for food security; and 3) sustain livelihoods derived from small-scale fisheries.

The transboundary tuna stocks of the WCPO are managed cooperatively. The Pacific Islands Forum Fisheries Agency (FFA) assists member countries to manage tuna fishing operations by foreign and domestic fleets within their EEZs. The Office of the Parties to the Nauru Agreement (PNA) allocates purse-seine fishing effort across the EEZs of its member countries through the "vessel day scheme". The broader approach needed to co-ordinate tuna catches within EEZs with those made on the high seas is managed by the Western and Central Pacific Fisheries Commission (WCPFC). These management arrangements are based on regular stock assessments for each species of tuna by the Oceanic Fisheries Programme of the Pacific Community (SPC).

SPC and partners support PICTs to manage small-scale fisheries using a community-based, ecosystem approach to fisheries management (CEAFM), underpinned by national regulations to maintain harvests within sustainable bounds (e.g. spatial and temporal fishing closures, size limits and gear restrictions). As a result of increased demand for fish by rapidly-growing human populations in many PICTs, and limits to sustainable harvests from coastal fish habitats, small-scale fishers are also encouraged to catch more tuna from nearshore waters (Bell *et al*., 2015, 2018).

14.2 OBSERVED AND PROJECTED EFFECTS OF CLIMATE CHANGE ON THE WCPO

14.2.1 Effects on physical and chemical features of the ocean

The surface temperature of the WCPO has increased by more than 0.7 °C since 1900 (Bindoff *et al*., 2007). Projections based on a suite of global climate models from the Climate Model Intercomparison Project version 5 (CMIP5) used for AR5 indicate that, under the highly ambitious RCP2.6 emissions scenario, increases in average sea surface temperature (SST) in the WCPO will remain below 1 °C by 2100 relative to 2000 to 2010. However, with increased CO_2 emissions corresponding to the "business-as-usual" RCP8.5 scenario, SST is expected to increase by 2.5 °C to 3.5 °C by 2100 (Table 14.1), and to rise most rapidly in equatorial waters (Figure 14.2). Critically, this long-term warming is expected to cause more extreme marine heat waves, resulting in much higher temperatures over short periods (Hobday *et al*., 2016). The warming ocean, and higher projected rainfall, are expected to increase stratification of the water column, reducing the supply of nutrient-rich water to the surface mixed layer (Bell *et al*., 2013; Bell, Johnson and Hobday, eds., 2011).

Globally, sea level has risen about 20 cm since the industrial revolution (Hay *et al*., 2015). Continued warming of the ocean to a depth of several hundred metres, together with melting of glaciers and ice sheets, is expected to cause sea level to rise by 0.4 m by the end of the century under RCP2.6, and by more than 0.6 m under RCP8.5 (IPCC, 2014).With the possibility of more rapid melting of the ice-sheets (not accounted for in climate models), sea level rise could be considerably greater, exacerbating the effects of storm surges on coastal fish habitats.

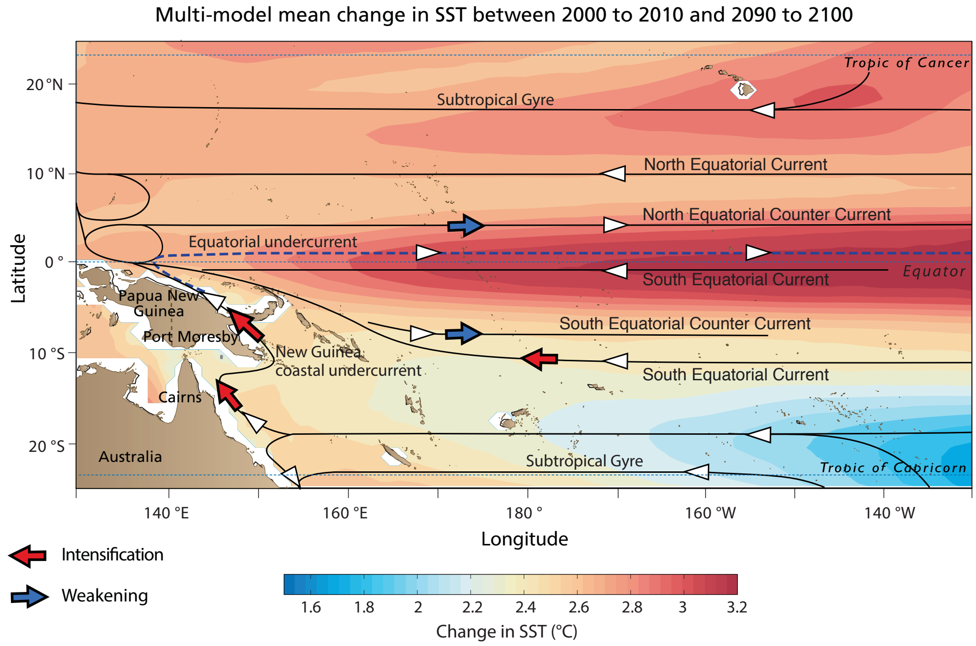
[2] www.ffa.int/node/1569

Increasing rates of ocean acidification in the WCPO through absorption of atmospheric CO_2 (Langlais *et al*., 2017) are reducing the aragonite saturation state, the main form of calcium carbonate used by corals and other marine organisms to build hard skeletons and shells. Since the industrial revolution, ocean acidification has reduced the pH of the upper water column by 0.1 (Royal Society, 2005) and the aragonite saturation level to 3.9 (Langdon and Atkinson, 2005). Aragonite saturation levels greater than 4 are optimal for calcifying organisms, saturation levels between 4 and 3 are marginal to very marginal for calcification, and below 3 complex coral reef systems do not occur (Langdon and Atkinson, 2005). Strong mitigation of CO_2 emissions (RCP2.6), is expected to maintain aragonite levels at approximately 3.5 (Figure 14.3), providing conditions adequate for some coral growth. In contrast, under RCP8.5 it is very likely that aragonite levels in the WCPO will drop below 3 between 2050 and 2100, causing serious degradation of coral reefs.

The CMIP5 simulations indicate that winds and ocean circulation in the region will also change significantly (Table 14.1; Figure 14.2). The northeast and equatorial trade winds are projected to weaken, whereas the southeast trade winds are expected to intensify. The South Equatorial Current and the associated New Guinea Coastal Undercurrent are projected to increase, whereas the velocities of the South Equatorial Counter Current and North Equatorial Counter Current are expected to decrease (Hu *et al*., 2015; Sen Gupta *et al*., 2016; Figure 14.2). In turn, changes in ocean circulation are expected to alter the location and strength of warm and cold eddies that reduce and enhance delivery of nutrient-rich water to the photic zone, respectively (Bell, Johnson and Hobday, eds., 2011).

FIGURE 14.2

Projected mean changes in SST, and major ocean currents (solid lines) and undercurrents (heavy blue dashed line), in the Pacific Island region between 2000 to 2010 and 2090 to 2100. The mean direction of currents is indicated by white triangles



Source: Bell *et al*., 2013.

TABLE 14.1
Multi-model median SST, wind stress, sea level, aragonite saturation and pH from the suite of CMIP5 models averaged over the 2000 to 2010 period, and projected change in these ocean variables by 2050 (2045 to 2055) and 2100 (2090 to 2100) for the RCP2.6 and RCP8.5 emissions scenarios. All changes are expressed as the multi-model inter-quartile range, except for aragonite and pH which are the multi-model median changes

Ocean variable	*Multi-model median 2000 to 2010*	*RCP2.6*		*RCP8.5*	
		2050	*2100*	*2050*	*2100*
Sea surface temperature[1] (°C)	27.4	+0.4–0.8	+0.3–0.8	+0.9–1.3	+2.3–3.3
Maximum warm pool SST, warmest 10% region (°C)	29.4	+0.4–0.8	+0.3–0.8	+0.9–1.3	+2.0–3.1
Warm pool edge, defined by 29 °C isotherm (degrees longitude)	170	180.8–191	179.5–193.3	187–205.3	213.3–EM[3]
Sea level rise (m)	0	+0.28–0.31	+0.4–0.44	+0.36–0.41	+0.6–0.66
Aragonite[1,2]	3.9	-0.32	-0.35	-0.63	-1.43
pH[1,2]	8.07	-0.06	-0.05	-0.12	-0.31
Westward wind stress,					
2 °S–2 °N, 130 °E–230 °W (10^{-4} Nm-2)	-32.6	-0.6– +3.3	0– +4.2	-0.3– +4.5	-2.1– +7.5

[1] Averaged over full domain 25 °S to 25 °N, 130 °E to 130 °W.

[2] Dataset described in Lenton, McInnes and O'Grady (2015).

[3] EM: eastern margin of Pacific basin.

14.2.2 Effects on biological and ecological features of the WCPO

Oceanic food webs

The predicted reductions of nutrients to the mixed layer (Section 14.2.1) have already had negative effects on phytoplankton production at various locations in the tropical and subtropical Pacific Ocean (Boyce, Lewis and Worm, 2010; Signorini, Franz and McClain, 2015). However, modelling of future phytoplankton production, and the knock-on effects on zooplankton and micronekton, indicates that changes in food webs supporting tuna are unlikely to be uniform across the region.

Spatial variability in the effects of increased SST and changes to ocean circulation on oceanic food webs are expected because of differences between the ecological provinces of the region (Bell *et al.*, 2013). Impacts are likely to be much lower in the Pacific Equatorial Divergence than in other provinces as a result of strong upwelling. Nevertheless, uncertainty remains. Some modelling suggests that there could be increases in primary production of more than 25 percent in the subtropical North Pacific (Polovina *et al.*, 2011). In the western tropical Pacific, other modelling indicates that little change may occur in primary production by 2050 because increases in sub-surface phytoplankton could offset declines in surface phytoplankton (Matear *et al.*, 2015).

The considerable uncertainty in how food webs in the WCPO are likely to respond to climate change is related to the complexity of the ecosystem (Bell, Johnson and Hobday, eds., 2011), and to difficulties in encompassing all mechanisms involved when modelling the effects of ocean warming (Evans *et al.*, 2015). Improved modelling will depend on a better understanding of prey-predator relationships between different trophic levels (Behrenfeld, 2014), and their autonomous adaptation to environmental change (Schaum *et al.*, 2013). Improved simulations of responses of the micronektonic food of tuna to climate change, and collection of better data (including acoustic and environmental DNA data) for model calibration, are particularly important.

The impact of ocean acidification on the food webs supporting tuna has yet to be determined. However, in the productive Pacific Equatorial Divergence, calcareous organisms represent only 1 percent to 5 percent of phytoplankton, approximately 6 percent of zooplankton and 2.2 percent of micronekton (Bell, Johnson and Hobday, eds., 2011). Thus, even severe ocean acidification may have limited impacts at these trophic levels.

Coastal fish habitats

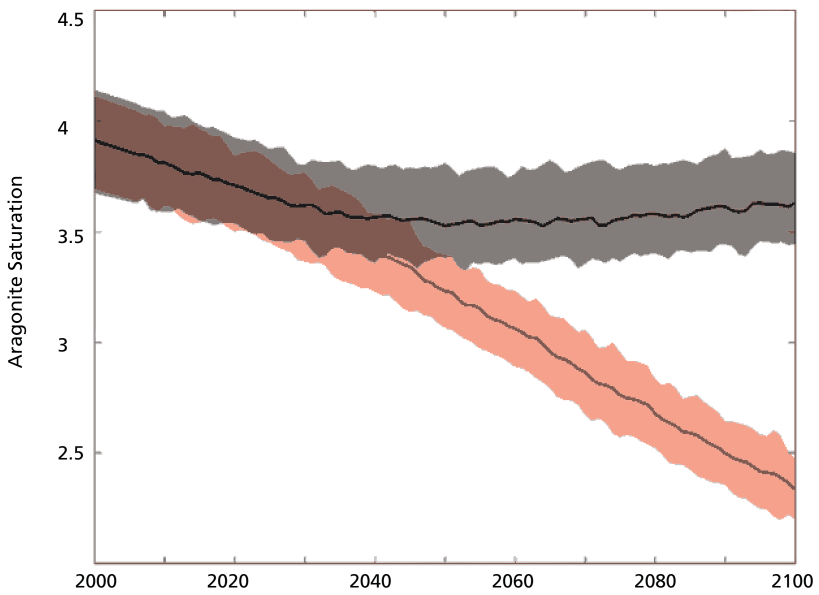
The coral reef, mangrove and seagrass habitats supporting small-scale fisheries in the region are already under stress from climate change and other anthropogenic impacts (Bell, Johnson and Hobday, eds., 2011; Johnson *et al*., 2017). Live coral cover has declined by 1 percent per year since 1980, extensive coral bleaching has occurred on Australia's Great Barrier Reef since 2015 (Hughes *et al*., 2018), and a vast area of mangroves was killed by heat stress in Northern Australia in 2016 (Duke *et al*., 2017).

The projected increases in air temperature, turbidity from more extreme rainfall, SST, marine heatwaves, ocean acidification, sea level, and physical damage from more intense cyclones are expected to cause further reductions in the extent and quality of coastal habitats (Bell *et al*., 2013; Johnson *et al*., 2017). Modelling of the future frequency of coral bleaching resulting from increased SST indicates that coral reefs in all PICTs and on the Great Barrier Reef will experience severe annual bleaching by 2050 under the RCP8.5 emissions scenario (van Hooidonk *et al*., 2016).

The combined effects of more regular, severe bleaching and ocean acidification are expected to reduce live coral cover by 50 percent to 75 percent by 2050, and as much as 90 percent by 2100 under a high AR4 emissions scenario (Bell, Johnson and Hobday, eds., 2011). As a result, macroalgae are expected to dominate reefs by 2100.

Sea level rise is expected to cause significant reductions in the area of mangroves because the trees cannot tolerate extended immersion in sea water. The steep terrain of islands in the Western Pacific, where most mangroves in PICTs occur, will prevent landward migration of mangroves as sea level rises in many places. Where the terrain is suitable, rapid sea level rise could outstrip the capacity of mangroves to migrate. By 2050, the area of mangroves across all PICTs could be reduced by 50 percent under a high AR4 emissions scenario (Bell, Johnson and Hobday, eds., 2011). The area of seagrass is also expected to decrease significantly (5 percent to 35 percent) by 2050 across the region under a high AR4 emissions scenario because of increased runoff from more extreme rainfall, as well as increases in cyclone intensity (Bell, Johnson and Hobday, eds., 2011).

FIGURE 14.3
Projected changes in aragonite saturation for the RCP2.6 (grey) and RCP8.5 (red) emissions scenarios averaged across the Pacific Island region until 2100



14.3 EFFECTS OF CLIMATE CHANGE ON INDUSTRIAL TUNA FISHERIES

14.3.1 Observed and projected effects on distribution and abundance

The effects of climate change on tuna[3] have been difficult to observe because of the strong influence of climate variability on their distribution (Hobday and Evans, 2013). Skipjack tuna is a prime example. The locations where the best catches of this species are made in the WCPO can vary by up to 4 000 km of longitude between strong El Niño and La Niña events (Lehodey *et al*., 1997).

Projected responses of tuna in the WCPO to long-term climate change (Figure 14.4), and the combined effects of climate change and potential increased fishing effort, have been modelled using SEAPODYM[4]. An eastward and poleward shift in distribution, and reductions in total biomass, are projected for both skipjack and yellowfin tuna under the RCP8.5 emissions scenario, driven mainly by changes in larval survival and spawning location (Lehodey *et al*., 2013, 2017). Decreases in biomass of these two species in most EEZs west of 170 °E, and increases in EEZs east of 170 °E, are also expected. Projected percentage decreases by 2050 and 2100 relative to 2005 are particularly marked for Papua New Guinea, the Federated States of Micronesia, Nauru and Palau. However, for Papua New Guinea, it is important to note that the modelling does not yet take account of possible beneficial effects of increased nutrients of terrestrial origin from higher rainfall (Bell *et al*., 2013). Substantial percentage increases in biomass relative to 2005 are projected for skipjack tuna in Vanuatu, New Caledonia, Pitcairn Islands and French Polynesia, and for yellowfin tuna in French Polynesia.

Somewhat different responses are projected for bigeye tuna and South Pacific albacore. For bigeye tuna, strong decreases in biomass are expected to occur in the EEZs of all PICTs, with the declines exceeding 60 percent in several EEZs by 2100 (Figure 14.4). For South Pacific albacore, the distributions of larvae and juveniles are expected to shift south towards the Tasman Sea after 2050 (Figure 14.4). Densities of early life stages are projected to decrease in their core area (Coral Sea) by 2050, resulting in a stabilized adult biomass approximately 30 percent lower than in 2000. However, the North Tasman Sea could emerge as a new spawning ground after 2080, reversing the downward trend in abundance (Lehodey *et al*., 2015).

14.3.2 Comparative effects of non-climate stressors

There are few concerns about the effects of other drivers on the supply of tuna from industrial tuna fisheries. Notwithstanding the need to reduce the impact of tuna fisheries on the ecosystem (FAO, 2003; Pikitch *et al*., 2004), the management arrangements described in Section 14.1 and associated harvest strategies should maintain stocks above the limit reference points for each tuna species.

14.3.3 Implications for economic development

Redistribution of skipjack and yellowfin tuna (Figure 14.4) is expected to result in lower catches across the prime fishing grounds by 2050. Ultimately, reduced catches are also expected to affect licence revenues and the existing plans to increase employment based on industrial fishing and processing in Papua New Guinea and Solomon Islands. This employment risk is tempered, however, by the fact that recent average tuna catches in the EEZs and archipelagic waters of Papua New Guinea and Solomon Islands (see supplementary material in Bell *et al*., 2015) well exceed the capacity of existing and proposed fish-processing facilities. Nevertheless, changes in licencing conditions may be needed to ensure that more of the fish caught within the EEZs of these countries

[3] For the purpose of this chapter, "tuna" also includes other large pelagic fish, such as wahoo (*Acanthocybium solandri*), mahi mahi (*Coryphaena hippurus*) and billfish (Family Istiophoridae).

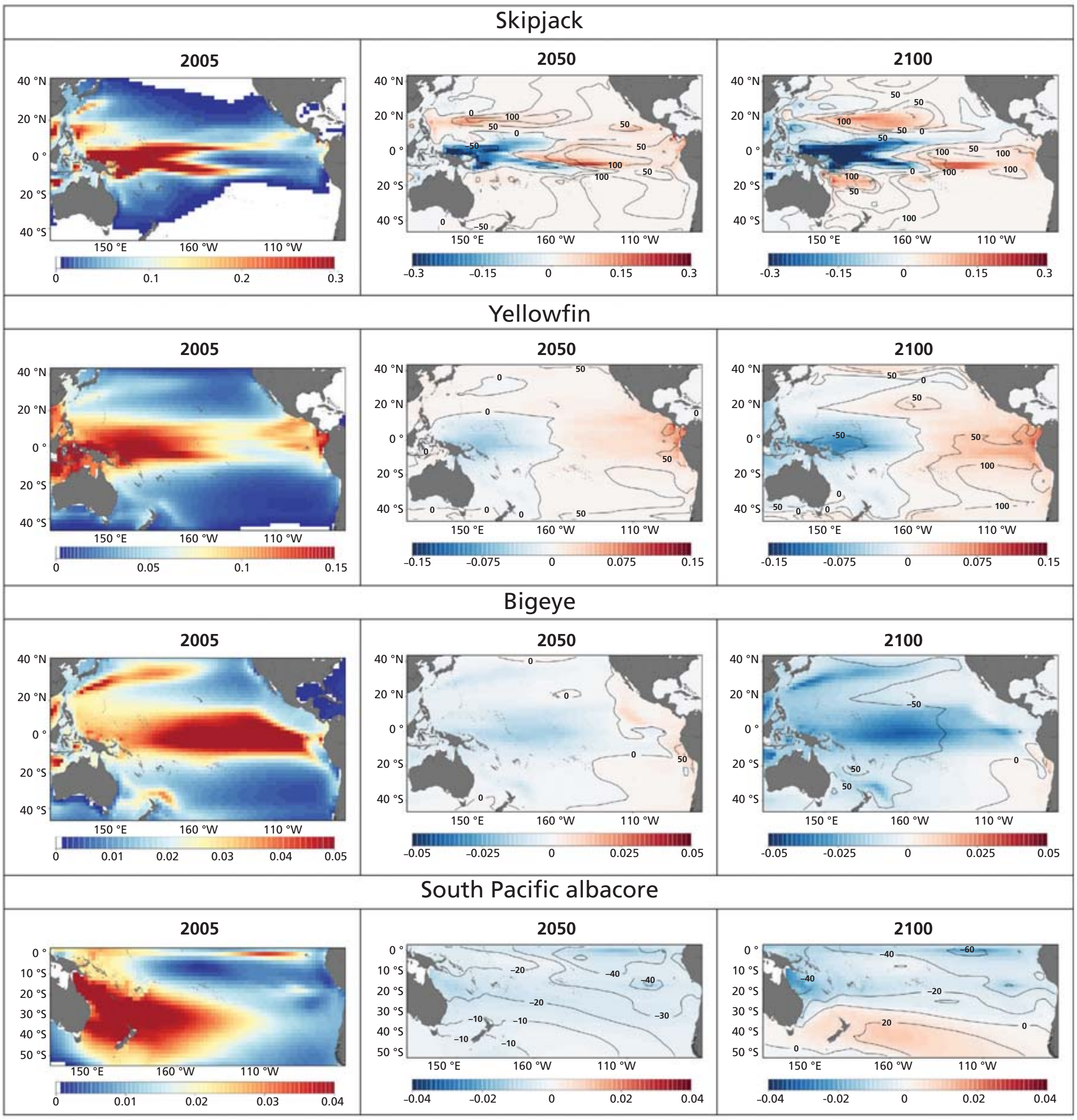
[4] A Spatial Ecosystem and Populations Dynamics Model; https://doi.org/10.1016/j.pocean.2008.06.004

is delivered to national canneries (Section 14.6). Other possible negative impacts on economic development may occur from the eastward redistribution of bigeye tuna and poleward movement of South Pacific albacore (Figure 14.4). In both cases, a greater proportion of longline fishing is eventually expected to occur outside the EEZs of PICTs, reducing government revenue from licence fees.

The projected eastward redistribution of skipjack and yellowfin tuna as a result of climate change could result in opportunities for PICTs in the eastern WCPO, e.g. French Polynesia, and PICTs in the subtropics, e.g. Vanuatu and Fiji, to obtain increased economic benefits. However, although modelling indicates that the percentage increases in catch could be substantial in these EEZs, the scale of benefits is likely to be modest because present-day catches are low.

FIGURE 14.4

Average historical (2005) distributions of skipjack, yellowfin and bigeye tuna and South Pacific albacore (Mt/km²) in the tropical Pacific Ocean, and projected changes in biomass of each species relative to 2005 under the RCP8.5 emission scenario for 2050 and 2100, simulated using SEAPODYM. Isopleths in the projections for 2050 and 2100 represent the relative percentage change in biomass caused by climate change



14.3.4 Consequences for fisheries management

The modelling summarized in Section 14.3.1 indicates that an increase in fishing effort will exacerbate the overall decreases in production of tuna species projected to occur as a result of climate change. To minimize negative effects on tuna catches, fishing effort will need to be constrained and future harvest strategies adjusted to account for alterations in distribution and abundance of tuna species. The depletion-based reference points used by WCPFC are well suited to adjusting management to cater for possible future changes in stock productivity because biomass levels are considered in relation to levels that would have occurred in the absence of fishing. Other possible consequences include 1) the need to transfer more management responsibility to WCPFC as a greater proportion of the catch is made in high seas areas; and 2) eventual consideration of Pan-Pacific tuna management through a merger of WCPFC and the Inter-American Tropical Tuna Commission. The existing monitoring, control and surveillance of tuna catches by FFA, PNA and WCPFC should help identify if and when such a change in management would be appropriate. Because eastward redistribution of tuna can be expected to increase the use of drifting fish aggregating devices (FADs) by purse-seine vessels (Williams, Terawasi and Reid, 2017), management will also need to ensure that the effects of FAD fishing on associated species (e.g. sharks) and juvenile bigeye tuna (Hall *et al*., 2017) are mitigated effectively.

14.3.5 Vulnerability of fisheries and economies

The four species of tropical tuna are expected to have relatively low vulnerability to the projected physical and chemical changes to the WCPO, and to alterations in oceanic food webs, because they can move to areas with their preferred conditions. However, increased stratification could make the surface-dwelling skipjack and yellowfin tuna more vulnerable to capture. This assessment is based on higher catch rates for yellowfin tuna in the warm pool (see Table 14.1 for definition) during El Niño events, when shoaling of the thermocline contracts the vertical habitat for this species (Johnson *et al*., 2017). Increased vulnerability to capture by the surface fishery, and projected decreases in availability of these two species across much of the region (Section 14.3.1), underscore the need for effective management (Section 14.4.3). The small national economies with a high dependence on licence fees are likely to be vulnerable to these changes by 2050. It is possible, however, that the plans to improve the value of tuna in the Roadmap could maintain existing levels of government revenue from licence fees even though catches decline. The economies of Papua New Guinea and Solomon Islands are expected to have low vulnerability because tuna fishing and processing make relatively small contributions to GDP of these relatively large economies.

14.3.6 Recommended adaptations

Priority adaptations to maintain the contributions of purse-seine fishing to economic development are based around continuing to 1) maintain licence revenue and distribute it equitably among PNA members and other PICTs; 2) deliver the tuna required by existing and proposed canneries in the region; and 3) finding ways to add more value to the abundant skipjack tuna. These adaptations are summarized in Table 14.2 and described in more detail in Bell, Johnson and Hobday, eds. (2011).

Two of the key adaptations are already in place. The VDS (Section 14.1.2) allows licence revenues to be shared among PNA member countries regardless of El Niño-Southern Oscillation phase and adjusts the fishing days allocated to countries as climate change alters the distribution of tuna. The Interim Economic Partnership Agreement with the European Union enables Papua New Guinea to source tuna for national canneries from outside its EEZ, guaranteeing sufficient tuna for processing as the fish move eastward. If needed, other adaptations that would help maintain the supply of tuna for canneries include reducing access for distant water fishing nations (DWFNs) to Papua New Guinea's EEZ to provide more fish for national vessels, and requiring DWFNs operating within the EEZ to land fish at local canneries. Finding ways to add more value to skipjack tuna would allow PICTs to earn more from this resource in the short-term, and help offset the consequences of lower projected catches caused by climate change.

TABLE 14.2

Examples of priority adaptations and supporting policies to assist PICTs reduce the threats posed by climate change to the contributions of industrial tuna fisheries to economic development, and capitalize on the opportunities. These measures are classified as "win-win" (W-W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or "lose-win" (L-W) adaptations, where benefits are exceeded by costs in the short term but accrue under longer-term climate change (Chapter 25)

<table>
<tr><th>Adaptation options</th><th>Supporting policies</th></tr>
<tr><td>Full implementation of the vessel day scheme (VDS) to control fishing effort by the Parties to the Nauru Agreement[a] (W-W).</td><td rowspan="6">• Strengthen national capacity to administer VDS.
• Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna.
• Promote partnerships to process and market skipjack tuna in new ways.
• Include implications of climate change in management objectives of the WCPFC.
• Apply national management measures to address climate change effects for subregional concentrations of tuna in archipelagic waters beyond WCPFC's mandate.
• Require all industrial tuna vessels to provide operational-level catch and effort data to improve models for projecting redistribution of tuna stocks during climate change.</td></tr>
<tr><td>Diversify sources of fish for canneries and maintain trade preferences, e.g. an Economic Partnership Agreement with the European Union (W-W).</td></tr>
<tr><td>Identify ways to add more value to skipjack tuna (W-W).</td></tr>
<tr><td>Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change (W-W).</td></tr>
<tr><td>Energy efficiency programmes to assist fleets to cope with oil price rises, minimize CO_2 emissions, and reduce costs of fishing further afield as tuna move east (W-W).</td></tr>
<tr><td>Environmentally-friendly fishing operations (W-W).</td></tr>
</table>

Source: Bell *et al*., 2013, Bell, Johnson and Hobday, eds., 2011.

[a] = The Parties to the Nauru Agreement (PNA) are Palau, Federated States of Micronesia, Papua New Guinea, Solomon Islands, Marshall Islands, Nauru, Kiribati and Tuvalu; more than 90% of the tuna caught from the waters of PICTs comes from the EEZs of PNA members.

14.4 EFFECTS OF CLIMATE CHANGE ON SMALL-SCALE FISHERIES

14.4.1 Observed and projected effects on distribution and abundance

Declines in abundance of coral reef fishes because of coral bleaching have been observed on the Great Barrier Reef (Pratchett *et al*., 2011). However, climate change and ocean acidification are projected to have a greater range of direct and indirect effects on distribution and abundance of demersal fish and invertebrates in the WCPO. The indirect effects will occur through changes to coastal fish habitats. The main direct effects are summarized below.

Higher SST is expected to alter the metabolic rates, growth, reproduction and survival of demersal fish and invertebrates, resulting in changes in their abundance, size and distribution (Asch, Cheung and Reygondeau, 2018; Munday *et al*., 2008). Alterations to the strength of ocean currents are likely to affect the dispersal of larvae, reducing recruitment success in some locations and improving success in others (Bell, Johnson and Hobday, eds., 2011). Ocean acidification has been demonstrated to affect the behaviour (Munday *et al*., 2013), auditory responses (Simpson *et al*., 2011) and olfactory function (Dixson, Munday and Jones, 2010) of early life-history stages of demersal fish species. These changes are expected to alter the homing and settlement success of juveniles and their ability to detect and avoid predators (Munday *et al*., 2013), with implications for population replenishment. Lower aragonite saturation levels are expected to reduce calcification rates for gastropod and bivalve molluscs and echinoderms, making juveniles more vulnerable to predation (Bell, Johnson and Hobday, eds., 2011).

The combined direct and indirect effects of climate change and ocean acidification are estimated to reduce productivity of demersal fish in the region by up to 20 percent by 2050, and by 20 percent to 50 percent by 2100, under a high AR4 emissions scenario (Bell, Johnson and Hobday, eds., 2011). The projected changes to coastal fish habitats (Section 14.2.2 – Coastal fish habitats) are also expected to alter the composition of catches. For example, herbivorous species are likely to be relatively more abundant as coral cover declines and macroalgae increase (Bell, Johnson and Hobday, eds., 2011). Recent modelling of expected changes in abundance and distribution of demersal fish in the tropical Pacific indicates that even greater decreases in production may occur, exceeding 50 percent under RCP8.5 by 2100, especially in the west of the region (Asch, Cheung and Reygondeau, 2018).

Productivity of invertebrates is projected to decrease by 5 percent by 2050, and by 10 percent by 2100 under a high AR4 emissions scenario, and their quality and size is expected to be affected by reduced aragonite saturation levels (Bell, Johnson and Hobday, eds., 2011).

The potential effects of climate change on coral reef fisheries are illustrated by the projections for coral trout (*Plectropomus* spp.), which are heavily fished in Northeastern Australia and elsewhere in the Indo-Pacific. The thermal optimum for *Plectropomus leopardus* is 27 °C to 30 °C (Johansen *et al*., 2014), however, stocks are now exposed to temperatures of more than 30 °C throughout much of their range. Although this species may be able to moderate its exposure and sensitivity to increasing temperatures by moving to deeper water, reducing energetic expenditure and adjusting food intake during periods of higher SST, ocean warming is expected to reduce sustainable harvests, especially at low latitudes (Johansen *et al*., 2015; Pratchett *et al*., 2017). The direct impacts of ocean warming will be compounded by degradation of coral reefs. In combination, these direct and indirect effects are expected to threaten the viability and sustainability of commercial fisheries by 2050 (even under RCP2.6) at low-latitude locations. At subtropical latitudes, fisheries for coral trout are expected to become increasingly uneconomical towards 2100.

14.4.2 Comparative effects of non-climate stressors

Coastal fisheries in the WCPO are expected to be at much greater risk from drivers other than climate change in the near term (Gillett and Cartwright, 2010). The strongest drivers are those associated with rapid population growth (see supplementary material in Bell *et al*., 2015), i.e. overfishing because of limited alternative sources of protein and degradation of fish habitats caused by more intense land use and pollution (Gillett and Cartwright, 2010).

The main challenges are to 1) keep coastal fish and shellfish stocks within sustainable bounds through conservative fisheries management approaches fit for purpose, e.g. primary fisheries management (Cochrane, Andrew and Parma, 2011); and 2) manage coastal fisheries to address the key drivers while simultaneously minimizing the risks to stocks posed by climate change, and capitalizing on opportunities (Section 14.4.6).

14.4.3 Implications for food security and livelihoods

The implications of climate change for the important role that fish plays in local food security have to be placed in the context of the other factors affecting availability of fish. In many PICTs, population growth alone creates a large gap between recommended fish consumption for Pacific Island people (35 kg of fish per person per year) and sustainable harvests from well-managed coastal fisheries (Bell, Johnson and Hobday, eds., 2011).

Based on the area of coastal fish habitats and the distance of these habitats from population centres, PICTs fall into three groups with respect to their capacity to provide the fish needed for food security (Bell, Johnson and Hobday, eds., 2011): 1) PICTs with coastal fisheries expected to meet increased demand for fish; 2) those with sufficient coastal habitat to produce the fish required, but where transportation of fish to urban centres will be difficult; and 3) PICTs where coastal fish habitats will be unable to produce the fish required.

There are few implications of the projected decreases in coastal fish production arising from climate change for PICTs in Groups 1 and 2. The main risk is for PICTs outside the equatorial zone, where increases in ciguatera fish poisoning as a result of degradation of coral reefs caused by ocean warming could result in localised shortfalls in fish supply (Bell, Johnson and Hobday, eds., 2011). In such circumstances, communities will need to rely more heavily on catching tuna in nearshore waters.

For PICTs in Group 3, the projected declines of up to 20 percent in coastal fisheries production by 2050 and up to 50 percent by 2100 are expected to increase the gap only marginally because the effects of population growth on availability of fish per capita are so profound (Table 14.3). The main implications centre on the need to provide better access to tuna to supply the fish required by growing populations (Bell *et al*., 2015). Developing fisheries for small pelagic fish (Bell *et al*., 2018) and expanding pond aquaculture (Johnson *et al*., 2017) will also be important (Section 14.4.6).

Maximising the number of livelihoods that can be sustained from coastal fisheries resources will involve progressively transferring some effort from demersal fish to tuna and small pelagic fish species (Bell *et al*., 2018; Bell, Johnson and Hobday, eds., 2011), and switching some demersal fishing effort from resource "losers" to resource "winners".

TABLE 14.3

Projected gap between recommended fish consumption of 35 kg per person per year, and the estimated annual supply of fish per capita from coastal fisheries, in 2050 and 2100 for selected Pacific Island countries because of the effects of population growth (P) and the combined effects of population growth and climate change (CC) under a high AR4 emissions scenario

Country	*Estimated sustainable catch (Mt)**	*Population***		*Total fish available per capita per year (kg)*		*Gap in fish needed per capita per year (kg)*			
		2050	*2100*	*2050*	*2100*	2050		*2100*	
						P	*CC*	*P*	*CC*
Papua New Guinea	83 500	13 271	21 125	6	4	29	29	31	32
Samoa	6100	210	240	29	25	6	11	10	16
Solomon Islands	27 605	1 181	1 969	23	14	12	15	21	24
Vanuatu	3 812	483	695	8	6	27	28	29	30

*Estimates assume sustainable median fisheries production of 3 Mt per km^2 of coral reef per year (but also include freshwater fisheries production for Papua New Guinea and Solomon Islands, and reef habitat to depth of 100 m for Samoa).
**Estimates provided by the Pacific Community's Statistics for Development Division (source: Bell *et al*., 2013).

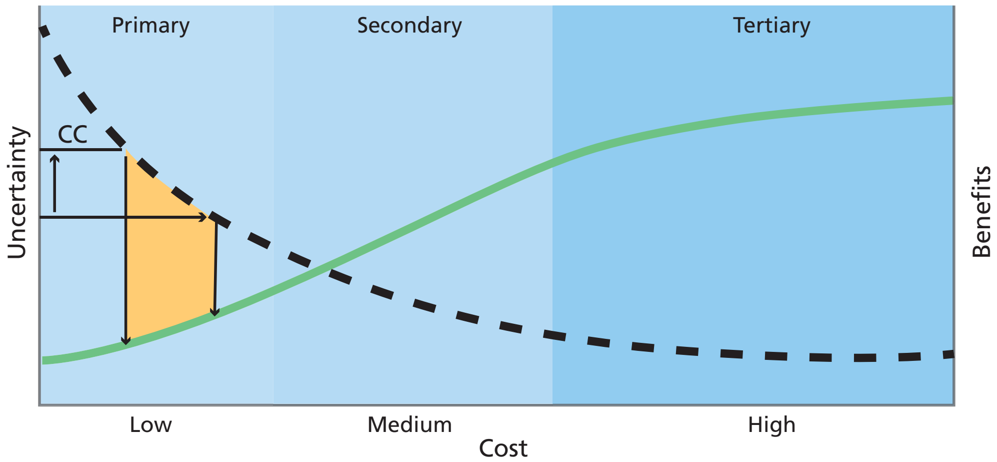
14.4.4 Consequences for fisheries management

The direct and indirect effects of climate change and ocean acidification are expected to increase uncertainty in replenishment of coastal stocks (Bell, Johnson and Hobday, eds., 2011). Increased uncertainty will require changes to the CEAFM and primary fisheries management approaches used by PICTs to keep coastal fisheries resources at sustainable levels. The reorientation of CEAFM needed to assist communities to adapt to climate change involves 1) informing all stakeholders about the risks to fish habitats, stocks and catches and facilitating their participation in decision-making; 2) supporting the trans-disciplinary collaboration needed to monitor the wider fisheries system for climate impacts and identify practical adaptations; and 3) providing the resources needed to implement climate-informed CEAFM (Heenan *et al*., 2015).

The more conservative application of primary fisheries management needed to address the increased uncertainty is illustrated in Figure 14.5. Examples of the types of management changes likely to be needed are revised size limits to account for altered growth rates and maturity schedules; and ensuring that the herbivorous species likely to be favoured by climate change are not overfished. Healthy stocks of herbivores will be needed to ensure that macroalgae do not unduly inhibit the growth and survival of remaining corals (Bell, Johnson and Hobday, eds., 2011).

FIGURE 14.5

General relationship between potential benefits from fisheries for coastal demersal fish species and invertebrates (green line), and uncertainty in information for management (dashed line), as functions of costs, for primary, secondary and tertiary fisheries management. The reduction in benefits under primary fisheries management as a result of the increased uncertainty caused by climate change (CC) is indicated by the orange shading



Sources: Bell, Johnson and Hobday, eds., 2011; Cochrane, Andrew and Parma, 2011.

14.4.5 Vulnerability of fisheries and communities

The small-scale, coastal fisheries underpinning food and livelihoods across the region have a moderate to high vulnerability to climate change for the following reasons: 1) the majority of the catch is derived from coral reefs (Bell, Johnson and Hobday, eds., 2011); 2) increases in SST will progressively drive many target species to higher latitudes (Asch, Cheung and Reygondeau, 2018); and 3) degradation of coral reefs is expected to reduce the productivity of species able to remain on reefs (Bell, Johnson and Hobday, eds., 2011). Even so, differences in vulnerability of the target species associated with coral reefs are expected between the Pacific Island region and Northeastern Australia. Coral-dependent species in PICTs are highly vulnerable (Table 14.4) because there are significant constraints on latitudinal shifts, mainly as a result of a lack of suitable habitat at higher latitudes. In Northeastern Australia, the vulnerability of reef-dependent fish species is lower because the connectivity of the Great Barrier Reef over 2 300 km should enable them to move to higher latitudes. The vulnerability of reef-associated and generalist species is expected to be moderate to high by 2100 because of their lower sensitivity to reduced live coral cover and structural complexity of reefs.

Many Pacific Island communities have a high vulnerability to decreases in productivity of demersal fish and invertebrates because they have few other sources of animal protein. A participatory approach is needed to raise awareness of the risks and identify practical adaptations to provide nutritious food for growing populations. The IPCC vulnerability framework and the Vulnerability Assessment and Local Early Action Planning Tool developed by the US Coral Triangle Initiative have been incorporated into such an approach for communities (Johnson *et al*., 2016). This approach scores and ranks the vulnerability of communities based on their exposure, sensitivity and adaptive capacity, using indicators of health, education, size of the economy and governance. This initiative is complemented by the climate-informed ecosystem approach to fisheries management (Heenan *et al*., 2015), and by assisting communities to evaluate alternative sources of food, e.g. access to freshwater for pond aquaculture and availability of tuna in nearshore waters (Bell, Johnson and Hobday, eds., 2011).

TABLE 14.4

Projected changes in productivity of the main types of demersal fish species associated with coral reefs in the Pacific Island region under a high emissions scenario in 2050 and 2100

Type of species	*2050*	*2100*
Coral-dependent	-90%	-100%
Reef-associated	-20 to -40%	-20 to -80%
Generalist	0%	-10 to -20%
All demersal fish	-20%	-20 to -50%

Source: Bell, Johnson and Hobday, eds., 2011.

14.4.6 Recommended adaptations

The priority adaptations to maintain the contribution of fisheries to food security and livelihoods of coastal communities involve finding ways to 1) minimize the gap between sustainable harvests from coastal fish habitats, and the quantities of fish recommended for good nutrition of growing human populations; and 2) fill the gap (Bell *et al*., 2018; Table 14.5). Adaptations to minimize the gap centre on avoiding and reversing degradation of coastal fish habitats and maintaining healthy stocks of demersal fish and invertebrates. Most of these adaptations are an integral part of coastal zone management and sustainable fisheries management (FAO, 2003, 2015). Climate-informed, ecosystem-based approaches to fisheries management (Heenan *et al*., 2015) provide the most effective way forward. Adaptations to fill the gap will need to focus largely on making it easier for small-scale fishers to access the region's rich tuna resources, developing fisheries for small pelagic fish, expanding pond aquaculture, and improving supply chains to avoid waste (Bell *et al*., 2015, 2018; Johnson *et al*., 2017).

TABLE 14.5

Examples of priority adaptations and supporting policies to assist PICTs reduce the threats posed by climate change to the contributions of small-scale fisheries to food security and livelihoods, and capitalize on the opportunities. These measures are classified as "win-win" (W-W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or "lose-win" (L-W) adaptations, where benefits are exceeded by costs in the short term but accrue under longer-term climate change (Chapter 25)

Adaptation	Supporting policies
Adaptations to minimize the gap	
Manage and restore vegetation in catchments (W-W). Avoid (and reverse) degradation of coastal fish habitats (W-W). Provide for landward migration of coastal fish habitats (L-W). Sustain production of coastal demersal fish and invertebrates (L-W). Maximize the efficiency of spatial management (W-W). Diversify catches of coastal demersal fish (L-W).	• Improve governance for sustainable use and protection of coastal fish habitats. • Strengthen fisheries legislation to apply community-based management, founded on an ecosystem approach and primary fisheries management. • Enhance national regulation of small-scale, commercial fishing. • Promote access to those groups of fish expected to increase in abundance. • Limit export of demersal fish. • Develop ecotourism to relieve fishing pressure on demersal fish stocks.

Adaptation	Supporting policies
Adaptations to fill the gap	
Transfer coastal fishing effort from demersal fish to nearshore pelagic fish (W-W). Expand fisheries for small pelagic species (W-W)*. Extend the storage time of nearshore pelagic fish catches (W-W). Increase access to small tuna and bycatch offloaded by industrial fleets during trans-shipping operations (W-W). Expand aquaculture of Nile tilapia and milkfish (W-W).	• Include nearshore FADs as part of the national infrastructure for food security. • Transfer some access rights and revenues from industrial tuna fisheries to small-scale fisheries. • Evaluate whether industrial fishing exclusion zones provide adequate access to tuna for small-scale fishers. • Apply targeted subsidy programmes to support key adaptations. • Limit tilapia farming to catchments with a shortage of fish and where tilapia are already established to reduce potential risks to biodiversity.

Source: Bell *et al*., 2013, 2018.
*Small pelagic fish are expected to be favoured by climate change only where changes to currents and eddies deliver more nutrients to surface waters.

14.5 CAPACITY DEVELOPMENT AND ENABLING ENVIRONMENT

Despite the practicality of the adaptations for industrial tuna fisheries and small-scale, coastal fisheries outlined above, uncertainty and gaps in knowledge remain about how best to apply them (Bell *et al*., 2013). Staged actions are needed to identify the research to be done; create effective research partnerships; overcome constraints to sharing knowledge and uptake of technology; and provide countries and communities with the resources needed for effective adaptation. Potential social barriers to the uptake of adaptations recommended for small-scale, coastal fisheries, e.g. cultural norms and gender issues that could limit broad-based community participation, also need to be considered.

The region also recognizes the need to build capacity for an integrated approach to climate change adaptation (CCA) and disaster risk management (DRM; Johnson, Bell and De Young, 2013). Combining DRM and CCA is particularly pertinent in the Pacific Island region, where there is a large overlap between the most common natural disasters (cyclones) and the impacts of climate change on the fisheries sector. The recent *Framework for resilient development in the Pacific: an integrated approach to address climate change and disaster risk management*[5] provides strategic guidance for stakeholders about how to enhance resilience to climate change and natural disasters. The Framework builds capacity to prepare for disasters, including those caused or exacerbated by climate change. The disaster preparedness, response and recovery initiatives in the Framework are designed to reduce undue human losses, and minimize adverse consequences for the region's social and environmental systems.

Ultimately, the most important ways for PICTs to improve the enabling environment for maintaining the socio-economic benefits of their marine fisheries will be to prepare, communicate and maintain their Nationally Determined Contributions under the 2015 Paris Agreement to adapt to the impacts of climate change, and reduce national emissions (Chapter 28).

Supplementary material, providing more detail for several aspects of this chapter, can be downloaded at http://oceanfish.spc.int/media/files/Supplementary%20Materials%20Chapter%2014.pdf

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[5] http://gsd.spc.int/frdp/

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Chapter 15: Climate change impacts, vulnerabilities and adaptations: Southwest Atlantic and Southeast Pacific marine fisheries[1]

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15A HUMBOLDT CURRENT SYSTEM

KEY MESSAGES

- In the Humboldt Current System (HCS), globally the most productive marine ecosystem in terms of fish caught, climate is considered to be the most important driving factor.
- Industrial fisheries developed during a period of exceptional productivity in relation to that of the last thousands of years. This also means that "normal or mean" productivity of the system is lower than at present and that it could "shift-back".
- An increase in upwelling-favourable winds off Chile and a decrease off Peru is projected, together with an overall decrease in plankton abundance.
- Climate change could shift the HCS out of its current favourable state in terms of fish productivity.
- El Niño events may become more frequent and major regime shifts may happen. These projections have a high level of uncertainty, but potential consequences are considerable.
- Institutionalizing participatory governance systems, promoting dedicated scientific studies and improving monitoring would increase the adaptive capacity of small-scale fisheries to cope with climate change.
- Strong control and enforcement and a reduction of capacity in small-scale fisheries could have a short-term negative social effect, but are important to safeguard their long-term sustainability.
- Increasing the share of fish dedicated to direct human consumption (DHC) would maintain or even increase food security and social and economic development under the predicted reduction in fish abundance and production.
- Stopping fish discards and waste through relevant policies and improved infrastructure (cold storage, sanitary conditions) would mitigate the projected reduction in fish productivity.
- Using natural gas instead of heavy fuel would help to mitigate the carbon footprint of the fisheries sector.

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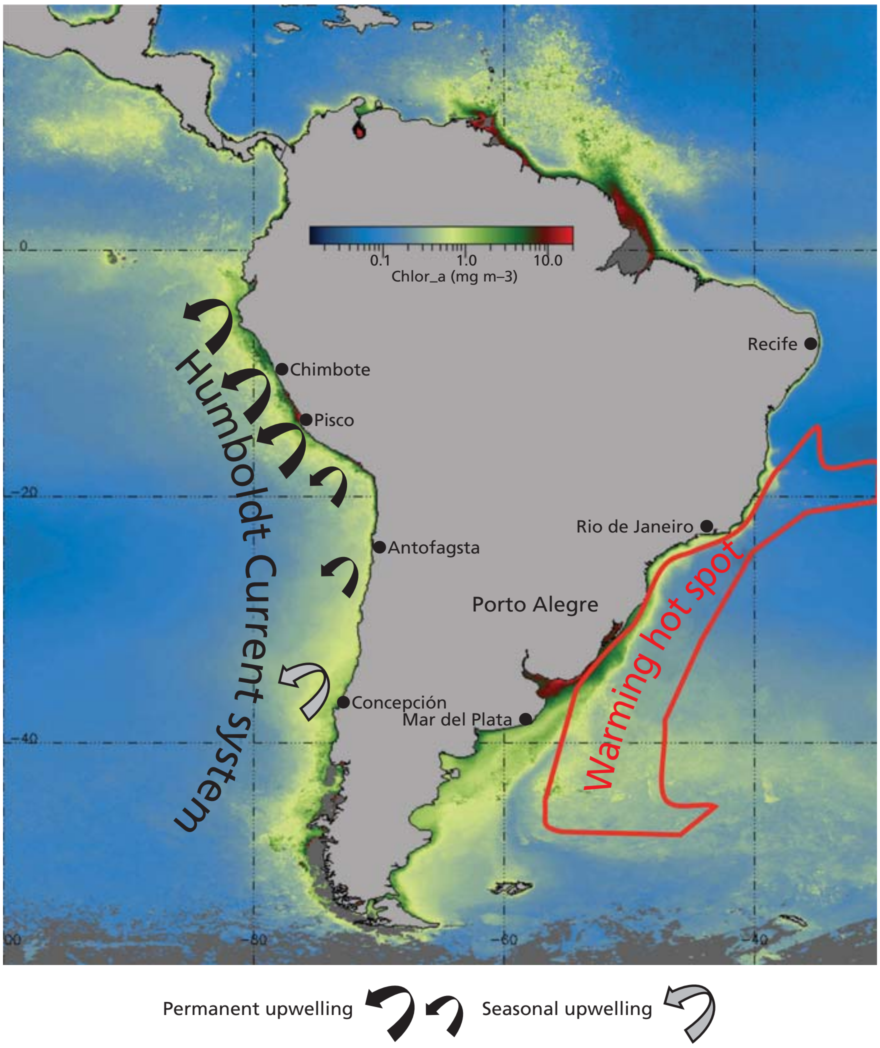
[1] In this chapter, we only considered areas for which enough information and model outputs are available to sustain recommendations.

FIGURE 15A.1
Within the FAO fishing area 87 region, the Humboldt Current System (HCS) extends from Southern Chile (approximately 45 °S) to Northern Peru–Southern Ecuador (approximately 3 °S) where cold and nutrient-rich, upwelled waters intersect warm tropical waters to form the equatorial front



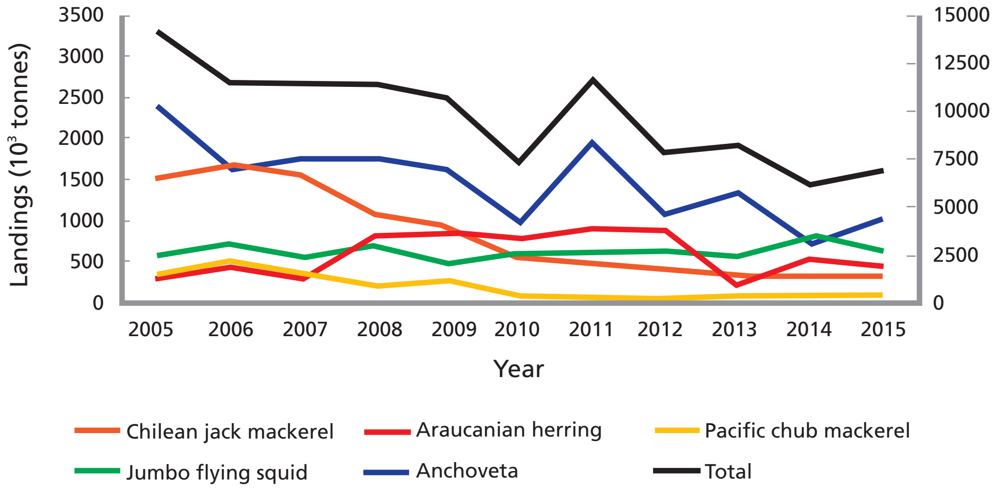
Source: Figure courtesy of Hervé Demarcq.

15A.1 MAIN FISHERIES OF THE REGION

On average, 9.35 million tonnes of marine fish, molluscs and crustaceans were landed each year in Chile and Peru during 2005 to 2015, with a noticeable decreasing trend (Figure 15A.2). This trend is primarily because of the implementation of stricter management plans but it also reflects climate variability and, in some cases, increasing overexploitation. The main landed species were the Peruvian anchovy or anchoveta (*Engraulis ringens*), the Chilean jack mackerel (*Trachurus murphyi*), the jumbo flying squid (*Dosidicus gigas*), the Araucarian herring (*Strangomera bentincki*) and Pacific chub mackerel (*Scomber japonicus*). The Northern–Central Peru region accounted for 75 percent of the total catches, Southern Peru–Northern Chile for nearly 20 percent, and central Chile represented less than 5 percent (Gutierrez, Akester and Naranjo, 2016).

FIGURE 15A.2

Total landings and landings of anchoveta (*Engraulis ringens*), Chilean jack mackerel (*Trachurus murphyi*), Pacific chub mackerel (*Scomber japonicus*), jumbo flying squid (*Doscidicus gigas*) and Araucarian herring (*Strangomera bentincki*) for Chile and Peru between 2005 and 2015



The second Y-axis corresponds to both total and anchoveta landings. *Source:* RFAO-FishStatJ, 2017.

15A.1.1 Peruvian fisheries

The Peruvian anchovy is by far the most fished species in the HCS, but Peruvian fisheries capture more than 300 species. By law, Peruvian industrial fleets can land anchoveta for reduction purposes only. DHC of anchovy is the prerogative of the small-scale fishing fleets, which are not allowed to land for reduction (Fréon *et al.*, 2017). By contrast, both industrial and small-scale fleets can only land Chilean jack mackerel and Pacific jack mackerel (and the South American pilchard or sardine, *Sardinops sagax sagax,* when present) for DHC. Some 98 percent of anchoveta catches are destined to produce fishmeal and fish oil (FMFO) and the remainder is processed into human food products (Fréon *et al.*, 2017).

Peru applies an adaptive management approach to industrial fisheries with at least two stock assessments per year and two seasonal catch limits in the form of total allowable catch (TAC), as well as provision for stopping fishing at any time, depending on the population and biological conditions of the stocks (e.g. when the proportion of juveniles in the catch is too high) and also on environmental conditions (IMARPE, 2016). Such adaptive management is well-suited to the highly variable HCS, especially in a changing ocean. To reduce the race for fish in the anchoveta fishery, individual vessel quotas were implemented in 2009 to allocate portions of the TAC. The TAC is decided by the Ministry of Production on the basis of a recommendation from the scientific authority, the *Instituto del Mar del Perú* (IMARPE).

Peruvian artisanal medium and small-scale fisheries (SSF) encompass vessels with haul capacity up to 32.6 m^3 and 15 m long. During 1997 to 2012, the number of SSF vessels increased more than twofold (17 068 in 2012), the number of fishers reached 67 400 in 2015, and landings increased by almost one order of magnitude to reach 1.2 million tonnes in 2012 (Guevara-Carrasco and Bertrand, 2017). This development was uncontrolled and mainly informal (Galarza and Kármiche, 2015).

A monitoring system for SSF was implemented in 1996 and covers 70 percent to 80 percent of landings (Guevara-Carrasco and Bertrand, 2017). In addition, the jumbo flying squid fishery is fully monitored in the Peruvian exclusive economic zone by onboard observers. Despite such monitoring, several aspects jeopardise the future of Peruvian SSF, including: 1) lack of scientific knowledge on ecology and population dynamics of most exploited species (Galarza and Kármiche, 2015); 2) open access regimes; 3) lack of regulations for most exploited species (e.g. quota, fishing closure, effort control, minimum size); and 4) a deficiency in monitoring, control, surveillance and enforcement of management actions.

15A.1.2 Chilean fisheries

Chilean fisheries management is based on TACs, closed seasons, and closed areas. TACs are determined each year from technical reports by the Scientific Technical Committees, which are based on the scientific research performed mainly by the *Instituto de Fomento Pesquero*. Over the past 30 years, the production of SSF has increased from less than 10 percent of the total industry catch to about 30 percent, because of both the increase of SSF landings and the decrease of industrial ones, the latter resulting from stricter management but also because of a reduction in Chilean jack mackerel biomass. Some 137 vessels were registered in the industrial fishery in 2014, while more than 91 000 fishers and 12 100 vessels were registered in the Artisanal Fishing Register. Since 2000, industrial and artisanal vessels must be equipped with a vessel monitoring system. Exclusive territorial use rights (TURFS) are granted to small-scale fishers for the management of bentho-demersal resources, where predefined extraction quotas are determined by the fishing authority. In 2013, Chile formally adopted a Management Plan (Law 20657, 2013[2]), that allows the management of a species or group of species within an administrative region, part of a region, or a set of regions through the establishment of management committees. Those committees include both small-scale and industrial fishers, government and private company representatives and are in charge of developing, implementing and monitoring and adapting management plans (Gelcich *et al*., 2015).

15A.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE ENVIRONMENT

15A.2.1 Physical and chemical

The HCS is one of the four major eastern boundary current systems of the world's oceans. In these systems, wind causes an offshore flow in the surface driving intense oceanic upwelling along the coast, bringing cold, deep, nutrient-rich waters to the surface. When the upwelled nutrient-rich water reaches the surface, sunlight triggers the onset of phytoplankton production. This is the first link of the marine food web and thus the basis for a high production from zooplankton to fish and top predators. The HCS is subject to large seasonal, interannual (e.g. El Niño-Southern Oscillation), decadal and secular to millennial scale fluctuations in climate, ecosystem and fisheries (e.g. Chavez *et al*., 2008).

A key feature of the HCS is the presence of an extended subsurface oxygen minimum zone (OMZ). The OMZ is a thick layer of water, the upper limit of which is located at a few tens of metres below the surface, and where oxygen concentration is so low that, except for bacteria, only some species can temporarily survive. Low-oxygen regions also have low pH. The OMZs of the world's oceans are expected to expand in a warming world (Schmidtko, Stramma and Visbeck, 2017). The acidic northern HCS OMZ could thus be considered as a sample of what could happen in the future in other ecosystems that currently have higher oxygen and low pH (Chavez *et al*., 2008).

Contrary to most other marine systems, the HCS experienced a cooling associated with upwelling intensification from the early nineteenth century to recent years.

[2] https://www.leychile.cl/Navegar?idNorma=1048776

Results of recent studies converge towards an expected increase in the intensity and duration of upwelling-favourable winds in the southern HCS off Chile, and a (moderate) decrease off Peru (e.g. Belmadani *et al*., 2014; Wang *et al*., 2015). The upwelling season is expected to become longer in central Chile, with an earlier onset and delayed end together with greater intensity, especially in summer (Belmadani *et al*., 2014; Wang *et al*., 2015). Furthermore, increased stratification and a strong surface warming of Peruvian waters and, to a lesser extent, of Chilean waters is forecast (e.g. Oerder *et al*., 2015).

The HCS is also the region where the effects of El Niño and La Niña events are most notable (Chavez *et al*., 2008). Although there is no consensus concerning El Niño changes in frequency or amplitude, extreme El Niño and La Niña events are expected to become more frequent over the whole region in a warming climate (Cai *et al*., 2015). Evidence from the early Pliocene, when temperatures were higher than today, suggests permanent El Niño conditions for this region (Fedorov *et al*., 2015).

15A.2.2 Biological and ecological

The cooling observed in the HCS for more than a century was associated with an increase in primary productivity (Gutiérrez *et al*., 2011). Satellite-based chlorophyll-*a* data exhibit positive trends off Peru and Northern Chile, and negative trends further south. Coupled physical-biogeochemical models predict a future reduction in phytoplankton and zooplankton abundances as a result of large-scale nutrient depletion in subsurface water (Brochier *et al*., 2013). The depth of the upwelling source waters becomes shallower in warmer conditions, which is expected to impact the system's biological productivity (Oerder *et al*., 2015). Indeed, the mean offshore extension of the zooplankton-rich area is expected to decline by approximately 33 percent in the northern and central HCS, and about 14 percent in the southern HCS (Brochier *et al*., 2013). The shallow OMZ in northern HCS constrains life on and close to the seafloor. The oxygen content on the continental shelf depends on local productivity and large scale climatic conditions, and increases during El Niño events. If the current trend in oxygen reduction persists (Schmidtko, Stramma and Visbeck, 2017), the zone that is unfavourable for macro-life in the seafloor could extend southwards.

15A.3 EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING THE MAIN FISHERIES

15A.3.1 Distribution, abundance, production and other dynamics

The HCS fish productivity is mostly controlled by climate and its effect on the production of phytoplankton and higher trophic levels (bottom-up control) at a variety of scales (Chavez *et al*., 2008; Salvatteci *et al*., 2018). Periods of high and low fish abundance occurred long before the development of the commercial fishery (Gutiérrez *et al*., 2009). Coastal pre-Inca and Inca communities depended heavily on ocean resources for their survival. The rise and fall of the different cultures were related to climatic events from interannual (El Niño and La Niña events) to decadal and secular scales (Moseley, 2001).

A shift towards higher primary productivity occurred in the early nineteenth century and persisted until now, accompanied by a dramatic increase in small pelagic fish abundance, in particular anchovy and in some periods, sardine. The development of industrial fisheries in the 1950s thus took place during a period of maximum fish productivity compared to the last thousands of years (e.g. Gutiérrez *et al*., 2009). During recent decades, the HCS produced more fish by surface unit than any other marine system (Chavez *et al*., 2008). However, climate change could shift Peru's marine ecosystem out of its current favourable state. Modelling studies on the impact of climate change on egg and larval dispersal phases show that climate change may significantly reduce the spawning success of small pelagic fish in the HCS (Brochier *et al*., 2013).

Global models predict a moderate decrease in catch potential by 2050 and 2095 (-1.6 percent to -3 percent for Chile and approximately 0 percent to -7.6 percent for Peru; Chapter 4). Moderate changes are also projected for the main fish resources in Chile by 2065 under the Intergovernmental Panel for Climate Change (IPCC) A2 and 4CO_2 climate change scenario (Yañez *et al*., 2018). However, these studies are at a global scale and do not account for the complexity of biophysical interactions in the region. Preliminary versions of regional ecosystem models forecast a strong risk of anchovy collapse in Peru before the end of this century (Oliveros-Ramos *et al*., 2017). However, considering the high variability in the HCS, these forecasts are expected to change in the future.

Although changes in physical conditions are projected to occur gradually, the ecological response may induce biological tipping points that shift ecosystems into different states. The HCS is subject to dramatic step-wise shifts in ecosystem productivity, community structure and function (Gutierrez *et al*., 2009; Salvatteci *et al*., 2018). These shifts are not accounted for in current modelling approaches but occurred in the past and can be expected to occur in a changing ocean. The HCS, at least its northern part, could shift towards a tropical dominated system.

In the northern HCS, the well-oxygenated surface layer can be less than 10 m deep, limiting considerably the volume of habitat for most fish species. In addition to productivity, oxygen is a key regulatory factor of fish populations in the HCS. For instance, in contrast to anchovy that have the physiological capacity to cope with low oxygen conditions, sardine and Chilean jack mackerel cannot prosper and they avoid areas and periods where low dissolved oxygen and shallow OMZ occur (e.g. Bertrand *et al*., 2016). Distributional ranges of bottom-related fish that are important for DHC, are strictly limited by the upper limit of the OMZ, which also directly affects catches (Joo *et al*., 2014), and seabird breeding and population success (e.g. Barbraud *et al*., forthcoming). The future oxygen content is critical in Peru where bentho-demersal species rely only on a very narrow shallow coastal area, and to a lesser extent in Chile. Any shrinkage of the oxygenated coastal habitat may have severe consequences for coastal resources exploited by SSF.

Latitudinal shifts in species distribution are observed at a variety of spatio-temporal scales. For example, oxygen decline likely allowed the jumbo flying squid to extend its poleward range of distribution (Gilly *et al*., 2013). Jumbo flying squid played an important role in the biomass reduction of Chilean hake (*Merluccius gayi*) in Central Chile (Alarcón-Muñoz, Cubillos and Gatica, 2008). Warming and a tropicalization of part of the HCS can be expected to lead to a shift of tropical species southwards, opening some opportunities for SSF.

15A.3.2 Within the context of other non-climate stressors

In the HCS climate is more important than any other factor, in particular for pelagic species exploited by the industrial sector. However, overfishing is likely to exacerbate the effects of climate stressors (Perry *et al*., 2010). Bentho-demersal resources targeted for DHC are more susceptible to being threatened by overfishing and habitat degradation than pelagic fish. Coastal pollution and temperature rise are expected to increase the number and size of coastal "dead zones" as well as harmful algal blooms (HABs). Fisheries-dependent communities dealing with highly variable upwelling systems with rapidly reproducing fish species may have greater capacities to adjust to climate change than other social systems focused on longer-lived and generally less variable species (Perry *et al*., 2010).

15A.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

15A.4.1 Fishing and post-harvesting operations

In the HCS, SSF have for millennia adapted to a high range of climate variability and uncertainty. They thus developed a variety of strategies including intensification, substitution, diversification, pluralism, migration and exit. Climate change is expected to lead to more extreme or altered variability and uncertainty, as a result of which highly specialized and localized fisheries would be more vulnerable. In addition, projected higher winds would increase the risk for fishers, particularly artisanal ones.

15A.4.2 Communities and livelihoods

Concentration of the commercial fishing companies has been intensified by the implementation of IQ. In Peru, IQ led to a decrease in the number of commercial fishing vessels, and many fishers moved towards SSF after 2009 (Guevara-Carrasco and Bertrand, 2017). Currently, Peruvian SSF heavily depend on two species, jumbo flying squid (over 600 000 tonnes in 2012, approximately 9 000 fishers) and anchoveta (200 000 tonnes to 300 000 tonnes in recent years, approximately 3 000 fishers). The jumbo flying squid shows strong variability in biomass and dramatically increased in the early 2000s. Its population is highly dependent on environmental conditions and prey availability (Rodhouse, Yamashiro and Arguelles, 2016). Therefore, a future decrease in catches or at least strong variability in catches is expected.

15A.4.3 Economic implications

Peru was classified among the eight most vulnerable countries to climate change impacts on fisheries (Allison *et al*., 2009). FMFO demand is growing, whereas supply remains limited and variable. Thus, prices of FMFO are increasing and volatile. Climate change models suggest an increase in maximum revenue potential in Chile but a severe reduction in Peru by 2050 (Lam *et al*., 2016). There is room to reverse this last trend by increasing the market value of the catches.

15A.4.4 Consequences for fisheries management

In the HCS, numerous fisheries have no management plans, biological reference points or quotas (Gutiérrez, Akester and Naranjo, 2016). In Chile, the "management plans" policy is a move towards polycentric governance of fisheries (Gelcich *et al*., 2015), i.e. a system with multiple governing authorities at different levels rather than a monocentric unit. Polycentric systems can have significant advantages given their mechanisms for mutual monitoring, learning and adaptation over time.

Any reduction in jumbo flying squid, and to a lesser extent the anchoveta population, could oblige thousands of fishers to target other species already under pressure. This may have serious consequences for local communities, which could lead to conflicts at different levels (communities, regional governments, national).

The Peruvian industrial sector would benefit from enforcing the current policy regarding management and sanitary conditions in order to address "black fishing", illegal and unregulated fishmeal plants in operation and the lack of compliance with environmental regulations (Fréon *et al*., 2017).

15A.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES AND THOSE DEPENDENT ON THEM

The vulnerability and opportunities opened by climate change are synthesized in Table 15A.1 for a series of issues in the HCS.

TABLE 15A.1
Synthesis of vulnerabilities, adaptation and opportunities opened by climate change for the main fisheries and those dependent on them

Category issue to address	Vulnerabilities	Adaptation and opportunities
Increased climate variability	System impacted by "natural" high climate variability plus climate change. The probability of regime shifts needs to be included in management plans.	Adaptive fisheries management has been implemented, particularly for Peruvian Industrial fisheries, which could help to mitigate negative effects of climate change.
Ecosystem changes	The ecosystem may reach tipping points with drastic changes in ecosystem structure and function.	An intensive ecosystem monitoring system is in place in Peru. Extending it to the whole HCS and including SSF would improve capacity to cope with climate change.
Increased variability of fish biomass	Industrial fisheries depend on a reduced number of species with globally negative perspectives in terms of stock level.	Even with less productivity, there is room for maintaining or improving food security, social and economic development by a transition towards higher DHC.
Increased variability of fish biomass	In Peru SSF mainly depend (in weight/ value) on some species undergoing drastic natural oscillations. A fall in abundance could lead to a redistribution of fishing effort towards already threatened species.	There is room for the exploitation of some oceanic species such as dolphinfish and tuna according to their availability.
More extreme events and increased uncertainty	Change in species composition at different spatio-temporal scales.	Increased adaptive capacity/versatility of SSF and of the informal sector for transformation. Fisheries-dependent communities dealing with upwelling-related, highly variable species may have greater capacities to adjust to climate change than those focusing on longer-lived and less variable species.
Stronger impact of overfishing	Most species caught (in number) by SSF for DHC are likely to be already fully exploited or overfished, with negative trends and strong ecosystem and social risks.	New opportunities for SSF may appear with the southern/coastal extension of tropical and subtropical waters.
Increased risk of regime shift	Risk of regime shifts towards a different and less productive ecological state. Risks of economic losses for industrial fisheries.	The fisheries have already coped with decadal changes in productivity. There is some potential for emerging SSF, which are able to adapt quickly to target alternative species.
Post-harvest and value chain	Lack of cold-chain and optimal sanitary requirements make conditions difficult for food fish production.	Improving the cold chain from fishing boats to the countryside markets should have positive results for food security, economic and social aspects, and reduce waste and hence carbon footprint.
Scientific knowledge supporting management	Scarce knowledge on the ecology and population dynamics for most species targeted by SSF, in particular in the northern HCS.	Scientific investment should increase, particularly for species targeted by SSF and their ecosystem(s).
Governance	Poor control, policies and rules for SSF in Peru.	Improve control and governance and move towards a polycentric governance of fisheries.

15A.6 RESPONSES AND ADAPTATION OPTIONS

15A.6.1 Adaptation (see also Chapter 25)

Nationally Determined Contributions to the climate change Paris agreement (NDCs) from Peru and Chile include fisheries as priority for adaptation. The Peru NDC considers protecting the sector and its contribution to the economy, and includes attending to the most vulnerable groups (small-scale fishers). Chile also has a specific National Plan of Adaptation (NAPA) dedicated to fisheries and aquaculture. The Plan considers 29 measures or actions to adapt, and deliver guidelines to target and mobilize financing and the means required to contribute to increasing knowledge about the impacts of climate change, strengthening the capacity for adaptation in the most vulnerable sectors, such as SSF. It is also directed to improve the socio-economic benefits for the fisheries and aquaculture sector, to guarantee food security and to safeguard Chilean aquatic biodiversity.

Institutional and management

- The HCS is subject to major regime-shifts. Including an awareness of the risk of regime-shifts in management plans and long-term policy goals would increase resilience of the sector to drastic changes.
- Natural variability, including El Niño events, plus climate change may lead to a drastic reduction of important species targeted by SSF (e.g. jumbo flying squid). In this case, redirecting fishing effort to other pelagic species (e.g. dolphinfish or tuna) instead of other coastal resources would avoid additional pressure on already threatened species.
- Most institutional and scientific efforts have been dedicated to industrial fisheries that are well managed overall. The main problematic issues (poverty, food, sustainability) are related to SSF. Considering conflict risks, overfishing could be addressed jointly with climate change issues (Perry *et al*., 2010). Promoting biological and ecological studies, improving spatial monitoring and institutionalising participatory governance systems would foster sustainability of SSF and their adaptive capacity to cope with climate change.
- Implementation of flexible integrated SSF management structures that can adjust rapidly to new circumstances would mitigate the expected effects of climate change.
- Seabirds and mammals would be affected by the reduction of small pelagic fish biomass. Reserving a minimal forage fish biomass (see Cury *et al*., 2011) and increasing the range of protected areas around seabird colonies (islands and headlands) would increase the resilience of top predators (Bertrand *et al*., 2012).

Livelihoods

- The HCS produces more small pelagic fish than any other marine system. Increasing the share of fish dedicated to HDC would allow preserving or even increasing food security, social and economic development under the predicted reduction of fish abundance.
- In SSF, substantial losses occur through post-harvest mishandling during transport, storage and processing, on the way to markets and while waiting to be sold (Béné *et al*., 2015). Eliminating fish discarding and waste by adapted policies and improved infrastructure (cold-chain, sanitary conditions) would mitigate the projected reduction in fish productivity. Developing infrastructure for improving the cold-chain is a pre-requisite to further development of DHC, poverty attenuation, and improving access to high nutritional and well balanced food.
- Among the cheaper fish species, anchovy and sardines are some of the richest in long-chain, polyunsaturated fatty acids and also contain high levels of calcium, phosphorus, iodine, zinc, iron and selenium, which are low in other foods (Béné *et al*., 2015). Beyond a more efficient and lower FMFO production, Andean populations would benefit from a greater availability of high nutritional DHC products.
- To keep anchoveta and other fish at desired DHC quality levels, vessels need to insulate their holds and carry ice (or use refrigerated seawater systems), reducing their holding capacity by at least 30 percent (Avadí, Fréon and Quispe, 2014). A scenario where chilled and frozen anchovy would replace more expensive and less environmentally friendly canned and salted product seems promising to improve food security and reduce the environmental impacts (Avadí, Fréon and Quispe, 2014).

- In addition to improving food security, the evolution towards DHC would provide other social benefits. For example, producing canned anchoveta could generate 10.8 times more employment in the processing sector compared to the production of FMFO (Christensen *et al*., 2014).
- A strong control and reduction of SSF capacity could have a short-term negative social effect, but would safeguard the long-term sustainability of this sector.

Risk and resilience

- Higher winds in the southern HCS would increase risks for fishers, particularly in SSF. Generalising the use of satellite communication devices and extending the vessel monitoring system to the small-scale fleet would contribute to meeting the objectives of safety-at-sea but also improve control, ecosystem monitoring and provide spatial data for management purposes.
- Versatile fishing vessels with the ability to use different fishing gears, and fish in different areas and seasons according to fish spatio-temporal availability, would increase fisheries resilience to climate change.
- The HCS is subject to major regime-shifts. Including consideration of the risks of regime-shifts in management plans and long-term policy goals would increase the resilience of the sector.

15A.6.2 Mitigation (see also Chapter 27)

- The HCS is responsible for the largest estimated ecological impact from reduction fisheries, with 4.2 percent of global natural primary production appropriated. The average carbon footprint of 1 tonne of FMFO production from anchoveta is estimated to be the equivalent of 0.67 and 1.06 tonnes CO_2, respectively (Cashion, Tyedmers and Parker, 2017). There is, however, room to decrease the environmental impact of the fish supply chains.
- Environmental impacts of the anchovy fishery could be decreased by technological improvements (e.g. electronic fuel injection engines, bulbous bow) or by chilling the fish on board (Fréon *et al*., 2017).
- The fishmeal industry could reduce its impact by decreasing its current overcapacity and using natural gas instead of heavy fuel as the energy source for fishmeal plants, which would have an important environmental benefit (30 percent to 41 percent impact reduction; Fréon *et al*., 2017). Additionally, producing Prime Fishmeal[3] has an impact that is twofold lower than low quality fishmeal (Fréon *et al*., 2017). Furthermore, dry unloading by pneumatic off-loaders can also result in cleaner production. A shift towards full prime fishmeal would increase economic revenues and reduce the ecological impact. Finally, using bags larger than the existing ones or storing the fishmeal directly in shipping containers at the plant would reduce the environmental burden (Fréon *et al*., 2017).
- Less energy-intensive preservation methods (freezing and salting) have 4 to 27 times less of an environmental impact than more energy intensive industries (canning and curing). Refrigerated transportation of fresh and frozen fish over long distances produces higher environmental impacts but those additional impacts do not eliminate the environmental advantage of fresh and frozen products over canned products (Avadí, Fréon and Quispe, 2014). Giving preference to less impacting packaging materials (e.g. glass over metal and tinplate over aluminium) and larger formats would improve the environmental performance of canned and cured products (Avadí, Fréon and Quispe, 2014).

[3] Prime fishmeal is a quality fishmeal produced with high technical and hygienic conditions and presents low histamine level, which indicates good freshness of the fish at production.

15B SOUTH AMERICA – ATLANTIC

KEY MESSAGES

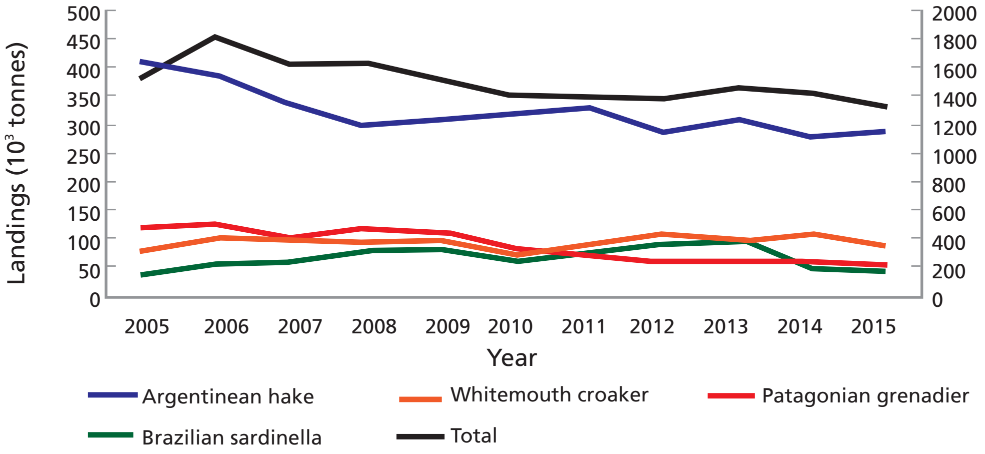
- The region encompassing Southern Brazil, Uruguay and Argentina is a warming hotspot where sea surface temperatures have increased rapidly over the past 50 years. This trend has been accompanied by increasing precipitation and river runoff and is projected to continue.
- Signs of tropicalization have been detected, with shifts in species ranges from tropical and subtropical Brazil towards higher latitudes. Expansion of some economically valuable species could open new fisheries opportunities from Southern Brazil to Patagonia.
- Mangroves could survive into the future as sea level, global temperatures, and atmospheric CO_2 concentrations continue to rise. By contrast, coral may disappear by the end of the century.
- The Southwestern Atlantic is a data-poor region under-represented in terms of climate-change models. Global model predictions suggest that a decrease in catch potential is projected.
- Human activities including urbanization, pollution, tourism, mining and oil are considered to exert a stronger effect on marine fisheries of the region than declines expected from climate change.
- The impact of climate change on coastal fisheries needs to be considered together with other human pressures within a marine spatial planning approach.
- Weak monitoring, control and governance have exacerbated climate-induced changes on SSF. Solid governance systems would help the fishing sector to face climate change impacts.

15B.1 MAIN FISHERIES OF THE REGION

On average, 956 000 tonnes of marine fish were landed per year in Argentina, Brazil and Uruguay from 2005 to 2015, with an overall decreasing trend (Figure 15B.2). The main landed species are the Argentine hake (*Merluccius hubbsi*), the whitemouth croaker (*Micropogonias furnieri*), the Patagonian grenadier (*Macruronus magellanicus*) and the Brazilian sardinella (*Sardinella brasiliensis*). Argentina accounted for 58 percent of the total catches, Brazil for more than 35 percent, and Uruguay represented less than 6 percent. Shrimps, shellfish and other fish also play an important socio-economic role. Most SSF are diverse and multigear. They target a variety of species, and play important social, cultural and economic roles, but face weak and unstable governance regimes.

FIGURE 15B.3

Total landings and landings of Argentine hake (*Merluccius hubbsi*), whitemouth croaker (*Micropogonias furnieri*), Patagonian grenadier (*Macruronus magellanicus*) and Brazilian sardinella (*Sardinella brasiliensis*) for Brazil, Uruguay and Argentina between 2005 and 2015



The second Y-axis corresponds to the total landings. *Source:* FAO-FishStatJ, 2017.

In Brazil SSF represent more than 90 percent of employment in the fisheries sector. In 2011, almost 600 000 fishers were engaged directly in full time fishing activities within fishing fleets composed of vessels of less than 12 m length. Most of the industrial fishing fleet is concentrated in Southern Brazil, while most SSF effort is concentrated in the north and northeast regions. Landings are composed of about 200 fish species, 20 crustaceans and 14 molluscs. Brazil has a poor record in fisheries management and several stocks in that country face over-exploitation and lack of systematic management (Gasalla, Abdallah and Lemos, 2017). Marine extractive reserves represent the most significant government-supported effort to protect the common property resources upon which traditional small-scale fishers depend. They benefit 60 000 small-scale fishers along the coast, even though their efficiency is hampered by low enforcement and other anthropic and economic pressures, including tourism (Santos and Schiavetti, 2014). Brazil imports aquatic food to contribute to national consumption, which increased the deficit in trade balance.

The Uruguayan fishery sector faces a crisis as a result of the critical role that global market forces play in the sector as an external driver. This crisis is reflected in the decreasing yields of the main species targeted, dwindling exports and increasing seafood imports (Gianelli and Defeo, 2017). Declining fishery yields and market contraction resulted from the interaction of two factors that negatively affected the Uruguayan fishing sector: 1) a declining trend in landings of traditional species (the Argentine hake *Merluccius hubbsi*, the whitemouth croaker *Micropogonias furnieri* and the striped weakfish *Cynoscion guatucupa*) and non-traditional species (notably shellfish); and 2) a drastic contraction of the main foreign markets for Uruguayan products, generated by the global financial crisis that occurred in the second half of the 2000s. These trends were especially noticeable between 2008 and 2013, when landings fell from 108 700 tonnes to 51 900 tonnes respectively, and the fishing fleet decreased from 99 vessels to 63 vessels. The three main traditional fisheries reached their lowest values of the last 35 years in 2013, showing signs of overexploitation for Argentine hake and whitemouth croaker (Gianelli and Defeo, 2017 and references therein).

In Argentina the diversity and abundance of marine species vary with latitude, as does the environment, ranging from a subtropical climate in the north to a sub-Antarctic climate in the south. The Argentinean fleet consists of 800 to 1 000 multipurpose vessels, the activities of which vary seasonally. The National Institute for Fisheries Research and Development determines annually the maximum sustainable yield (Article 12, Law 24922[4]) and recommends a biologically acceptable catch for each species. From this information, the Federal Fisheries Council sets the TAC for each of those species. The total reconstructed catch in Argentina increased from 67 000 tonnes in 1960 to over two million tonnes in 1997, thereafter declining to approximately 1.36 million tonnes per year in the 2000s (Villasante *et al.*, 2015).

15B.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE ENVIRONMENT

15B.2.1 Physical and chemical

In contrast to the Pacific side of South America, SST along the Atlantic coast of South America has warmed over the past 30 years at rates between 0.2 °C and 0.4 °C per decade (Lima and Wethey, 2012). South Brazil, Uruguay and part of the Patagonian shelf in Argentina are included in a climatic hotspot, i.e. a region where SST has changed most rapidly over the past 50 years and is projected to rise by more than 3 °C by 2099 (Popova *et al.*, 2016). Since the 1980s, the position of the warm front (represented by the 20 °C isotherm) showed a consistent long-term poleward shift at a rate of approximately 9 km/year (Ortega *et al.*, 2016). SST rise is expected to be accompanied by acidification and a resulting pH reduction of 0.3 to 0.4 by 2081 to 2100 (IPCC, 2014). The main climatic-driven risk factors for this hotspot are considered to be temperature rise and reduction of the circulation of the Brazil Current (Popova *et al.*, 2016). Small changes in oxygen content, acidification and productivity are expected.

Drier conditions are projected along the semi-arid coast of Northeast Brazil (Jennerjahn *et al.*, 2017) but precipitation and river runoff are increasing in Southeastern South America (25 °S to 40 °S; Barros, 2006). This last region has shown one of the greatest increases in precipitation worldwide during the last century, which led to high river runoff. The trend is expected to continue, with an increase in precipitation of 5 percent to 20 percent by 2050 (Nagy *et al.*, 2008). Freshwater discharges increase during El Niño and decrease during La Niña periods (Vögler *et al.*, 2015). In addition to massive occasional precipitations and high river flow associated with El Niño events, an increase in frequency and strength of storm surges was observed in coastal areas of the Río de la Plata (D'Onofrio, Fiore and Pousa, 2008). These were accompanied by an increase in speed and frequency of onshore southerly winds augmenting coastal erosion rates (Gutiérrez *et al.*, 2016). These factors could have severe consequences for the marine ecosystem and the economy, including flood risks, destruction of coastal infrastructure, mass mortality of marine species, and introduction of invasive species.

15B.2.2 Biological and ecological

Brazilian reefs might suffer a massive coral cover decline in the next 50 years and may become extinct in less than a century (Francini-Filho *et al.*, 2008). Rhodoliths, which are non-geniculate nodules of coralline algae that occur in shallow waters (less than 150 m depth), are important ecosystem engineers that could also be affected. Ocean acidification could cause tropical coralline algae to stop growing by 2040 and subsequently to start to dissolve (Doney, 2009).

Brazil harbours the second largest mangrove area in the world. Threats to mangroves arise from climate change and human interventions such as land use changes, urbanization, alterations to river catchment hydrology, over-exploitation of natural resources, and coastal construction (Jennerjahn *et al.*, 2017). Climate change

[4] http://www.cfp.gob.ar/index.php?inc=ley24922&lang=en

may lead to a maximum global loss of 10 percent to 15 percent of mangrove forest by 2100 (Alongi, 2008). Nevertheless, mangroves are currently expanding into temperate regions, including along the South Atlantic coast. Mangroves are expanding rapidly in Northeast Brazil as result of drier conditions and saline intrusion (Jennerjahn *et al*., 2017). By contrast, sea level rise is expected to jeopardise some mangrove areas in Southern Brazil. Overall, mangroves of the region are not expected to be strongly impacted by the expected effects of climate change (Alongi, 2015).

15B.3 EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING THE MAIN FISHERIES

15B.3.1 Distribution, abundance, seasonality, fisheries production

The lack of reliable data on industrial and SSF increases the uncertainty induced by climate change and related drivers on the dynamics of local fish stocks. Most attempts to estimate the effect of these global drivers include high uncertainty (Béné *et al*., 2016). Nevertheless, global models (which do not include species close to the coast) predict decreases in catch potential by 2050 and 2095 of 1 percent to 10 percent for Argentina, 2 percent to 14 percent for Brazil and 6 percent to 15 percent for Uruguay (Chapter 4).

Increasing SST in tropical estuaries and coral reefs could affect the long-term growth and reproductive performance of tropical organisms, which are already close to their upper thermal limit. Tropical and subtropical Brazilian waters are expected to serve as a source of distributional shifts for species towards higher latitudes in Uruguay and Argentina (Fogarty *et al*., 2017), modifying ecosystem structure and representing challenges or opportunities for new fishery developments. The main changes are expected in the warming hotspot extending from South Brazil to Uruguay and Argentina. For example, increasing SST may jeopardize sardinella recruitment, particularly in the current spawning areas (Soares *et al*., 2014). In addition, low and high shrimp catches are related to El Niño (flood) and La Niña (drought) events and high and low river discharge. Increasing river discharges in Southern Brazil are accompanied by a decrease in shrimp catches (Gasalla, Abdallah and Lemos, 2017). A projected long-term increase in precipitation is expected to affect these fisheries.

Shellfish are often strictly associated with sedimentological variables and several are unable to adapt their distribution to compensate for climate change. In the Atlantic sandy beaches of South America, mass-mortality events of cool-water clams occurred in response to warming waters, a phenomenon that also occurred in Pacific sandy shores (Defeo *et al*., 2013). None of the affected populations has yet recovered to pre-mass-mortality levels (Ortega *et al*., 2016), denoting a low adaptive capacity of these clams to respond to the changing climate. These mass mortalities had negative socio-economic implications (Defeo *et al*. 2018). Some warm water species have also shown decreasing lengths and increasing individual growth rates with increasing SST over warming periods, as expected by climate change predictions (Celentano and Defeo, 2016).

15B.3.2 Comparative effects of non-climate stressors

Human activities (e.g. urbanization, pollution, mining) and population growth may exert more powerful detrimental effects on marine fisheries of the region than those expected from climate change (Gasalla, Abdallah and Lemos, 2017). Overfishing has particularly affected high trophic level species (e.g. Milessi *et al*., 2005), notably cartilaginous fish (sharks, rays, chimeras). By contrast, total landings of herbivorous, detritivorous and omnivorous species have increased.

Species invasions have also been detected. For example, the Pacific–Atlantic oceanographic connection allowed the invasion of Patagonian waters by the exotic Chinook salmon (*Oncorhynchus tshawytscha*). The growing presence of exotic anadromous salmonids may impact key forage species and the ecosystems of Atlantic

Patagonia (Becker, Pascual and Basso, 2007). In the Rio de la Plata, a trophic model showed widespread food web impacts of two invasive molluscs (*Rapana venosa* and *Corbicula fluminea*) over several groups (Bergamino, Szteren and Lercari, 2012).

The long-term consequences of plastic waste on the marine ecosystems of South America have not yet been quantified, but their accumulation in coastal zones and in the centre of the South Atlantic oceanic gyre could trigger a change in oxygen availability of the surface layer as a result of insufficient photosynthesis, which could affect the structure and functioning of marine food webs. The dispersion of this pollution source and its connection with the dynamics of surface ocean circulation should be carefully monitored.

15B.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

15B.4.1 Fishing and post-harvesting operations

Small-scale fishers already face numerous challenges, including marginalization by large-scale industrial operations, poor market access, lack of working capital, and pressure to diversify their livelihoods (Emdad Haque *et al*., 2015). Fishers' income in this region is generally low and can drop below the poverty line in bad seasons (Kalikoski and Vasconcellos, 2012). Small-scale communities are already in a vulnerable socioeconomic position and any additional pressure could have dramatic impacts.

In Paraty, Brazil, in an attempt to address the challenges they face (e.g. poor market access, climate change impacts) more than one-quarter of small-scale fishers recently opted to downsize their fishing operations and some 60 percent diversified into tourism activities while still actively engaged in the fishery sector. However, the transition is complicated by the fact that many fishers are reluctant to obtain credit from government-sponsored programmes and seek credit elsewhere (Emdad Haque *et al*., 2015). In Uruguay, the development of national markets and diversification of products (a portfolio approach) has been useful for improving the livelihood of small-scale fishers (Gianelli, Martínez and Defeo, 2015).

15B.4.2 Communities and livelihoods

Brazil has already recognized the potential of fish for food security and has included fish in its national school-feeding programmes. Despite this, the lack of reliable data on SSF complicates the uncertainty induced by climate change on the dynamics of local fish stocks and future food security (Béné *et al*., 2016). Provided the fisheries are sustainable, fishing has the potential to play a critical role as a "bank in the water" for the poorest fishers that can rely on this activity to access cash and purchase goods and services (Béné *et al*., 2009).

Coastal shellfish species are increasingly constrained by the accumulation of toxins associated with HABs, which can render them unsafe for human consumption. The budget for monitoring, control and surveillance of red tides is currently insufficient, and the risk of diseases for consumers is therefore high (Defeo *et al*., 2013). Increasing occurrence of HABs has been related to the interactive effects of climate warming and eutrophication, with harmful algae being increasingly represented in coastal subtropical ecosystems (Martínez *et al*., 2017).

15B.4.3 Consequences for fisheries management

The Atlantic coast of South America is a data-poor region. Weak governance, the erosion of traditional resource use systems, open-access regimes, poverty, lack of alternative employment, and easy access to stocks with low investment and operating costs have promoted overfishing and exacerbated climate-induced changes in SSF. These issues represent major threats to the social security of fishers (Defeo *et* *al*., 2013). Developing partnerships between the responsible government departments or agencies, stakeholders, the scientific community, other government agencies, and fishing communities is critical to improve data, management and governance (Gianelli, Martínez and Defeo, 2015). A combination of flexible spatial property rights (TURFs) and Marine Protected Areas strategically sited could increase both fishery profits and abundance, and provide effective mitigation and adaptation measures to address the effects of climate change (Defeo *et al*., 2013). In cases of migratory species, input/output controls are also required.

15B.5 RESPONSES AND ADAPTATION OPTIONS

The vulnerability and opportunities opened by climate change are synthesized in Table 15B.2 for a series of issues.

TABLE 15B.2
Synthesis of vulnerabilities, adaptations and opportunities opened by climate change for the main fisheries and those dependent on them in Atlantic South America

Issue to address	Vulnerabilities	Adaptations and opportunities
Climate variability	Most of this region is a climate hotspot where SST is changing more rapidly than in most other regions.	High adaptability and versatility of SSF and of the post-harvest sector could increase resilience to changes.
Fish variability	Poleward shifts in fish species distribution will lead to higher costs (fuel, learning, shifting); disruption in fishery support and seafood value chain; displacement of existing fishery operators; modified or expanded social networks.	Expansion of some economically valuable species will open new fisheries opportunities from Southern Brazil to Patagonia.
Overfishing	Decrease in availability, mainly in top predators traditionally exploited during the last five decades.	Small-scale exploitation of non-traditional resources can open new opportunities.
Post harvesting	Lack of cold-chain and optimal sanitary conditions hinder food fish production, in particular in Brazil.	Improving the cold-chain from fishing boats to countryside markets should have positive results for food security, economic and social aspects.
Scientific knowledge	Scarce knowledge on the ecology and population dynamics for most targeted species.	Scientific investment should increase to enable assessment of the status of stocks.
Governance	Poor monitoring, control, policies and rules.	Improve monitoring, control and surveillance and move towards polycentric governance.

15B.6 RESPONSES (SEE ALSO CHAPTERS 25 AND 27)

NDCs to the Paris agreement from Argentina, Brazil and Uruguay make no or some reference to fish and fisheries (Uruguay included adaptation measures for fishing resources in its Program of General Measures for Mitigation and Adaptation, which was declared of Ministerial Interest in 2004). Brazil included the fisheries sector in its NAPA, proposing two dedicated "no-regrets measures for reducing the vulnerability of biodiversity to climate change": 1) strengthen fisheries management for conservation and sustainable use of fish stocks, considering the vulnerability of fish species associated with coral, mangrove and estuary environments; and 2) implement monitoring of coastal and marine ecosystems and associated information systems to address the impacts of climate change.

15B.6.1 Adaptation

Institutional and management

- Establishment or improvement of systematic long-term national and local collection of spatio-temporal fisheries data (including landings, fishing effort and economic information) would provide the data essential for understanding climate change impacts on fish and fisheries.

- Determining tipping points, early warnings and scenarios to forecast changes in ecosystem state (e.g. coral reef or rhodoliths decreasing with shift towards another ecosystem state) would help in managing fisheries that are increasingly threatened by long-lasting and large-scale stressors.
- Developing strategies to help the transition towards less habitat-destructive fishing gears and for emerging fisheries would help the sector to deal with species distributional shifts.
- Protecting nursery grounds and/or essential fish habitat, in particular mangroves and estuaries. Limiting the development of shrimp aquaculture in hyper-saline areas would facilitate mangrove expansion under sea level rise.
- Weak governance has exacerbated climate-induced changes on SSF. Solid governance systems grounded in long-term policy goals incorporating local knowledge, collaborative planning and community-based data collection programmes for fisheries and other uses (tourism, mines, oil, etc.) would help the society to face climate change impacts. Implementing ecosystem-based management initiatives will be essential to address cross-sector trade-offs (Gianelli and Defeo, 2017).
- Incorporation of flexible fishery control rules would allow for coping with species range shifts and ecosystem changes.
- Increased funding of scientific programmes with a long-term perspective. Supporting long-term climate change impact projection projects would provide information to build long-term management scenarios.
- Development of capacity building programmes to strengthen fisheries co-management partnerships between responsible government agencies, stakeholders, academia and other government agencies, particularly in SSF, would improve ecosystem health and food security.
- Enhancing institutional and enforcement strength would limit the development of uneven power relationships between stakeholders that open the way for ocean grabbing (i.e. the dispossession or appropriation of use, control or access to ocean space or resources from prior resource users, rights holders or inhabitants; Bennett, Govan and Satterfield, 2015), which currently disadvantages SSF already impacted by climate change.

Livelihoods

- Increasing interactions among scientists, managers and fishing communities to use local knowledge to inform and build long-term plans addressing expected and unexpected changes.
- Evaluation of the vulnerability of fishing communities would enable a better allocation of support efforts and capacity building.
- Easier access to credit for small-scale fishers would provide more options to diversify their livelihoods, provided that no additional fishing pressure on already overfished stocks is exerted (Emdad Haque *et al.*, 2015).

Risk and resilience

- Reducing, mitigating or eliminating stressors, including the use of habitat-destructive fishing gears (e.g. bottom trawl, dredge) and main pollution sources, would increase resilience to climate change impacts.
- Implementation of co-monitoring and community-based data collection programmes would foster data acquisition for scientists, fishers and citizen science groups.

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Chapter 16: Climate change impacts, vulnerabilities and adaptations: Australian marine fisheries

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KEY MESSAGES

- There are long-term trends in the temperature and currents of the oceans around Australia that are already leading to substantial changes in associated marine ecosystems; these trends are projected to continue and to have greater impact in the future.
- Temperatures are warming at almost three and four times the global average off Southwest and Southeast Australia respectively; ecological and fishery impacts are compounded in these locations as the currents are also changing.
- There have been extensive climate-related changes in distribution of sea urchins, intertidal molluscs, seaweeds and many coastal fish species over the last few decades.
- Long-term change and extreme events, such as marine heatwaves and cyclones, have impacted commercial fish habitat such as mangroves, kelp beds and coral reefs, and reduced populations of important commercial species. The coral reef systems of Australia have experienced severe and extensive bleaching, multiple times and over large areas, in recent years.
- Multiple assessment approaches suggest that invertebrates are most at risk from climate change, and pelagic fishes the least. Australia's most valuable fisheries target invertebrate species.
- Adaptation options are being considered by fishery managers in Australia, particularly around access rights and spatial management. Although research to underpin adaptation efforts is underway, much remains to be done.

16.1 INTRODUCTION TO AUSTRALIAN FISHERIES

Australia has three major oceans, several climate zones and extensive temperate and tropical reef systems. Many species are found only in Australia, and much of the marine biodiversity is not yet identified. Overall, Australia has a strong record in fisheries management supported by robust science that positions it well to cope with the impacts of climate change. It has been estimated that less than 15 percent of assessed fisheries are overfished, with an improving trend (FRDC, 2016). Australia's fisheries jurisdictions have generally adopted ecosystem-based fishery management as a policy goal, with extensive use of spatial management, participatory or co-management and rights-based harvest allocations.

Australia's relatively low productivity waters mean it has a low volume of catch (174 247 tonnes in 2015/16, or 0.2 percent of global landings), but high value per volume (AUD 1.75 billion, equivalent to USD 1.36 billion), representing two percent of global landed value), comprising high value species such as abalone, rock lobster, tuna and prawns (ABARES, 2017). Overall, Australia exports over 50 percent of the wild fisheries catch and imports about 70 percent of seafood used for human consumption. Demand for seafood is likely to increase, both domestically and in the region, placing additional pressure on sustainable production of seafood. Landings from wild fisheries are generally stable and commercial fisheries employ approximately 22 000 people (ABARES, 2017).

The Australian Government manages commercial fisheries within the Australian Fishing Zone (which generally extends from three to 200 nautical miles off the coast), as well as the activities of Australian-flagged fishing vessels operating on the high seas. Commonwealth fisheries range from the northern tropics to the Southern Ocean (Figure 16.1), while state governments administer fisheries generally within three nautical miles from the coast. Both state and Commonwealth fisheries encompass a wide range of active (e.g. trawl) and passive (e.g. traps) fishing gears[1].

FIGURE 16.1
Approximate distribution of Australian Commonwealth fisheries

Source: Map http://www.agriculture.gov.au/fisheries/domestic/zone; courtesy of the Australian Fisheries Management Authority, 2008.

Recreational fishing is a growing sector in Australia with up to four million people participating per annum and catches of some species exceed commercial catches (Henry and Lyle, eds., 2001). The growth in this sector is increasing competition for marine resources, sometimes resulting in conflict with other users, including commercial fishers. There is also a long cultural history of indigenous fisheries, particularly in Northern Australia, and these are co-managed with state and Commonwealth governments. Participation is managed under a range of native title and fishery regulations.

[1] http://fish.gov.au/Fishing-Methods/

16.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT RELEVANT TO FISHERIES

16.2.1 Physical and chemical changes around Australia

Australia is bounded by two major poleward flowing current systems, the west coast Leeuwin Current (LC), which extends to the Southern Australian coast and Tasmania, and the East Australia Current (EAC). The southeast and southwest coasts are both global warming hotspots with observed temperature increases approaching 2 °C over the past 80 years (Hobday and Pecl, 2014). The LC has weakened by 10 percent to 30 percent in the past 50 years with strong decadal variation (Pearce and Feng, 2007) and is predicted to weaken by a further 15 percent by 2060 (Sun *et al.*, 2012). In contrast, the southern component of the EAC has steadily increased in strength (Ridgway, 2007) despite little change in the overall volume of the core EAC region (Sloyan and O'Kane, 2015). Climate models suggest that there will be an increase in strength of 12 percent in the EAC core area, and 35 percent in the EAC poleward extension by 2060 (Sun *et al.*, 2012). Sea surface temperatures around Australia are projected to be approximately 1 °C warmer in the north and about 2.0 °C warmer in the south within the next 100 years under representative concentration pathway (RCP)2.6, or 2 °C warmer in the north and about 5.0 °C warmer in the south within the next 100 years under RCP8.5 (Lenton, McInnes and O'Grady, 2015). This warming is likely to result in increased stratification, which has also been associated with declining oxygen concentrations (Thompson *et al.*, 2009). Changes in water chemistry, as a result of the oceans absorbing CO_2, are not well documented around Australia (Lenton, McInnes and O'Grady, 2015), but are not substantially different from the pH decrease of 0.1 reported for the global ocean. Projections of pH change under RCP8.5 are the largest, with a decrease of 0.68 (0.61–0.73) by 2050, doubling to 1.35 (1.24 to 1.44) in 2090, relative to the historical period (Lenton, McInnes and O'Grady, 2015).

16.2.2 Biological and ecological changes around Australia

Climate-related changes in dozens of fish and invertebrate distributions have been reported around Australia, particularly along the eastern coastline, and are primarily because of increases in water temperature and changes in ocean currents (Robinson *et al.*, 2015a; Sunday *et al.*, 2015). Changes at the southern edges of the boundary currents appear to have reduced productivity and degraded the state of temperate ecosystems in Western Australia (Wernberg *et al.*, 2013), New South Wales (Verges *et al.*, 2014) and Tasmania (Johnson *et al.*, 2011).

Impacts span a range of trophic levels (Frusher *et al.*, 2014). At the base of the food chain, a 50 percent decline in phytoplankton biomass during the spring bloom has been reported from Eastern Tasmania (Thompson *et al.*, 2009), where cold water zooplankton have also become less common (Johnson *et al.*, 2011), and a change in small pelagic fish composition has occurred (McLeod *et al.*, 2012). Growth of southern rock lobster (*Jasus edwardsii*), positively related to water temperature, have increased in Southern Tasmania (Johnson *et al.*, 2011; Pecl *et al.*, 2009). Declining growth rates in coastal fish (e.g. banded morwong, *Cheilodactylus spectabilis*), particularly at the warm end of their range may lead to declining productivity in the north and range contraction towards the southern limit in Tasmania (Neuheimer *et al.*, 2011). Regime shifts in productivity have already been recognized for some key target species (e.g. jackass morwong, *Nemadactylus macropterus*; Wayte, 2013). Importantly, impacts have largely been described at the single-species level, with comparatively fewer investigations exploring the interactive effects of multiple species shifts in the region, or impacts at the ecosystem level (Marzloff *et al.*, 2016).

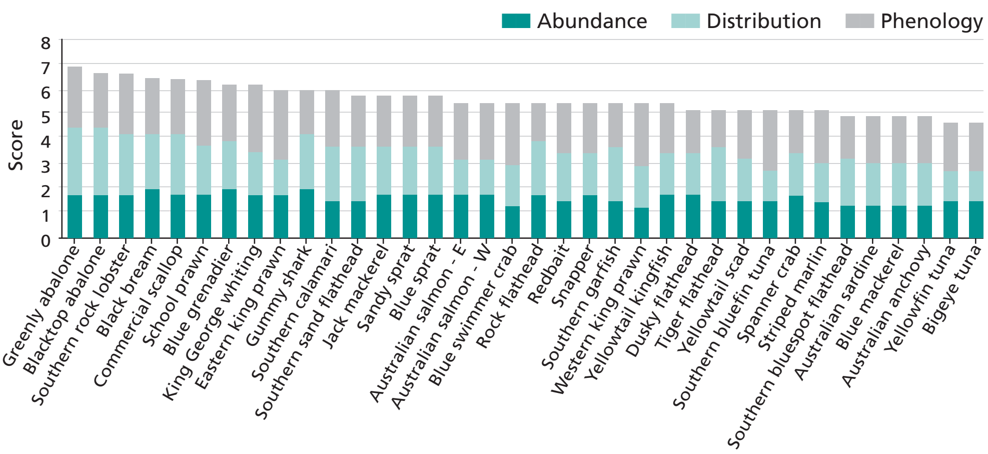
Australia's marine habitats have also been impacted by climate change, including coral reefs, temperate kelp forests and tropical mangroves. Giant kelp (*Macrocystis* *pyrifera*) forests, an important fish habitat in Southeast Australia, were the first marine community listed as an endangered community under Australia's *Environment Protection and Biodiversity Conservation Act*[2] in 2012. In Southwest Western Australia, there has been a rapid climate-driven regime shift of temperate reef communities, with kelp forests replaced by seaweed turfs over more than 100 km and a tropicalization of the fauna (Wernberg *et al.*, 2016). Key fishery species such as abalone (*Haliotis roei*), tiger prawns (*Penaeus esculentus*) and western rock lobster (*Panulirus cygnus*) have also been impacted (Caputi *et al.*, 2016), with the later particularly adversely affected by changes in the timing of spawning due to warming winter temperatures (de Lestang *et al.*, 2014). In tropical regions changes in habitat quality and productivity declines are likely (Pratchett *et al.*, 2011); large scale and repeated bleaching events have contributed in recent decades to declining coral cover (Hughes *et al.*, 2017).

At their poleward (southern) edge, some range-extending species may be considered pests, for example the long-spine sea urchin (*Centrostephanus rodgersii*; Ling *et al.*, 2015). A number of harmful viruses, bacteria and microalgae have caused significant economic harm in the last ten years, resulting in temporary closure of several fisheries (Frusher *et al.*, 2014). Monitoring is currently inadequate to detect such pests until they become established. A more prepared industry, plus anticipatory monitoring based on the likelihood of an outbreak, could reduce risks.

16.2.3 Projected climate change effects on stocks sustaining the main fisheries

Vulnerability assessments have been developed to identify Australian fished species likely at risk from climate change (Pecl *et al.*, 2014b). Scoring of traits that indicate sensitivity to distribution, abundance and phenological change allows for relative ranking of species (Figure 16.2). These rankings reveal strong regional differences in the identity of the most sensitive species (Figure 16.3), indicating a need for regional management responses, but generally demersal invertebrates are likely more sensitive than pelagic fishes.

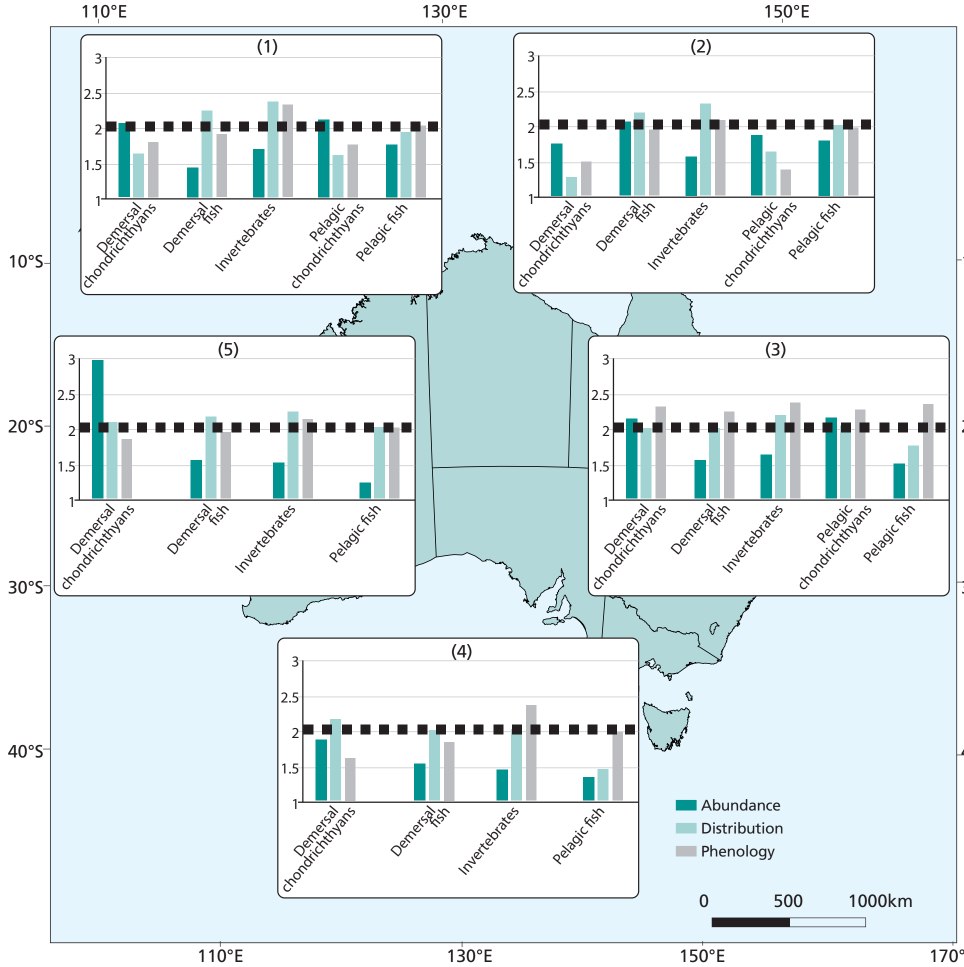
FIGURE 16.2
Example of a sensitivity assessment of fished species in Southeast Australia



Higher scores indicate greater sensitivity, with a maximum score of three for each of the distribution, abundance and phenology categories, and a combined maximum score of nine.
Source: Modified from Pecl *et al.*, 2014a where scientific names are listed.

[2] https://www.environment.gov.au/resource/giant-kelp-marine-forests-south-east-australia.

FIGURE 16.3
Example sensitivity assessment results for groups of fished species across five Australian regions



1) Southeast Australia, 2) Western Australia, 3) Northwest Australia, 4) Gulf of Carpentaria and 5) Eastern Queensland. Higher scores indicate greater sensitivity. The dashed lines on each plot represent an indicative threshold dividing low and high sensitivity.

Global size-based food web models being used to project changes in marine ecosystems and fisheries around the world indicate that Australian waters are expected to see a ten percent, or greater, reduction in total fish production (Blanchard *et al.*, 2017) and a concomitant drop in catch potential of 10 percent to 75 percent in many regions. However, shifts in species distributions in the southern corners (east and west) of Australia may see total catches maintained, or increased (Cheung, Reygondeau and Frölicher, 2016), but made up of different species. In Southeast Australia, ecosystem models indicate that while some pelagic species increase in abundance under climate change, demersal species are more vulnerable, especially to the combined effects of climate change and other pressures on Australia's coastal ecosystems (Fulton and Gorton, 2014). These models indicate that under the high IPCC scenarios (e.g. RCP8.5) there is potential for a regime shift in Southeast Australia, as habitat for important species may disappear by 2050. Under more moderate levels of climate change these species are better able to adapt (Fulton and Gorton, 2014).

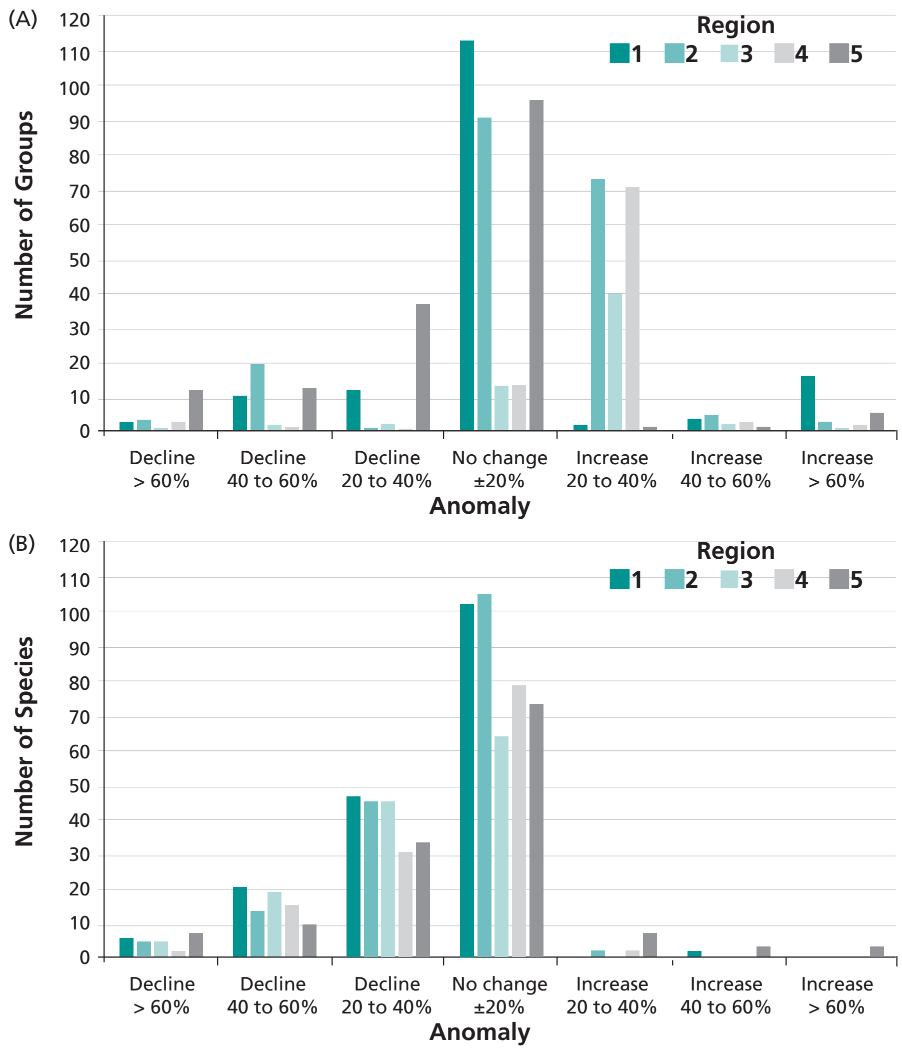
Distribution modelling of large pelagic fish in Northeastern Australia indicates that the habitat centres for tuna, billfish and shark species are likely to shift by 40 to 45 km per decade by 2030 under a high emissions scenario, and by 50 to 55 km by 2070 (Robinson *et al.*, 2015b). A recent compilation of species distribution models for

150 of Australia's main fished species showed declines in abundance for most species in all regions by 2025 (Fulton *et al.*, 2017). However, ecosystem models that included ecosystem linkages (such as predator prey and habitat relationships) showed differing results, indicating the need for additional research (Figure 16.4).

16.2.4 Other non-climate stressors (e.g. overfishing, pollution, habitat modifications)

In addition to climate change, commercial fisheries face a range of challenges around rising costs, the strength of the Australian dollar (making exports relatively expensive), logistics and supply chains, and resource allocation. "Social license to operate" (an unwritten social contract that reflects opinions and expectations of the broader community on the impacts and benefits of industry and government practices) is also becoming a significant challenge, reflecting community concerns regarding the sustainability of fisheries (Kelly, Pecl and Fleming, 2017). This challenge has contributed to the drive for eco-certification by a number of Australia's fisheries in recent years.

FIGURE 16.4
Compilation of results from Australian ecosystem models for five regions



(A) projected abundance change based on models without trophic linkages and (B) models with trophic linkages.
Regions are: 1) Southeast Australia, 2) Western Australia, 3) Northwest Australia, 4) Gulf of Carpentaria and 5) Eastern Queensland.

16.3 IMPLICATIONS FOR LIVELIHOODS AND ECONOMIC DEVELOPMENT

With over 80 percent of Australia's population living within 100 km of the coast, there are strong connections with the sea, supporting livelihoods that include commercial fishing and aquaculture, coastal management, retail, industry, transport, tourism and recreation. Food security is not a current acute concern in Australia, although changing agricultural conditions mean fisheries and aquaculture may have a growing role in the future, affecting both import and export markets.

Ecosystem models used to consider potential futures for Australia's fisheries indicate that sustainable fisheries will be possible, but will likely require a change in target species (Fulton and Gorton, 2014). Redistributing target species require new access rights (Box 16.1) and quota setting needs to respond to stock productivity changes (Box 16.2). The need for timely management responses in areas where climate is changing rapidly means dynamic spatial management may be important under climate change (Hobday *et al.*, 2014). Australian fisheries are also shifting to more conservative maximum economic yield reference points (Caputi *et al.*, 2015; Smith *et al.*, 2014), which provide for increased ecological resilience.

BOX 16.1

Impact of climate change on access rights for fisheries

If climate change opens up opportunities to exploit new species or stocks, because of changes in their spatial distribution, then access rights will need to consider the existing exploitation on these species elsewhere. The overall sustainability of the stock and its new distribution will need to be considered in deciding whether to grant new access rights or give access to these new areas by existing rights holders.

Range extending species can also give rise to cross sector allocation issues. For instance, if a range expanding species is particularly attractive to recreational fishers, when should commercial fishers be allowed access? Should species be allowed to establish first or can fisheries (recreational or otherwise) be permitted before populations of fish become established in a new region? Given that landings by recreational fisheries can match those from commercial fisheries for some inshore stocks it is safe to say that access to establishing stocks will remain a management challenge.

Decisions may also differ if the range expanding species are considered a threat to the fundamental structure of an ecosystem. Then it may make sense to allow fisheries targeting them to act like a pest eradication programme, preventing their effective establishment. Other species may be arriving as part of biodiversity turnover, replacing species which can no longer maintain abundance under shifting environmental conditions. If these range extending species are fished heavily to prevent establishment then ecosystem diversity could be at risk in the long-term. It will be necessary for managers to act on a case-by-case basis, evaluating what role the new species will have in a future ecosystem.

BOX 16.2

Impact of climate change on quota setting for fisheries

Climate change can affect two main inputs in quota systems: 1) the setting of target and limit reference points and 2) the reliability of forward projections from management strategy evaluation models. The latter should, where possible, acknowledge and incorporate current and projected climate change impacts into operating models, so as to provide more accurate projections of stock status into the future. The former will need to be conservative to build species resilience. The updating of reference points has been suggested as the best practice means of adapting current management strategies for changing climate conditions (Brown et al., 2012), however, modified reference points will be hard to estimate given variation in monitoring data and short time series for many species.

Changes in spatial availability, increased natural mortality and/or decreased reproductive potential, all have different implications in the context of quota setting. For example, a change in spatial distribution of a species or stock may result in local changes in availability, without the overall stock status being compromised. From a species sustainability perspective, quotas could remain unchanged (although there may be pressure for access rights in response to a shifting stock), but local economic objectives may be compromised. While the outcome of an overall stock assessment may be unchanged, local assessments may be preferred with quotas determined on local availability. Alternatively, if the species sustainability is compromised by increased stress, then this should be accounted for by ensuring that the operating model and assessment inputs and assumptions (such as natural mortality and stock-recruitment parameters) are not temporally static, but reflect the perceived stresses being experienced by the stock.

The challenge for quota-setting is to translate current and future projected climate change impacts into currencies (e.g. reproductive success, changes in natural mortality) that directly reflect impacts on the stock. In the absence of direct estimates of such impacts, they will have to be indirectly estimated from other projected environmental indicator changes, or incorporated by introducing conservative estimates of parameters or building in high levels of uncertainty.

16.4 ADAPTATION IN AUSTRALIAN FISHERIES

Australian fishing businesses generally recognize that they will have to modify practices in response to climate change, right along the supply chain (Fleming *et al.*, 2014; Plagányi *et al.*, 2014). Likewise, management, regulation and governance will have to change to maintain fishery sustainability (Creighton *et al.*, 2016). Ecosystem models used to explore potential futures for Australian fisheries suggest some of the biggest challenges will be in the ability of human users to adapt their behaviours and in providing management that allows ecosystems the maximum potential to adapt to the environmental changes (Fulton and Gorton, 2014).

Adaptation options exist for a range of marine species and their fisheries (Hobday, Poloczanska and Matear, 2008; Pecl *et al.*, 2009), such as maintaining freshwater flows to keep estuaries and reproductive areas open (Jenkins, Conron and Morison, 2010). For species on the southern continental shelf, options may be more limited as suitable habitat may not be present in the future. Given spatial flexibility, however, adaptation is considered possible by most fishers in the short-term, such as for the Tasmanian southern rock lobster fishery (Pecl *et al.*, 2009). Translocation of wild species to more suitable growing regions may also be possible for some high value species and has been trialled and implemented for southern rock lobster (Green *et al.*, 2010).

There has been emphasis in developing adaptation efforts for the production end of supply chains with less investigation further along the chain (Fleming *et al.*, 2014). Lim-Camacho *et al.* (2015) argued that considering supply chains may lead to additional options, thus maximizing opportunities for improved fishery profitability, while also reducing the potential for maladaptation. Supply chain implications and adaptations should not be considered in isolation because they are directly connected to coastal community socio-economic vulnerability to climate change. A direct relationship can be found between, for instance, the relative population size of coastal communities, their dependence on the marine resources, and their relative vulnerability (Metcalf *et al.*, 2015).

While Australian economic mitigation policies (e.g. a carbon tax aimed at reducing greenhouse gas emissions) have lapsed in recent years, preparation for carbon emission labelling has already begun ahead of anticipated market demand and potential increases in production, packaging and distribution costs. The energy budget of products such as lobsters and prawns has been derived (e.g. Farmery *et al.*, 2015; van Putten *et al.*, 2015), and the toothfish (*Dissostichus eleginoides*) operations of Austral Fisheries have already become carbon-neutral.

Recreational and indigenous fishers will also need to adapt to climate-related changes. Recreational anglers in some locations appear to have already begun adapting (van Putten *et al.*, 2017), displaying relative flexibility and a range of approaches to dealing with changes in the resources they use, including switching target species. Evidence suggests the citizen science project Redmap (Range Extension Database and Mapping project[3]) has likely had an influence on marine users in Tasmania's understanding and attributions of change and their perspectives (Bannon, 2016). Moreover, formal evaluations of the Redmap project have demonstrated that marine community members trust the information on climate change being produced by the project, and self-report learning more about climate change processes (Nursey-Bray *et al.*, 2012). This illustrates the importance and potential value of trusted information as potential conduits for autonomous adaptation. The situation for indigenous fishers is less clear as they target fewer and specific resources, many of which have been identified as sensitive to climate drivers, and are both constrained and supported by a complicated mix of social, cultural and economic drivers (Plagányi *et al.*, 2013). Attachment to "country" may limit the willingness of fishers to follow range-changing species, while social objectives may see more fishers supported and remaining in fishery activities, even as conditions change.

16.4.1 Management responses to climate change

The majority of Australia's fished species are now considered sustainably managed. However, future climate change may impact industry profitability (Hobday, Poloczanska and Matear, 2008; Pecl *et al.*, 2011). Poleward shifts of sharks, tuna and billfish along both the east and west coasts of Australia (Hobday, 2010) may change the distribution of fishing vessels amongst ports and may lead to shifts in species overlap and bycatch management (Hartog *et al.*, 2011). Changes in distribution and abundance of species can also influence access rights provisions and processes (Box 16.1) and quota setting (Box 16.2). Inflexible rights (where any change requires costly legal processes) could hamper adaptive management. Access provisions and their implementation (e.g. developmental fisheries for range extending species or species changing abundance or value) will need to take account of potentially rapidly changing conditions and should not hamper rapid management responses (Bonebrake *et al.*, 2017, Madin *et al.*, 2012).

[3] www.redmap.org.au

Spatial management is a quintessential component of integrated management, but static zoning currently used as the basis of fisheries and conservation management is not well suited to the more fluid nature of future marine ecosystems (Hobday, 2011). Future spatial management zones may instead be defined around oceanographic features, as occurred in Australia's east coast longline fishery (Hobday *et al.*, 2011).

Coordinated management over large spatial areas and across sectors may provide improved adaptive capacity for Australian fisheries. This broader scale, cooperative approach to management, is becoming a goal in Australian fisheries and in coastal management. A transition to fully integrated management has yet to happen, and potential barriers to adaptation include the process of reshaping historical jurisdictional management. It may take some time for Australian jurisdictions to agree on coordinated stock management, with delays potentially inhibiting effective adaptation (Productivity Commission, 2012).

Precautionary approaches under climate change

Resource management in Australia still largely depends on an equilibrium approach and fixed reference points. While new management methods may be implemented in the coming decades, Australia is likely to proceed by modifying well-accepted management procedures so that they are more non-stationary – such as allowing for regime shifts in stock assessments (Pecl *et al.*, 2014b; Wayte, 2013), considering for non-stationarity in management strategies, or using dynamic forms of management (Hobday *et al.*, 2014).

Given differing degrees of system change under different climate emission scenarios, managers will need to remain flexible and adaptable if they are to successfully negotiate an uncertain future, using approaches that respond to changes in distribution, abundance and phenology of key species (Creighton *et al.*, 2016; Pecl *et al.*, 2014b). Overall, the management approaches generally used in Australian fisheries have the potential to enable climate change adaptation to varying degrees. Ecosystem-based management, in combination with adaptive management and co-management as nested management approaches, possesses the full array of adaptation capacities and attributes required for adaptation in fisheries (Ogier *et al.*, 2016). The existing acceptance of adaptive management and ecosystem-based fisheries management in Australia will help this transition.

Additional issues can limit adaptation to climate change

Regulatory inertia or other institutional processes that prevent action have also been identified (Creighton *et al.*, 2016). While there is academic support for the proposition that more stringent management reduces stress on ecosystems and gives stocks more adaptive capacity (Hobday, Poloczanska and Matear, 2008), there is some ideological opposition to increased regulation. Moreover, the differential impacts and opportunities could also complicate adaptation by regulatory bodies. Likewise, individual adaptive capacity will influence the incentives of fishers and other stakeholders to comply with changing regulations (Fulton and Gorton, 2014; Metcalf *et al.*, 2015), as will perceptions of fairness (Gilligan and Richardson, 2005).

16.4.2 Research and management priorities

Australian impacts and adaptation research on fisheries has been guided by the Marine National Adaptation Research Plan (Hobday *et al.*, 2017), and the National Action Plan for Fisheries (DAFF, 2010); both have a strong focus on ecosystem and industry adaptation. Priority research questions for fisheries also focus on improving the policy and governance that supports adaptation to climate change in fisheries (Table 16.1; Hobday *et al.*, 2017).

To aid managers and funding agencies, Pecl *et al.* (2014a) developed an objective, flexible and cost effective framework for prioritizing future ecological research and subsequent investment in adaptation responses using key species within the fast warming region of Southeast Australia. This approach has enabled fisheries managers to understand likely changes to fisheries under a range of climate change scenarios, highlighted critical research gaps and priorities, and assisted marine industries to identify adaptation strategies that maximize positive outcomes (Creighton *et al.*, 2016). Objectives are being revised to accommodate climate change effects (Jennings *et al.*, 2016) and ongoing work with managers is now implementing adaptation responses in management plans in some jurisdictions, but more remains to be done to climate proof Australian fisheries.

TABLE 16.1
National Adaptation Research Plan priority questions for research on fisheries under climate change (from Hobday *et al.*, 2017)

Priority questions	Category of question
What options or opportunities are there for commercial fishers in identified vulnerable fisheries to adapt to climate change effects through changing target species, capture methods and management regime, risk management, or industry diversification, relocation or divestment?	Adaptation
What are the key fisheries policy issues that need to be addressed to enable adaptation to climate change (e.g. dealing with fixed fishery zones when the stock distribution is changing and development of harvest strategies that are robust to climate change effects)?	Policy & governance
How will fisheries policy be affected by future mitigation and adaptation policies in other sectors, such as no-harvest conservation measures?	Policy & governance
How have enablers to adaptation been used and barriers to adaptation overcome? What significant changes in fisheries have occurred before because of extrinsic factors and what can be learned from those changes that will inform adaptation to climate change?	Policy & governance

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Chapter 17: Climate change impacts, vulnerabilities and adaptations: Southern Ocean marine fisheries

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KEY MESSAGES

- The Antarctic region is characterized by complex interaction of natural climate variability and anthropogenic climate change that produce high levels of variability in both physical and biological systems, including impacts on key fishery taxa such as Antarctic krill.
- The impact of anthropogenic climate change in the short-term could be expected to be related to changes in sea ice and physical access to fishing grounds, whereas longer-term implications are likely to include changes in ecosystem productivity affecting target stocks.
- There are no resident human populations or fishery-dependent livelihoods in the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Area, therefore climate change will have limited direct implications for regional food security. However, as an "under-exploited" fishery, there is potential for krill to play a role in global food security in the longer term.
- The institutional and management approach taken by CCAMLR, including the ecosystem-based approach, the establishment of large marine protected areas, and scientific monitoring programmes, provides measures of resilience to climate change.

17.1 FISHERIES OF THE REGION

17.1.1 The CCAMLR Area

The CCAMLR Area is defined in the Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) and is based on the mean position of the Antarctic polar front (APF); an ocean boundary that reflects the northward extent of the Antarctic marine ecosystem. The APF is a significant ecological transition zone that restricts the movement of marine species, although it is not an impermeable biological boundary (see for example Chown *et al*., 2015; Fraser *et al*., 2017). The CCAMLR Area covers 35.7 million square km and represents about 10 percent of the world's ocean surface. There is no permanent resident human population or commercial port facilities in the CCAMLR Area and the products from all fishing activities are landed outside the region.

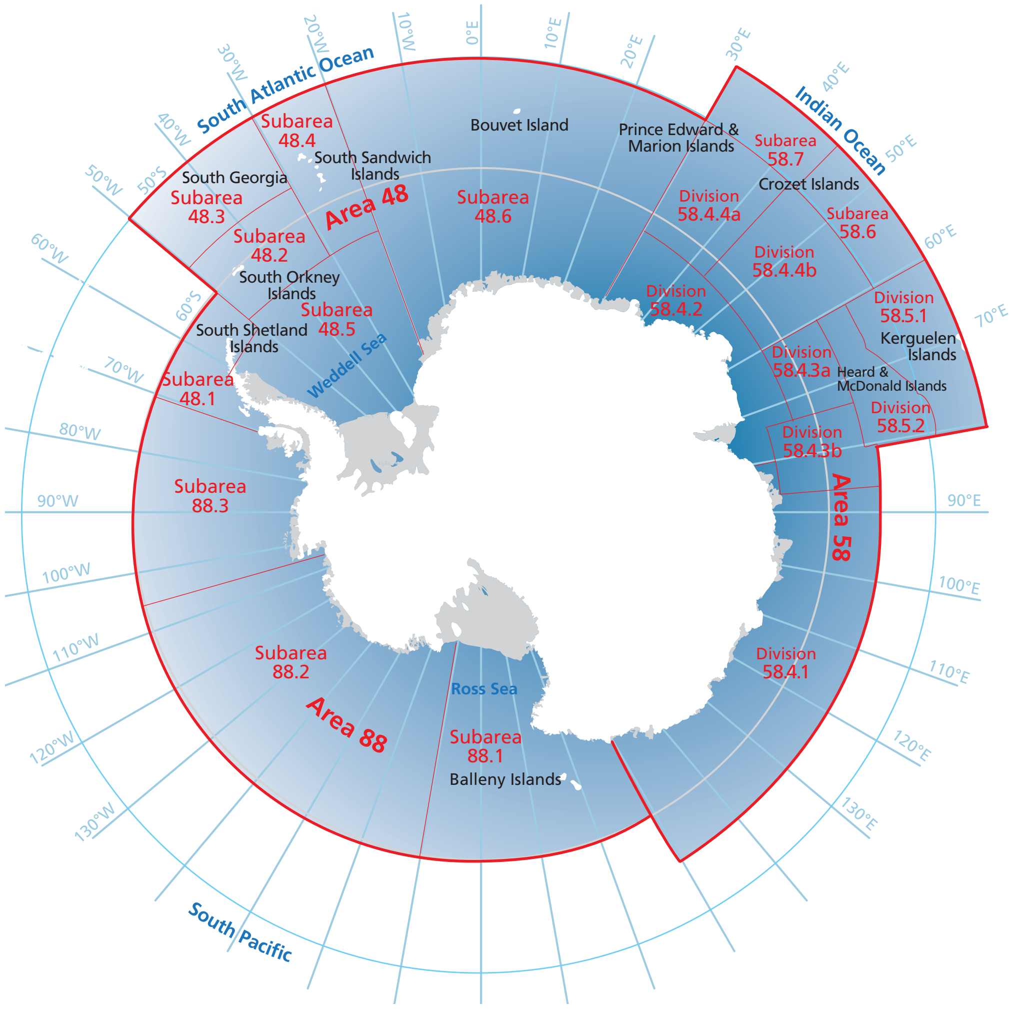
For management purposes the CCAMLR Area is divided into a series of FAO areas, subareas and divisions. In order to consider the fishery management regimes in CCAMLR in the context of the scientific literature on climate change relevant to the region it is useful to merge the FAO nomenclature in Figure 17.1 with the ocean region nomenclature generally used in the scientific literature.

FAO major fishing area 48 in the Atlantic sector includes Subarea 48.1 that includes the West Antarctic Peninsula and the easternmost part of the Bellingshausen Sea. Subarea 48.5 includes the Weddell Sea while Subareas 48.2, 48.3 and 48.4 encompasses the region of the Scotia Arc and the South Orkney Islands, South Georgia and the South Sandwich Islands respectively. Area 48 also includes Subarea 48.6 that extends from the Antarctic continental shelf to north of Bouvet Island and includes the eastern part of the Weddell Sea as well as Maud Rise.

FAO major fishing area 58 in the Indian Ocean sector includes the subantarctic islands of Marion Island and Prince Edward Island (Subarea 58.7), Crozet Islands (Subarea 58.6), Kerguelen Islands (Division 58.5.1) and Heard and McDonald Islands (Division 58.5.2). It also includes the east Antarctic region spanning both Divisions 58.4.1 and 58.4.2.

FAO major fishing area 88 in the Pacific sector includes the Ross Sea in Subarea 88.1, the Amundsen Sea in Subarea 88.2 and the Bellingshausen Sea in Subarea 88.3.

FIGURE 17.1
The CCAMLR Area



Source: https://gis.ccamlr.org.

FIGURE 17.2
Fishery management areas in CCAMLR. a) Antarctic krill (the main area of fishing is shown in red, the grey area has only been fished once in the last 20 years), b) icefish, c) Patagonian toothfish and d) Antarctic toothfish

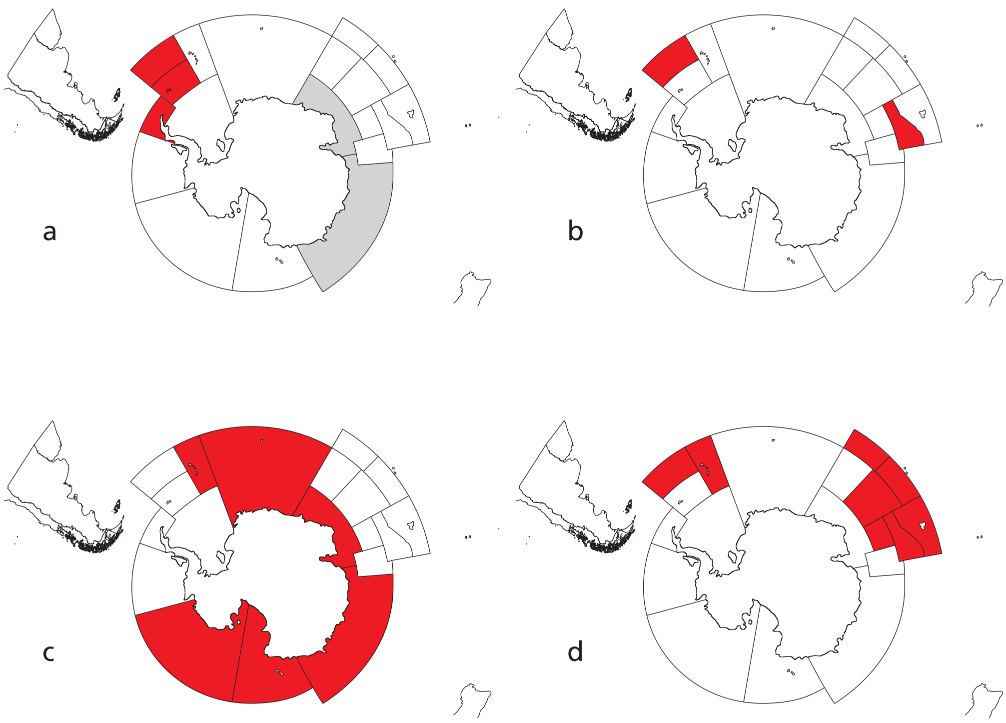
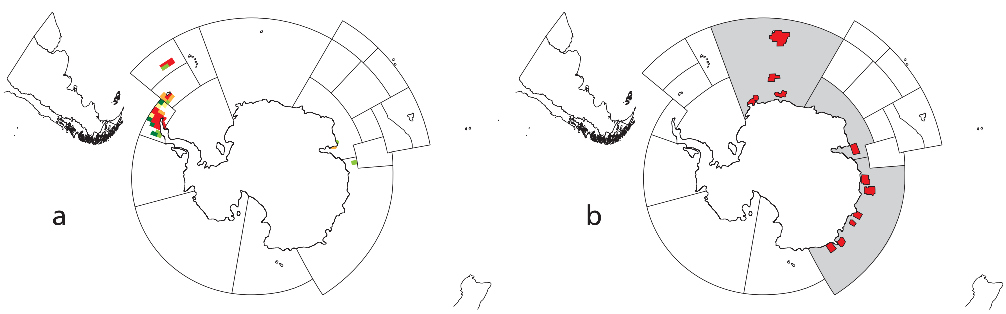


FIGURE 17.3
Areas of operation of a) krill fisheries in the South Atlantic sector and b) Antarctic toothfish fisheries in the Atlantic and Indian Ocean sectors



17.1.2 Main fisheries of the region. Fisheries resources, socio-economics and governance.

Kock *et al*. (2007) provide a general overview of the history of fishing in the Southern Ocean. The focus here is to provide a brief overview of the contemporary fisheries operating in the CCAMLR Area. There is a mid-water pelagic trawl fishery for Antarctic krill (*Euphausia superba*) that operates almost exclusively in the Atlantic sector in Subareas 48.1, 48.2 and 48.3 with an annual catch of 200 000 tonnes to 300 000 tonnes, of which approximately 60 percent is taken by Norway, 20 percent by China and 10 percent by the Republic of Korea. Mackerel icefish (*Champsocephalus gunnari*) is also taken in trawl fisheries on the shelf regions of South Georgia and Heard Island with an annual catch of 400 tonnes to 500 tonnes taken predominantly by the United Kingdom of Great Britain and Northern Ireland (57 percent) and Australia (25 percent). Demersal longline fisheries for Patagonian toothfish (*Dissostichus eleginoides*) within the CCAMLR Area operate near to the subantarctic islands in the Atlantic sector (Subarea 48.3 – South Georgia) and Indian Ocean sectors (Subarea 58.7 – Prince Edward Island, Subarea 58.6 – Crozet Island, Division 58.5.1 – Kerguelen Islands and Division 58.5.2 Heard Island). Annual catches of 11 000 tonnes to 12 000 tonnes are taken primarily by France (50 percent), Australia (30 percent) and the United Kingdom of Great Britain and Northern Ireland (10 percent). The fishery for Antarctic toothfish (*D. mawsoni*) is also a demersal longline fishery and operates in exploratory fisheries in Subarea 48.6, Divisions 58.4.1 and 58.4.2 as well as Subareas 88.1 and 88.2 with an annual catch of around 4 000 tonnes, which is taken by the Republic of Korea (22 percent), New Zealand (18 percent), the Russian Federation (16 percent), the United Kingdom of Great Britain and Northern Ireland (13 percent), Spain (8 percent) and Ukraine (8 percent). All data from CCAMLR (2017).

The overall areas to which specific fishery regulations apply (Figure 17.2) are in many cases much larger than the actual area of operation of the current fishery (Figure 17.3), for example the krill fishery actually operates in 14 percent of the spatial area of Subarea 48.1, 48.2 and 48.3 (Figure 17.3a) while the fishery for Antarctic toothfish in Subareas 48.6 and Divisions 58.4.1 and 58.4.2 (Figure 17.3b) is limited to a series of research blocks as part of the CCAMLR management procedure for data-limited fisheries.

All of the fisheries in the CCAMLR Area are managed by CCAMLR with the exception of the fisheries for Patagonian toothfish in Subarea 58.7 – Prince Edward Island, Subarea 58.6 – Crozet Island and Division 58.5.1 – Kerguelen Islands that fall within the exclusive economic zones of South Africa and France.

17.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT RELEVANT TO FISHERIES

The Scientific Committee for Antarctic Research (SCAR) produced an *Antarctic Climate Change and the Environment* (ACCE) report (Turner *et al*., 2009, 2013) that provides a synopsis of regional climate science relevant to CCAMLR and the fisheries that occur in the region. The ACCE provides details of climate change from temporal scales that range from "deep time" in the geological record to the "instrumented period" that started with the International Geophysical Year in 1957. Annual updates of the ACCE are provided by SCAR to Antarctic policy forums such as the Antarctic Treaty Consultative Meeting and CCAMLR.

17.2.1 Effects on physical and chemical features of the ocean

Polar regions typically exhibit greater climate variability than temperate and tropical regions and climate variability at a range of temporal scales is one of the defining characteristics of the Antarctic. There are examples of regional warming trends and reduction in sea ice that are consistent with climate models. However, the South Pole has experienced a significant cooling in recent decades that is thought to be linked to the presence of a low-pressure system associated with the ozone hole. Surface air temperatures have shown well-documented increases in the Antarctic Peninsula but have also shown a cooling in East Antarctic (Smith and Polvani, 2017). This regionally divergent pattern is not represented well in the outputs from global models in the Coupled Model Intercomparison Project (CMIP5; see Chapter 4) that predict a general warming across the entire Antarctic. Smith and Polvani (2017) suggested that this regional difference possibly indicates that the observed changes are driven by natural climate variability rather than long-term climate change.

The air pressure difference between the tropics and the South Pole is a major driver of southern hemisphere climate variability as it determines the latitude and intensity of the westerly winds around the Antarctic. This pressure difference, an index referred to as the Southern Annular Mode (SAM), is positive when pressures are lower than normal over Antarctica and is associated with a poleward shift and increased strength of the westerly winds around the Southern Ocean. The SAM index shows considerable interannual variability, however, it is currently at its highest level for at least the past 1 000 years. The increase in the SAM index since 1940, considered to be a major driver of increased temperatures in the Antarctic Peninsula as a result of increased eddy formation and southward heat transport, is consistent with the outputs of climate simulations that are forced with rising greenhouse gas levels and ozone depletion (Abram *et al*., 2014).

The annual sea ice cover in the Antarctic has increased over the past two to three decades, an opposite and apparently paradoxical trend to that shown in the Arctic (Hobbs *et al*., 2016). However, rather than being a simple response to temperature increase, the observed change in ice extent appears to be a response to wind-driven changes in the formation and distribution of sea ice. While there has been an overall increase in ice extent, there are, as with the temperature records, distinct regional variations, with the Bellingshausen Sea showing a significant decrease while the Ross Sea has shown an increase in sea ice. These regional differences appear to be linked to the deepening of the Amundsen Sea low that brings warm winds south into the Bellinsghausen Sea, impeding ice formation, and colder winds northwards into the Ross Sea, enhancing ice formation (Turner *et al*., 2016). The reasons for the deepening of the Amundsen Sea low remain the subject of much scientific debate and unfortunately current global climate models are not able to replicate the observed changes in sea ice extent and distribution (Hobbs *et al*., 2016).

The increase in concentration of atmospheric CO_2 is causing an increase in the absorption of CO_2 into the ocean, which in turn causes an increase in hydrogen ion concentration and hence lowering of pH. The capacity for absorption of CO_2 is higher in cold polar oceans and therefore the process of acidification, and the consequential reduction in the ability of organisms that produce exoskeletons from calcium carbonate to absorb calcium carbonate from seawater, is higher in the Antarctic than in temperate regions (Bellerby *et al*., 2008; Manno, Morata and Bellerby, 2012).

Distinguishing natural variability from changes arising from anthropogenic climate change in the Antarctic remains challenging. Hobbs *et al*. (2016) describe this as the low signal to noise ratio in high latitudes, where the multi-decadal variability (noise) is high compared to the comparatively low climate change response (signal), and suggest that the complex interactions that drive multi-decadal variability may entirely mask any anthropogenically forced change in sea ice. In considering the observed and potential future change in the physical environment and how this might impact fisheries, the effects can be conveniently separated into those physical changes that directly impact fishing operations, predominantly through changes in sea ice extent and duration, and those changes in the physical environment that propagate into the biology and ecology of current or future commercial fishery species. In the short-term the impact of changes in sea ice and physical access to fishing grounds may be expected to be more readily detectable whereas second order effects on ecosystem productivity affecting target species might be expected to have impacts that are only detectable at longer timescales.

17.2.2 Effects on biological and ecological features of the region

As indicated above, the physical environment of the Antarctic is characterized by high variability at a range of scales and inevitably this is reflected in biological systems. The mechanisms for the transmission of these effects from the physical to the biological environment are not always straightforward, especially for mobile or migratory taxa. As a result, linking physical changes with drivers of ecological change may be unrealistic at a regional scale (Cavanagh *et al*., 2017). Constable *et al*. (2014) provided an extensive synthesis of the potential biological consequences of changes in the physical environment of the Antarctic marine ecosystem and concluded that the physiological response of primary producers, and how these changes in primary production interact with temperature, will shape the overall changes in ecosystem productivity.

Attributing signals of long-term change in populations of krill and krill predators to climate change is further complicated by the effects of the large-scale removal of baleen whales in the Antarctic during the twentieth century. This is because the predicted observable ecosystem consequences of this relatively rapid removal of a huge biomass of krill predators are potentially similar to those predicted by climate warming (Murphy, 1995).

Contemporary studies that examine the role of climate variability on the life history of key taxa can provide insights into the future status of those taxa under conditions of a warming environment. On the basis of the correlation between krill recruitment and ocean temperature at South Georgia, Murphy *et al*. (2007) predicted that, based on a warming of 1 °C over the next 100 years, there would be a 95 percent reduction in krill biomass in approximately 50 to 60 years. Seyboth *et al*. (2016) showed that the reproductive success of southern right whales (*Eubalaena australis*) in Brazil was linked to krill abundance in their Antarctic feeding area and that this in turn was inversely correlated with propagation of warm sea surface temperature anomalies associated with Pacific El Niño-Southern Oscillation events. Based on this relationship, Seyboth *et al*. (2016) suggested that continued warming in the Antarctic may negatively impact the ongoing recovery of southern right whales. However, while such correlative studies clearly demonstrate a link between climate and ecosystem responses, the causal mechanisms remain elusive and this in turn limits the scope for prediction.

17.3 EFFECTS OF CLIMATE CHANGE ON STOCKS SUSTAINING THE MAIN FISHERIES

17.3.1 Distribution, abundance, production and other dynamics

Krill

The potential impacts of climate change on krill relate primarily to the consequences of changes in the locations of the optimum conditions for krill growth and recruitment (Flores *et al*., 2012; Hill, Phillips and Atkinson, 2013; Melbourne-Thomas *et al*., 2016; Pinones and Fedorov, 2016). However, a comparison of the mesozooplankton community in the Southwest Atlantic sector in the periods 1926 to 1938 and 1996 to 2013 showed no evidence of change despite a significant warming of 0.74 °C (Tarling, Ward and Thorpe, 2017). These results suggest that predictions of range changes based on apparent thermal optima from current/baseline conditions may not adequately reflect the thermal resilience/adaptation of key taxa.

Apparently dramatic observed and predicted declines in krill populations reported by Atkinson *et al*. (2004) appear to reflect a step change in krill abundance around the late 1980s rather than an ongoing decline and there is little evidence of changes in more recent data of krill abundance in long-term krill abundance surveys (e.g. Fielding *et al*., 2012 for South Georgia and Kinzey, Watters and Reiss, 2015 for the Antarctic Peninsula).

Based on empirical evidence of relationships between temperature and krill growth, the optimum conditions for krill are predicted to move polewards, with the decreases in conditions most apparent in the areas with the most rapid warming, which coincide with the current areas of operation of the krill fishery.

Kawaguchi *et al*. (2013) used laboratory conditions to study the potential consequences of ocean acidification on hatching rates of krill eggs and found a dramatic decrease at 1 750 µatm pCO_2. Based on this observation, and the outputs from CMIP5 models with no emission mitigation, Kawaguchi *et al*. (2013) predicted a 20 percent reduction in hatching success of krill by 2100. As with other potential stressors, the predicted impacts of ocean acidification are not homogeneously distributed and the predictions of Kawaguchi *et al*. (2013) indicate that the greatest reduction in hatching success is likely to occur in the Southwest Atlantic/Weddell Sea sector; the area of highest krill concentrations.

Toothfish

Most research on the potential effects of climate change on demersal fish relies on inference from current distributions and apparent optimum temperature conditions. However, Peck *et al*. (2014) reported evidence for broad thermal resilience in some Antarctic fish. Patagonian toothfish occur from Ecuador to the Antarctic continental shelf, over a large thermal range, whereas Antarctic toothfish is generally restricted to the Antarctic continental shelf and some areas of the subantarctic. If range contraction occurs in Antarctic toothfish then it might well be that this results in a southerly shift in the areas of overlap between the two species. Therefore, for fisheries that target toothfish (both species are sold under the same product name) there may be little shift in fishing activity, although the species composition and/or fishing depths might change in response to changes in the transition zone between the two species.

Icefish, in the family Channichthyid, lack haemoglobin in their blood as an adaptation to living in oxygen rich low-temperature environments. It is possible that an adaptation that is so highly specialized to low temperature environments could make then particularly sensitive to warming. However, there are Channichthyids that live north of the APF, for example *Champsocpehalus esox* is found around the coast of southern South America (Calvo, Morriconi and Rae, 1999), suggesting that the thermal range over which such an adaptation is effective may be relatively large. At South Georgia *C. gunnari* feeds predominantly on krill and the spatial distribution and body condition of icefish show distinct responses to years of episodic low krill abundance (Everson and Kock, 2001; Kock *et al*., 2012). Given this linkage there is a clear potential for interaction between any climate change driven changes in krill abundance and icefish that may not simply reflect the physiological response of icefish to a changed thermal regime.

17.3.2 Comparative effects of non-climate stressors

The remote and extreme nature of the region means that overfishing is unlikely to be economically viable for "reduction" fisheries like krill. However, overfishing has occurred historically and high value products like toothfish continue to attract illegal fishing that remains a concern in some areas. Although the Antarctic is not immune to marine debris, local sources of pollution are very limited and unlikely to impact fisheries in the same way as is observed and/or predicted for other marine areas (Law, 2017).

17.4 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

As there are no local communities and all post-harvesting and processing operations are in other regions there are relatively limited direct implications for regional food security in the short-term. However, as an "under-exploited" fishery there is potential for krill to play a role in global food security in the longer term. The factors driving the future of Antarctic fisheries are likely to be indirect effects arising mainly through the drivers of change in fisheries elsewhere, as these will likely determine the relative economic viability of fisheries expanding into more remote regions.

17.5 VULNERABILITY AND OPPORTUNITIES FOR THE MAIN FISHERIES AND THOSE DEPENDENT ON THEM

In the Arctic and surrounding regions, there tends to be a gradual temperature gradient from the tropical to polar water but, in contrast, in the Antarctic, the APF represent a step-change in environmental conditions. The thermal gradient of five to six degrees across the APF is much greater than the extent of predicted warming on either side of the front so the front is likely to remain an impediment to range expansion. Using measurements of the thermal gradient to map the position of the APF, there is little evidence for a latitudinal shift in the position of the front in the past two decades (Freeman, Lovenduski and Gent, 2016). Therefore, while the potential exists for the range expansion of more northern species of commercial interest into the CCAMLR Area, a gradual distributional shift in pelagic species is unlikely.

Projections of physical climate variables using Intergovernmental Panel on Climate Change class models are typically at timescales of 30 to 100 years and at spatial scales of 200 km grid resolution especially at high latitudes. As such they do not resolve variability at temporal and spatial scales that are relevant to operational fishery management decision-making, therefore there is mismatch in the time periods over which management decisions need to be made and predictions of the impacts of climate change are available. Furthermore, the translation of the outputs from physical climate models to the biological consequences of predicted changes introduces considerable uncertainty into prediction of biological change. It is therefore essential that fishery management approaches are able to adapt to change, rather than focusing on the attribution of the drivers of change, and not be dependent on an ability to forecast future change with sufficient confidence to use as the basis of management decisions. If a fished population undergoes a distributional range shift then the first priority is that management should be able to adapt to accommodate that change irrespective of the ability to ascribe the causes of that change.

17.6 RESPONSES AND ADAPTATION OPTIONS

The absence of local-scale fisheries in the region and the status of CCAMLR as a conservation body that is a component of the Antarctic Treaty System, means that climate change adaptation and response are focused on institutional and management components. Relative to other bodies, including national governments, this allows CCAMLR to focus on broader-scale and longer term approaches to climate change adaptation as it is not mandated to address adaptation to the short-term vulnerabilities of immediate consequence for livelihoods.

The ecosystem-based and precautionary approach that is implemented by CCAMLR requires that management must be responsive and designed to adapt to change. Importantly, effective ecosystem-based management under the Convention should not require a definitive attribution of the causes of change before management actions are taken. It is anticipated that the timescale of detectable effects that can be attributed to anthropogenic climate change is much longer than the timescales of the implementation of ecosystem-based fishery management. However, multiple interacting stressors can lead to highly non-linear responses that can produce “tipping points” in which changes can be far more rapid than predicted at the temporal and spatial scale of climate models. Cavanagh *et al*. (2017) cautioned that climate prediction models should not be considered as “operationally predictive” for fisheries management but, nevertheless, they are important for illustrating potential future scenarios for the CCAMLR Area that policymakers and scientists need to be aware of and prepare for. Given the uncertainties in forecasts, the precautionary approach requires management to be adaptive and responsive and thereby contribute to resilience to the effects of climate change. CCAMLR's spatial management includes the establishment of large marine protected areas (CCAMLR, 2017) that provide, in part, resilience to the potential impacts of climate change.

The data collected by CCAMLR via its Scheme of International Scientific Observation (each vessel fishing in the CCAMLR Area is required to carry a scientific observer) and the CCAMLR Ecosystem Monitoring Program, through which data on key components of the marine ecosystem are collected, provide a detailed surveillance mechanism from which to provide information on changes in the ecosystem and/or the operation of fisheries that require management action. The data from these programmes, along with other scientific analyses including those on climate change effects, are integrated in the management process of CCAMLR through its Scientific Committee and expert working groups.

Within the CCAMLR management framework there is a fishery notification system in which each vessel must notify its intention to participate in a fishery at least six months prior to the start of that fishery. This system was established to ensure that fisheries do not expand at a rate that compromises the ability to collect the data required to determine the potential impact of the fishery and to ensure the continued sustainable management of those fisheries. This system also serves to alert the Commission to changes in interest in fisheries in Antarctic. In the future it may be important for CCAMLR to have enhanced institutional arrangements with fishery management bodies in adjacent areas to provide greater awareness of potential excess capacity in fisheries in those areas. This might provide an early warning of the potential movement of fishing effort into the CCAMLR Area. A monitoring mechanism that highlights range shifts of commercially-exploited species, where this might trigger new interest in fishing further south, would also provide an early warning system for management.

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Chapter 18: How climate change impacts inland fisheries

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KEY MESSAGES

- Inland fisheries are found on every continent apart from Antarctica and provide important contributions to global food demands.
- Most food producing inland fisheries are found in developing countries and are largely located in the tropics. Some of the poorest, most food insecure countries in the world are disproportionately dependent upon inland fisheries for nutritional and food security.
- Worldwide, freshwater ecosystems that support the majority of inland fisheries are subject to a variety of anthropogenic pressures reflecting global change including over-extraction of water, over-exploitation of fish, introduction of non-native species, pollution, habitat degradation (including fragmentation) and increases in human populations. The impacts of climate change will interact with many of these factors.
- Climate change will lead to changes in freshwater habitats and the fish assemblages that they support: only a few of these effects are expected to be beneficial to inland fisheries especially those based on native fish populations.
- Freshwater ecosystems have relatively low buffering capacity and are therefore relatively sensitive to climate-related shocks and variability. There is a wide range of physiological and ecological impacts on both fish and the freshwater ecosystems supporting inland fisheries related to water temperature, water availability and flow, and other ecological perturbations.
- Given the scale of direct and indirect impacts of global change, the adaptive capacity of all temperate, tropical and subarctic freshwater ecosystems and existing inland fisheries is relatively low.
- Direct (and indirect) climate change impacts may see considerable shifts in species compositions, but overall productivity might be sustained because of the high diversity and resilience typically shown by tropical systems and many invasive fish species.

18.1 INTRODUCTION

Human activities have resulted in marked global changes in the Earth's atmosphere, soil and waters, and the biosphere that links them. By changing the world's climate, modifying and degrading habitats, over-exploiting and over-extracting resources and permitting the movement of non-native species outside of their natural distributions, we have affected the capacity of the natural world to continue to support human populations, including inland fisheries. Climate change has and will continue to have large and often unpredictable impacts on inland fisheries, with its influence interacting with other anthropogenic stressors. Observed and predicted impacts on freshwaters, fish and those who rely on them vary over space and time, reflecting the heterogeneity in geography, land use and human activities.

The importance of inland fisheries is often focused within countries, with some subsets of the population more dependent than others. Inland fisheries are recognized as a positive means to achieve food security, and to provide employment, income, recreation and cultural enrichment to increasing human global populations. It is essential for stakeholders, including governments, resource managers, fishers and citizens, to understand what climate change means in terms of fisheries.

There is now clear evidence that anthropogenic climate change has had a clear and rapid impact on human and natural systems across the globe, with evidence of change most apparent in natural systems. Air and surface temperatures have changed, while shifts in precipitation have led to modifications in the hydrological cycle and water quality (IPCC, 2014a, 2014c). These systems have already been subject to a range of non-climate stressors driven by human activities including over-exploitation of natural resources, habitat degradation, over-abstraction of water and the introduction of non-native species.

Projections under a range of different scenarios reflecting different levels of emissions, atmospheric concentrations of greenhouse gases and land use, all indicate that the Earth will continue to warm, that heat waves will become more frequent and last longer, and that precipitation patterns will continue to change, with changes in the frequency and magnitude of extreme events such as droughts, storms and floods (IPCC, 2014a, 2014b, 2014c). Climate change has been a characteristic (and natural) feature of life on Earth over much of geological time, and has driven the global distribution and suitability of habitats and in turn, of species, genotypes and phenotypes. The rate of climate change as a result of anthropogenic impacts is acting at a rate that challenges the ability of species and ecosystems to adapt. This means that recent, rapid changes in climate will continue to impact natural systems including freshwater ecosystems, and the services that they provide to human society including inland fisheries. Interactions between climate change and non-climate anthropogenic stressors mean that ongoing climate change can amplify these impacts.

18.2 THE ROLE AND VALUE OF INLAND FISHERIES

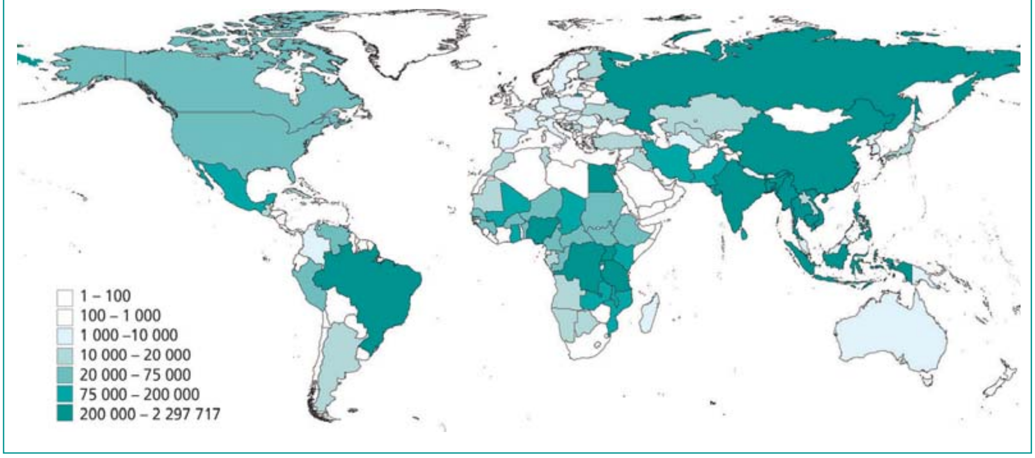
Inland fisheries can be defined as fisheries exploiting fish in waters located inland of the coastline. These fisheries have a long history: evidence from Africa suggests at least 90 000 years (Yellen *et al.*, 1995). Today, fish are exploited in freshwaters of all types and sizes, from the largest rivers and lakes, down to reservoirs, small ponds, streams and wetlands, on every continent apart from Antarctica. Freshwater habitats supporting inland fisheries can be transnational and can cross different climatic zones. Inland fisheries activity ranges in scale, reflecting different economic-drivers, from small-scale subsistence (that permit survival) and artisanal (providing income) fisheries, typical of less-developed nations, through to medium- and even large-scale commercial fisheries. A further important sector is recreational fishing, common in industrialized nations, but gaining in importance worldwide.

TABLE 18.1
Inland fishery catch (2015) by major region, per capita production and contribution to global total (FAO, 2017)

Region	Inland capture fishery catch (2015: tonnes)	Per capita inland fishery production (2013: kg/year)	Percentage of global inland fishery catch (2015)
Asia	5 304 612	1.99	46.2
Africa	2 860 131	2.56	24.9
China	2 281 065	1.63	19.9
Americas	570 515	0.57	5.0
Russian Federation	285 090	1.84	2.5
Europe	150 017	0.24	1.3
Oceania	18 030	0.5	0.2
Arabia	0	0	0
Global	11 469 460	1.64	100

FAO reported a total inland fisheries catch of 11.5 million tonnes in 2015, representing just over 12 percent of total global capture fishery production. This production is dominated by the Asian region (Table 18.1). The most important inland fisheries of the world in terms of food production lie within the tropical belts of South and South East Asia, sub-Saharan and West Africa and the northern half of South America. Central Asia, the Russian Federation, parts of Europe and Central and North America also have important inland fisheries. Seventeen countries produce 80 percent of this inland fishery catch ranging between 151 000 and 2.3 million tonnes per country and the remaining 20 percent is spread across a further 134 countries (Figure 18.1; FAO, 2017).

FIGURE 18.1
Map showing the distribution of annual national inland fishery catch in tonnes (2015), of countries worldwide



Source: FAO, 2017.

The overall biomass and economic value of fish taken from inland fisheries is overshadowed by marine fisheries at a global scale but freshwater fisheries provide many benefits to society, including support for cultural systems, food security and the economy, and are often particularly important in less developed countries. Inland capture fisheries deliver quality food to some of the world's most vulnerable populations in a manner that is both accessible and affordable. These nutritional and food security benefits are an integral part of the agricultural landscape of these countries and as a result will be impacted and changed as countries increasingly develop their water and land resources to produce food for their growing populations.

Inland fisheries are important tools for the maintenance of human populations on Earth: many important and productive freshwater fisheries are found in regions of the world with low food security, and 90 percent of inland capture fishery catch is used for direct human consumption (Welcomme *et al.*, 2010). Inland capture fisheries are also globally important sources of income and employment: 21 million fishers, equivalent to 36 percent of the global capture fishery workforce, and more than 36 million individuals in post-capture activities are employed in the sector (Lynch *et al.*, 2016). Furthermore, inland fisheries frequently represent important means of empowerment for disadvantaged groups, with women dominating (90 percent) post-capture processing (World Bank, 2012). Inland fisheries also play an important cultural role in the supply of nutrition and support for cultural diversity, through the provision of food and maintenance of tradition and customs in indigenous groups worldwide, and subsistence fishing provides access to much needed proteins, calories and micronutrients.

While inland fisheries are important for many low income food deficit countries, they are often markedly understudied, leaving stakeholders such as policymakers, managers and fishers with little guidance regarding climate change and how it will affect inland fisheries and future livelihoods of those who rely on them for food, income and employment.

This review (and subsequent Chapters 19 and 26) aims to provide an informative global summary of how climate change impacts key freshwater systems, fish and the inland fisheries that they support. Given their importance in provision of food and employment, the review will focus primarily on food-fisheries, but will also consider recreational fisheries. The impacts of climate change on aquaculture are discussed in Chapters 21 and 22.

18.3 INLAND FISHERIES AND CLIMATE CHANGE

Fisheries scientists and ecologists first began to discuss climate change and its impacts on freshwater ecosystems and fisheries in the 1980s. We now know that climate change has, and continues to have, a marked global impact on freshwater ecosystems, fish and other aquatic taxa, and the provision of goods and services including fisheries (Myers *et al.*, 2017). Freshwater ecosystems can be sensitive indicators of climate change. Following global mean land and ocean surface temperature increases of 0.85 °C (between 1880 and 2012), freshwaters have warmed globally (Bates *et al.*, eds., 2008). These changes have been occurring for decades, and have potentially influenced our perceptions of what represents baseline ecological conditions.

A large and growing literature exists on the impacts of climate change on freshwaters and their fisheries, although data are still lacking for many of the key regions and countries supporting productive inland fisheries, e.g. the tropics. The importance of the issue is reflected in the inclusion of sections focusing on freshwater systems and fisheries in the Intergovernmental Panel on Climate Change Assessment Reports. Despite this, the global reviews discussing the impacts of climate change on fisheries are generally, strongly biased towards marine fisheries. Although this bias is largely because of the difference in fishery yield or economic worth of marine fisheries relative to freshwater fisheries, it also reflects marked differences between the two types of fisheries. It is important to consider these differences, since failure to develop and implement suitable policies and strategies for climate change specifically targeted at inland waters will result in negative effects on these ecosystems and the people who rely on associated fisheries for food, employment and income.

Marine and freshwater fisheries clearly have some features in common. Over-exploitation is, for instance, a problem common to both, and both are systems that include three separate, but interacting components: aquatic biota, aquatic habitats and the humans exploiting these renewable natural resources. Furthermore, they are part of complex and unpredictable ecosystems. Although similarities exist, they also have fundamental differences that are important to recognize when considering fisheries management under climate change.

At a global level, inland fisheries are characteristically heterogeneous, showing large regional differences that reflect the wide global distribution of freshwater habitats, and marked geographical gradients in climate, geology, land use, biodiversity and human population density and economic activity. The provision of sector-wide guidance or predictions is therefore challenging, made even more difficult by the fact that many globally important fisheries are found in remote, low income areas with little scientific infrastructure. The bias against reporting and predicting climate change impacts in inland fisheries partly reflects the difficulties in developing a simple combined message from these extremely heterogeneous and diverse systems. The diversity of inland fisheries also frequently hinders them from having a strong voice at a national or international level.

18.4 FRESHWATER ECOSYSTEMS ARE STRONGLY DRIVEN BY ANTHROPOGENIC PRESSURES

An important contrast dividing marine and inland fisheries is the particularly close association between freshwaters and their catchments, meaning that inland fisheries effectively share water with activities taking place in their catchment. The natural and human processes and activities found upstream or adjacent to a given lake, reservoir, river stretch, or wetland influences their physical and biological characteristics. This is of particular concern, as many human activities are detrimental to fisheries, including river regulation for hydropower, abstraction for agricultural, industrial and municipal uses, discharge of cooling waters and contamination, and can result in habitat loss. A recent study estimated that worldwide, approximately 65 percent of inland waters were moderately or highly threatened by such anthropogenic stressors (Vörösmarty *et al.*, 2010), limiting their utility to support human populations. Many of the anthropogenic stressors acting on freshwaters involve the use of water; and fisheries in freshwater habitats are effectively competing for water with other human activities, many of which, such as the production of food and energy, can be extremely demanding.

Human activities in a given catchment often result in the quantity and quality of water available to support inland fisheries to be much reduced below that found under natural conditions. For example, Postel, Daily and Ehrlich (1996) estimated that by the late 1990s, humans worldwide were appropriating more than 50 percent of all accessible freshwater, and predicted that this would increase to 70 percent by 2025. By the same year, Arnell (1999) predicted that 60 percent of the world's population would be living in areas where more than 20 percent of available water resources were used (i.e. under water stress). Climate change has led, and is predicted to continue to lead, to changes in the availability and quality of water (Vörösmarty *et al.*, 2000), with associated impacts on aquatic taxa and systems (Dudgeon *et al.*, 2006), although this varies in space and time (IPCC, 2014b). Demands for water are predicted to increase in future, driven by human population growth and movement, changes in land use and agriculture (e.g. to grow biomass) and industrial demands, suggesting further degradation and problems for inland fisheries.

Alongside more recent stressors directly associated with climate change, freshwater systems have also been subject to considerable anthropogenic pressure over the past 150 years. A recent review suggested that 90 percent of global inland catch originates from systems with above average stress levels (McIntyre, Reidy Liermann and Revenga, 2016), providing an indication that systems are far from sustainable. Such stressors potentially interact with climate change, in many cases resulting in a strengthening of the negative effects of climate change on inland fisheries both directly (e.g. changes in water temperature, water availability, shifts in flow patterns) and indirectly (changes in land use, human behaviour, increased human populations). Humans have also purposely and accidentally introduced fish species outside of their natural distribution, often in order to support inland fisheries. Such species can fundamentally affect ecosystem function, compete for food and space or consume native target species, and these impacts may become enhanced under climate change (Rahel and Olden, 2008).

18.5 TEMPERATURE HAS A KEY INFLUENCE ON FISH IN FRESHWATER ECOSYSTEMS

Climate has a strong controlling influence on physical, chemical and biological processes in freshwater ecosystems. The link between air and water temperatures has long been recognized, and water temperature drives most physico-chemical and biological processes in aquatic systems (Table 18.2). Abiotic and biotic conditions are both sensitive to water temperature as a result of the Arrhenius relation, i.e. chemical reaction rates double with every 10 °C increase in temperature (Regier, Holmes and Pauly, 1990). Almost all biological and chemical processes in freshwater ecosystems are influenced by temperature, from key chemical transformations including dissolution (e.g. affecting dissolved oxygen concentrations), degradation and evaporation, through to the rate of biochemical processes within aquatic organisms, disease risk (Miller *et al.* 2014), parasite transmissions and the trophic interactions between consumers and their prey (Dell, Pawar and Savage, 2013).

As such, the most obvious environmental shift associated with global climate change is in temperature, which will increase globally with predictions varying by scenarios. Given that freshwater fish (and many of the taxa with which they interact) are poikilotherms or thermal conformers, changes in water temperature have subsequent impacts on almost every component of the ecology of freshwater fish including sub-organismal, individual, population, species, community and ecosystem levels (Brett, 1971; Harrod, 2016), and fish have specific temperature requirements that differ between species and even life-stages (Souchon and Tissot, 2012). It is not just warming that will affect fish; cold shocks have also impacted stocks in Bolivia (Szekeres *et al.*, 2016).

TABLE 18.2

Physiological and ecological impacts of climate change on freshwater fishes and fisheries at a range of levels of biological organization (see Harrod, 2016 for references)

Impact at level of biological organization	Potential influence on fishery
Individual/population level	
Phenotypic capacity	The capacity of an individual fish to respond to abiotic or biotic variation presented by short-term climate related stressors.
Epigenetic effects	These are (relatively short or rapid) temperature influenced gene responses resulting in phenotypic changes. This affects the capacity of fishery professionals to predict characteristics of the stock.
Physiological functions	Temperature, dissolved oxygen affect the fishes' performance and affect the capacity of an individual to thrive and to grow to a fishable size.
Growth rate and body size	Linked to physiological function, this has a direct impact on fish yield. This is strongly influenced by temperature.
Metabolic rate and energetic requirements for growth and reproduction	As water temperatures fall outside of individual tolerances, fish have to devote increased energy to maintaining their metabolic status, reducing the amount of energy available for investment in somatic growth (potential yield) or gonadal investment (capacity of fish to replace themselves).
Developmental time	Time taken for fish to fulfil their life cycle and to recruit to the fishery. Risk of larval mortality (and lack of supply to the fishery) if hatching does not coincide with abundant food or suitable conditions. This is linked to climate change through variations in timing of flows in rivers, temperature and rainfall cues and seasonal fertility in water bodies.
Maturation, sex determination, reproductive investment and behaviour	The reproductive cycle and breeding behaviour of many fish are driven by predictable seasonal changes in temperature or water levels. Changes in these factors may affect breeding and population dynamics of fishes supporting fisheries.
Migration	Cues for migration are typically environmental (water level, flow, temperature) and if conditions shift following climate change this may affect the timing and scale of migration in fish, or even form barriers to migration with consequences for reproduction, growth and yield.
Immune response, disease and parasitism	Changes in water temperature, flow, depth, etc. can affect the capacity of individual fish to withstand infection as well as the probability of encountering disease and parasites, with subsequent impacts on growth and potential yield.
Heat shock, hypoxia, UV and other stresses	Short-term impacts from extreme weather events (e.g. high or low temperature). Results in reduced individual growth and performance, even mortality – affecting quality and size of the fishable stock.
Exposure to stressors and uptake of contaminants	Increased water temperatures and reduced flow/water levels can result in increased contaminant concentrations and uptake, reducing the quality or suitability of the catch for consumption.
Prey availability, foraging capacity and diet	As freshwater fishes are poikilotherms, their metabolic demands scales with water temperature. Increased water temperatures result in increased food requirements and feeding rate. Changes in water levels and temperature can affect the availability and quality of prey. Together, these factors can impact availability of sufficient food.
Mortality and predation risk	Fish mortality is related to water temperature – increases in water temperature will likely result in increased mortality and reduced potential fisheries yield. Changes in water temperature, flow and depth affect the probability that an individual fish will be consumed by a predator.
Habitat suitability and availability	Abiotic shifts following climate change may result in habitats not being suitable or available to fish stocks, affecting abundance and biomass, or even access for fishers.
Life history characteristics Size, age and sex structure Recruitment, population dynamics and potential fishery yield	Long-term changes in selective forces driven by climate change may result in fish stocks undergoing changes in key life history characteristics (age and size at maturity, maximum size, growth rate) with consequences for fisheries (regulations, gears used, catchability, yield).
Distributional shifts, colonization, local extinction and population fragmentation	The suitability of individual habitats and ecosystems will vary following climate change and subsequent shifts in abiotic conditions. For some sensitive species, conditions will no longer be suitable and if possible, they will have to migrate to a suitable new habitat, which may mean that they are no longer accessible to local fishers (but will represent potential opportunities for fisheries in their new distribution). Some fishes (or locally adapted genotypes) will be unable to migrate and will become locally or even globally extinct. Other fishes that are currently limited by unsuitable conditions will gain potential habitat and widen their distribution and potential for exploitation.
Community	
Interspecific interactions	Fishes exist in a complex biotic network interacting with other species (prey, predators, competitors, parasites, etc.), all of which will show different reactions to the impacts of climate change. This will affect the strength and form of ecological interactions between species, limiting our capacity to predict responses and associated ecosystem function e.g. multispecies fisheries yield.
Changes in fish community structure, loss of functional diversity and biotic homogenization	As species change their distribution in response to shifts in conditions, the species composition of freshwater ecosystems will change, including increased potential for non-native fishes to become established, if conditions are suitable. Species assemblages may be formed that have no current analogue, making it difficult for fisheries scientists to provide guidance on fishery operations: conversely, these may represent significant opportunities for new fisheries. As generalist, warm-water adapted species become increasingly widespread, it is likely that fish communities will become more homogeneous over space and time. Although this is generally considered negative from an ecological viewpoint, it may represent an opportunity for fishers as fishing gears and methods will be able to be standardized.
Capacity of protected areas or closed seasons to conserve fishes	It is common that fishing is prohibited during certain times of the year (spawning period) or areas (spawning habitats) in order to help conserve stocks. Following climate change, these restrictions may no longer provide protection because of shifts in phenology or habitat suitability, and therefore provide little support for stock maintenance.

Variation in temperature drives fish distribution both across wide geographical scales (biogeography) (Cussac *et al.*, 2009) and between habitats within a particular freshwater ecosystem (Magnuson, Crowder and Medvick, 1979). This fundamental influence led to Brett (1970) describing temperature as the master abiotic factor, and changes in water temperature associated with human activities or climate change have and will continue to affect the capacity of freshwater fish to support inland fisheries. Fish species can be classified into different ecological guilds regarding their thermal niche or preferred habitat characteristics, i.e. where their ecological performance is optimized. This approach provides a useful means by which fishery biologists can estimate the likely response of species and communities to climate change. In temperate habitats, fish are often classified as cold-, cool- and warm-water following Magnuson, Crowder and Medvick (1979). Classifying fish by the thermal niche concept has less utility in tropical and subtropical regions, but fishes from tropical lowland habitats can typically be divided into functional guilds based on their migratory habits (Welcomme, 1979): black fish are species that are physiologically and behaviourally adapted to utilize wetlands or other flooded, often low-oxygen, habitats; white fish are species that are sensitive to low water quality and characteristically make long migrations between habitats (sometimes of more than 1 000 km); and grey fish are intermediate and migrate into flooded areas to breed or feed, and return to the main channel during the dry season.

18.6 THE STRONG INFLUENCE OF CLIMATE ON THE HYDROLOGICAL CYCLE

Beyond shifts in air and water temperatures, climate change has changed the global hydrological cycle, with subsequent changes in the timing, volume and type of precipitation (IPCC, 2014a, 2014b), with regional differences in the sign and scale of the changes. These changes will continue, with the intensity of changes in precipitation (and evaporation) increasing. Changes in precipitation have follow-on effects on other characteristics of the hydrological cycle, including run-off, groundwater recharge and river discharge, with subsequent impacts on the availability, quality and origin of water. In turn, these affect the capacity of freshwater systems to provide ecosystem services such as fisheries, dilution of waste and other pollutants, and to supply water for abstraction, which will raise the potential for conflict between different user groups. The impact of these factors will likely worsen with ongoing climate change, with consequent effects arising from interactions between discharge and other physiochemical characteristics such as temperature (van Vliet *et al.*, 2013). Within a multi-user scenario with limited water resources, fisheries will probably lose out to other sectors, in some cases resulting in the total loss of some freshwater fisheries, e.g. due to diversion of water for agriculture (Miranda, 2016).

River regulation, dam construction and water abstraction are recognized as being among the most serious (non-climate) anthropogenic stressors of inland fisheries causing habitat degradation and fragmentation, marked shifts in community structure, loss of sensitive species and of population connectivity. As an indicator of the potential significance of climate change impacts on inland fisheries, Döll and Zhang (2010) suggested that by mid-twenty-first century, climate change may have had a larger impact on ecologically-relevant river flow characteristics than river regulation and water abstraction have had up to the time of writing. McIntyre, Reidy Liermann and Revenga (2016) noted that global riverine fish catch scaled steeply (and positively) with discharge, and suggested that water abstraction and climate change likely have disproportionately large effects on riverine fisheries, especially in large intensively fished rivers like the Yangtze, Mekong, Zambezi and Ganges.

Climate change has and will continue to affect catchment hydrodynamics through shifts in the timing, types and intensity of precipitation (de Wit and Stankiewicz, 2006). This will affect discharge patterns (i.e. the availability of water for fisheries and other resource users), as well as affecting physico-chemical conditions and processes. Where temperatures increase, and precipitation decreases as a result of climate change, the issue of evaporation can lead to habitat loss and fishery degradation, an issue worsened by over-abstraction of water. In endorheic lakes, evaporation leads to increased salinization affecting species composition and fish stocks.

Approximately 10 percent of the Earth's land surface is covered by glaciers that hold 75 percent of the Earth's freshwater in a frozen state (Milner, Brown and Hannah, 2009). Following recent warming, there is a consensus that most (but not all) glaciers are shrinking, and that the rate of recession has increased over the last three decades (Milner, Brown and Hannah, 2009). As climate warming has continued, the snow line (the point above which precipitation falls in solid form) has shifted toward increasingly higher altitudes, resulting in increased rain, and less snow, reducing inputs to glacier mass. As the climate warms, and precipitation patterns shift, glaciers will shrink, and even be lost. This will in turn modify water supply to river systems (and associated fisheries).

Sustained warming will probably be followed by continued increased river flow in the near future, followed by a subsequent breakdown of the well-defined seasonal variation in discharge (that drives the phenology of these systems, as well as seasonal changes in exploitation), followed by a marked reduction in discharge as glaciers are finally lost (Immerzeel, van Beek and Bierkens, 2010). Warming is also affecting the distribution of permafrost in high latitude and altitude regions, affecting freshwater habitats and ecosystem function (Grimm *et al.*, 2013).

The late stages of glacial retreat and possible disappearance will be greatest in those basins fed by waters from the glaciers in the Himalayas and the Tibetan Plateau, but less so in the large rivers of South America, where the bulk of the water budgets is contributed by rainwater (Hamilton, 2010).

Climate change affects the natural fluctuations in lake volume, water levels and hydraulic retention times, i.e. the rate at which lake waters renew themselves, as well as stratification patterns (George, Hurley and Hewitt, 2007), chemical and nutrient cycling (Jeppesen *et al.*, 2010), phenology (Winder and Schindler, 2004), including ice cover (Magnuson *et al.*, 2000), and ultimately habitat suitability for the fish that support fisheries (Lappalainen and Lehtonen, 1997).

Such factors have marked implications for inland fisheries e.g. because of impacts on primary and secondary productivity (O'Reilly *et al.*, 2003), fish yield (Hickley *et al.*, 2002) or access to or quality of key habitats for fish (Fang *et al.*, 2004a, 2004b, 2004c) and on the fishers themselves (MacKay and Seglenieks, 2013).

18.7 IMPACTS OF CLIMATE CHANGE ON INLAND FISHERIES AND RELATED LIVELIHOODS

The inland fisheries sector has contributed little to anthropogenic climate change, but it is argued to be one of the first sectors to feel its impacts. The vulnerability of fishers to climate change is based upon their exposure to change, sensitivity and capacity to adapt. Climate change will likely affect fisher livelihoods through a multitude of pathways beyond the fishery sector alone.

Climate change will likely alter fishery production and fishing operations. The drivers which impact inland fisheries and consequently the livelihoods of those dependent upon inland fisheries, range across environmental, economic and social factors. Increases in extreme weather events, such as droughts and floods, and changes in the intensity, frequency and duration of these will affect the fishery sector and fish-dependent livelihoods differently.

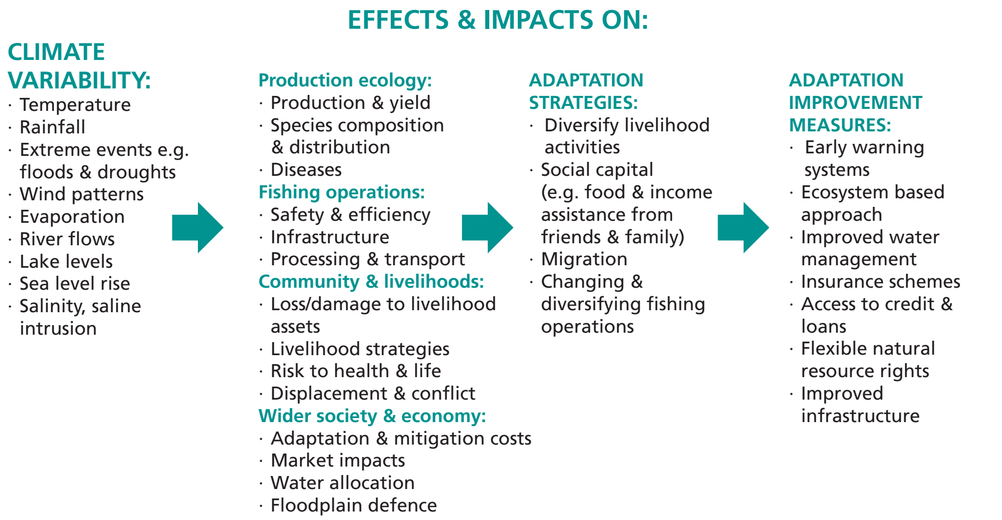
Changes in fish composition, relative abundance, biomass and distribution will alter fish yields and the efficiency of different fishing gears. Once predictable patterns of fish movements or relationships between locations and different species or life stages may become weakened or even lost, reducing the utility of traditional ecological knowledge as a tool in fisheries. Warming of locations that currently have long-periods of ice cover will lead to reduced ice cover, potentially restricting access to fisheries, or the transport of catches, fishing gear and personnel. Extreme weather patterns could cause loss of fishing days, pose a danger to life, cause damage or loss of fishing equipment and landing sites.

Fish processing and trading will also be affected via challenges with processing techniques, such as sun drying, and through reduced transport, such as from flooded roads. Warming will also see a need for improved refrigeration and cold storage, especially in those areas undergoing large increases in temperature e.g. at high latitudes in the northern hemisphere.

Fishers also experience exposure to water borne diseases, lack of access to health care and education, lack of wider economic opportunities and marginalization. Climate change will likely amplify these stresses, and it will be important to enhance local adaptation strategies and link with wider development initiatives to reduce poverty and improve resilience.

The degree to which households can adapt to change is however based upon multiple factors including their livelihood asset base, social class, religion, origin, gender, age, wealth, education, location, policies and institutions (Williams and Rota, 2011).
Fishers have, and will continue to adopt diverse adaptation strategies to cope and adapt to climate changes (Figure 18.2). These include intensifying or reducing exploitation rates, modifying fishing operations (gears, timing, locations and target species), migration, livelihood diversification and drawing on social capital for food and income assistance. A given household's livelihood asset base is important for increasing capacity to cope and adapt to change.

FIGURE 18.2
Examples of direct climate change impacts on inland capture fisheries, adaptation strategies (reactive/autonomous actions) and adaptation improvement measures (planned/longer-term measures)



Source: Adapted from Badjeck *et al*., 2010.

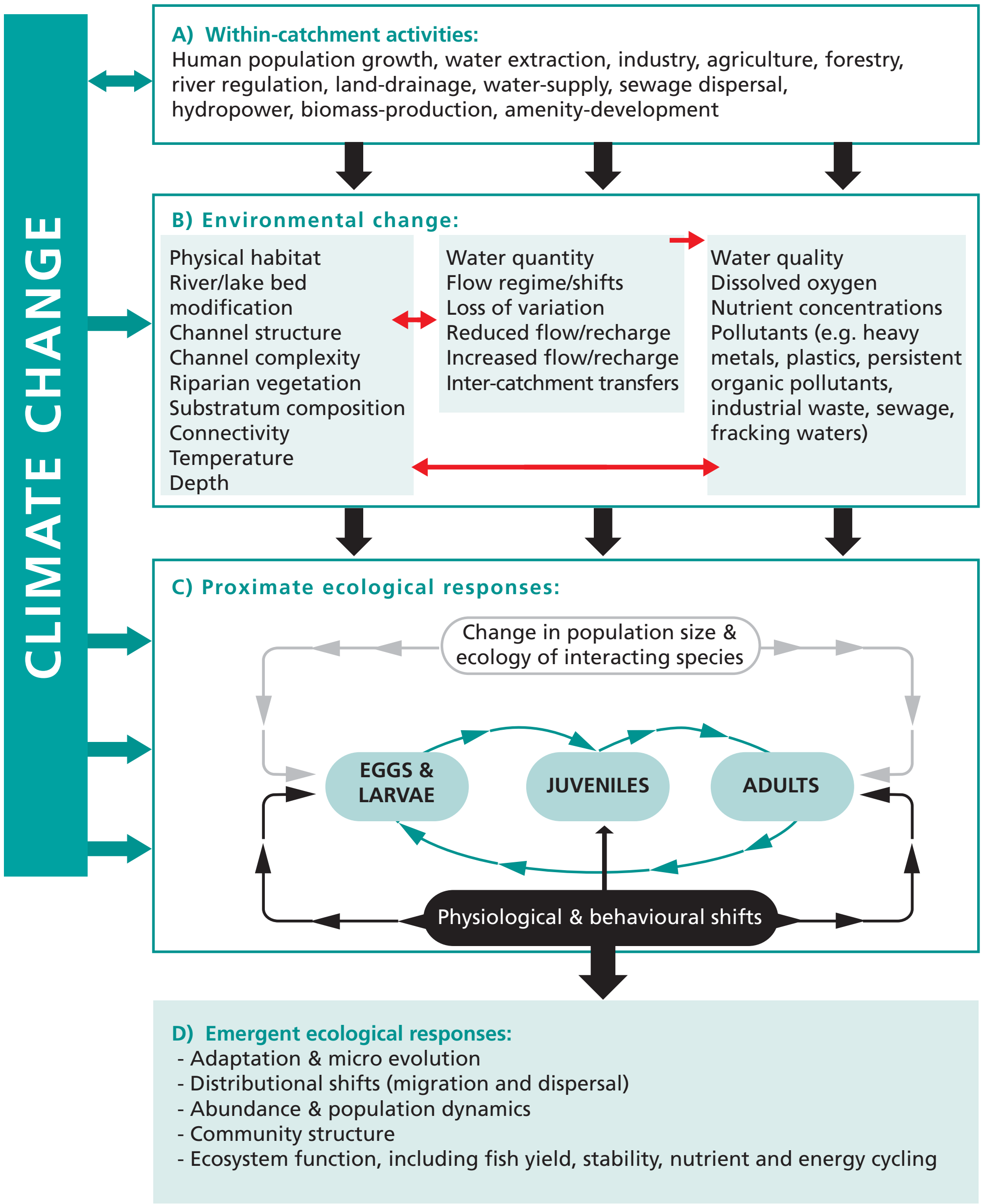
Freshwater ecosystems are largely driven by water dynamics, where water level fluctuation is a natural characteristic that promotes nutrient cycling, primary production, access to essential habitat and subsequently fish yields (Junk, Bayley and Sparks, 1989). The marked seasonal dynamics in the inundation of the floodplain influences the accessibility and availability of fisheries, agricultural crops, wild game and fruits. Many communities are dependent on inland fisheries that regularly fluctuate and thus they have existing adaptive capacity, although climate change may affect the scale and impact of seasonal variation. In the Peruvian Amazon region of Ucayali, Murray (2006) found that the health and nutritional status of communities "rhythms"or fluctuates with the annual flooding and subsequent rise and fall of the river. It has been argued that many inland water ecosystems, such as in dryland areas that are unstable environments, are well-adapted to change (Kolding and van Zwieten, 2012). The importance of these fluctuating inland fisheries in drylands are often overlooked, yet when integrated with other activities they provide opportunities to diversify livelihoods, and with proper preservation and storage can contribute to food and nutritional security in significant ways.

18.8 THE CHALLENGE OF PREDICTING CLIMATE CHANGE IMPACTS ON INLAND FISHERIES

There is an obvious need to provide predictions of the impacts of climate change on inland fisheries. At the most fundamental level, stakeholders want to know if fisheries will persist or undergo significant change (either negative or positive). To answer this, fisheries professionals need to describe responses, and identify vulnerability to climate change, but also provide predictions on how stocks, communities and fisheries will respond to climate change. This is notably more complex than climatic modelling as the links between cause and effect are typically provided by a range of interacting environmental variables, which are also directly or indirectly influenced by climatic variables, e.g. temperature and precipitation, as well as interactions with other stressors acting on the fishery (including responses to disease and non-native species) and associated catchment. The further inclusion of biological, ecological and human responses in models greatly increases their complexity, which in turn reduces predictive power. Attempts to predict inland fishery responses to climate change are therefore extremely complicated.

FIGURE 18.3

Schematic showing how climate change has the potential to affect freshwater fisheries through its influence across a range of different factors ranging from catchment-level activities, habitat characteristics, and responses of individual fish, which together combine to affect fish yield and other measures of ecosystem function



A) Catchment level activities that affect freshwater habitats and B) abiotic factors governing fish and other aquatic taxa. C) Potential ecological responses of individual fishes to climate change. As changes in abiotic conditions affect molecular and cellular process, the physiology and behaviour of individual fish shift and their performance in intra- and interspecific interactions changes, resulting in climate change driving D) emergent ecological responses, e.g. changes in ecosystem function, community structure, fishery yields and the fish communities.

Source: Adapted with permission from Harley *et al*. (2006) © 2006 Blackwell Publishing Ltd/CNRS, and Milner (2016) © 2016 by John Wiley & Sons, Ltd.

Beyond climatic and non-climatic impacts on habitats, fish do not exist in isolation in freshwater ecosystems, but exist within communities made up of other taxa and functional groups, which will also be impacted by climate change, ranging from microbes (Marcos-López *et al.*, 2010), parasites (Marcogliese, 2001), primary producers (de Senerpont Domis *et al.*, 2013), fish predators (Moore *et al.*, 2009) and humans, including fishers (Haines *et al.*, 2006).

Individual life stages and genotypes of non-fish taxa will display different proximate responses to climate change, the resulting emergent ecological responses (predator-prey relationships, competition, parasitism, fish yield) will likely change as conditions and ecological interactions change under climate change and shifts in environmental conditions as humans respond to climate change (Figure 18.3).

Climate change will probably result in changes to the relative importance of top-down and bottom-up processes that influence fish production. Responses to climatic change in freshwater systems may be nonlinear, complex, sudden and possibly non-reversible (Isaak and Hubert, 2004). Shifts in water temperature and physical conditions will drive much of the response of fish to climate change, and the subsequent yield to inland fisheries, but ecological interactions between species will also play a key role (Crozier and Hutchings, 2014).

As noted above, inland fisheries are characterized by their diversity and this greatly limits any potential to provide generalized predictions regarding the likely effects of climate change on freshwater fisheries. However, climate change has and will continue to affect freshwater fisheries worldwide and will specifically have to be accounted for in fisheries management policy and operations. The relative impact of climate change will vary according to geographical location and over time, meaning that policy will have to be developed at a regional- or catchment-level. In some locations, it is possible that climate change will be the dominant stressor affecting inland fisheries, but given the overwhelming impact of other stressors such as land-use change, over-abstraction of water or habitat fragmentation following river regulation for hydropower, the main impact of climate change may be how it interacts with these existing stressors (see Chapter 26 for implications for policies and management).

The impacts of climate change on inland fisheries will ultimately depend on which warming and land use scenarios are followed, but in most cases the influence of climate change on inland fisheries will intensify over the next decades (with marked regional heterogeneity). As such, fishery professionals and policymakers will have to incorporate climate change into policy and management strategies. The next chapter (Chapter 19) outlines predicted consequences of climate change on inland fisheries using case studies of key catchments from tropical, temperate, and subarctic regions.

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Chapter 19: Current anthropogenic stress and projected effect of climate change on global inland fisheries

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KEY MESSAGES

- Global inland fisheries are going to undergo considerable changes because of human-derived climate change, with large-scale increases in air (and water) temperature, shifts in the amount and timing of precipitation (both negative and positive) and discharge.
- Changes in precipitation, temperature, flooding and flows, and ice cover will all have some effect on current fishing methods.
- There will be a reduction in the viability of commercial and artisanal inland fisheries for food in the most stressed systems and recreational fishing may be more restricted.
- Direct climatic factors and indirect effects of water regulation and habitat loss impact inland fisheries. Allocation of water for inland fisheries will become increasingly challenged.
- The potential for inland fisheries habitat may expand as temperate and subarctic regions warm, but fisheries may be bypassed with a direct move towards aquaculture in large water bodies.
- As economic conditions change, inland fisheries may shift from food provision to recreational fisheries. This may coincide with stronger environmental regulation, desire to conserve biodiversity and the requirement for high quality water for drinking water supply.
- The climate change impacts on inland fisheries that are foreseen are overshadowed by existing threats posed by population increase and related human development. These include overfishing, over-extraction of water, introductions of non-native fishes and other taxa, and the modification, degradation and loss of key habitats.
- It is projected that two major inland fishery producers (China and India), are likely to face considerable stressors affecting their inland fisheries in the future.
- A large group of countries that produce around 60 percent of total yield from global inland fisheries are projected to face medium or relatively low future stress and will be subject to relatively less severe impacts of climate change. A small group of countries that are highly dependent upon inland fisheries will face the least severe impacts.
- In all cases, where there is high dependence on inland fisheries for food security, care must be taken to ensure the sustained viability of the inland fishery.

- The increase in water storage, in response to uncertain precipitation and water stress will see increased reliance on culture-based fisheries as well as freshwater aquaculture development to replace or supplement inland fisheries.
- In some of the most important inland fisheries, detailed information is limited and there is a need for downscaled evaluations of the impacts of climate and other drivers on fisheries for the different water bodies and fisheries within a basin system.

19.1 INTRODUCTION

There is an enormous number of individual waterbodies and water courses that support inland fisheries globally. The variation in their geographical and regional location (occurring in all continents apart from Antarctica), water body type (wetlands, streams, rivers, pools, reservoirs, lakes), economic classification (subsistence, artisanal, commercial, recreational), defies the convenient summarization of impacts. Inland fisheries are only one part of a diverse and demanding set of sectors that use or impact freshwater (e.g. irrigation, municipal use, industry, hydropower; Millennium Ecosystem Assessment, 2005). Not only are inland fisheries' demands for water typically ranked lower than other sectors, *inter alia* because of a lower perceived economic value (Cooke *et al.*, 2016a), the removal of water and the degradation of the aquatic environment by other sectors often represents a major impact on the freshwater fisheries (Chapter 18). These impacts can act alone or interact with other stressors such as climate change, and increase impacts on fisheries (Jackson, Woodford and Weyl, 2016). In addition to climate change, this review provides information on other key, non-climate stressors including human population growth, deforestation, irrigation development, hydropower development and water storage.

This chapter examines the potential future threat presented by climate change and development on the countries and regions which provide 95 percent of the world's inland fishery catch. There is considerable variation in the volume and quality of information available, reflecting the wide geographical distribution and diversity of the systems covered. The information presented in this chapter is based on an in-depth literature review using sources from the primary literature, relevant review articles, water stress modelling (e.g. World Resources Institute (WRI) Aqueduct and FAO Aquastat), as well as reports from the Intergovernmental Panel for Climate Change (IPCC) (e.g. IPCC, 2014a), international and regional development agencies, including the FAO (Ainsworth and Cowx, forthcoming; FAO, forthcoming) and inter-governmental agencies (e.g. MRC, 2014a, b).

19.2 THE EXPECTED CHANGES IN TEMPERATURE AND PRECIPITATION IN THE WORLD'S MAJOR INLAND FISHERIES (SUBREGIONS AND COUNTRIES)

To provide a wide-scale overview of the likely impacts of climate change on inland fisheries, this review examines predicted country-level changes in temperature and precipitation from recent projections simulated by global climate models in the Coupled Model Inter-comparison Project Phase 5 (CMIP5) (Alder and Hostetler, 2013; Taylor, Stouffer and Meehl, 2012). From these models, multi-model mean values based on two representative concentration pathway (RCP) scenarios were used: one representing low (RCP2.6) and another high (RCP8.5) emissions, to provide a likely range of future conditions. National mean projected values for temperature and precipitation for the period 2050 to 2074 were examined, providing an indication of impacts over the medium-term. Data were shown as changes relative to observed values from the period 1980 to 2004 (derived from the historic climate databases CRU TS3.10 and TS3.10.01, University of East Anglia Climatic Research Unit, 2008[1]). Mean

[1] http://catalogue.ceda.ac.uk/uuid/3f8944800cc48e1cbc29a5ee12d8542d

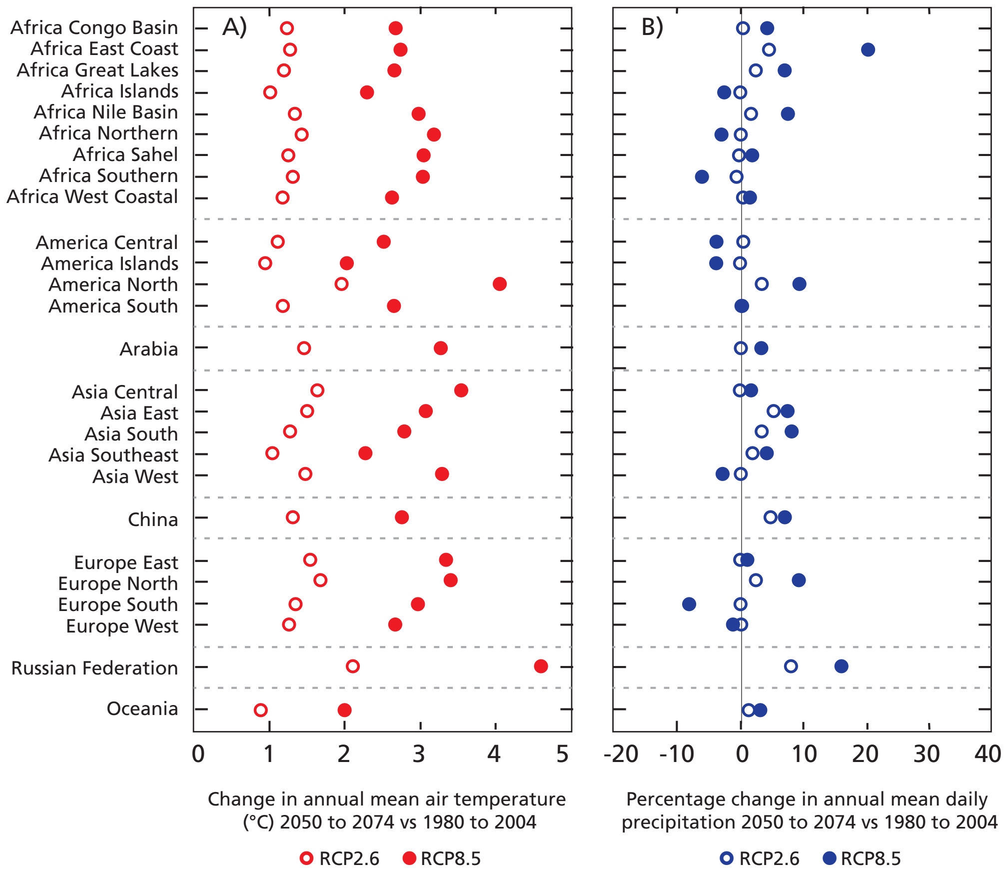
changes in annual mean air temperature (°C) and annual mean daily precipitation (mm/d) were calculated for each of 28 inland fishery subregions (Figure 19.1), as well as mean national values for countries supporting the 20 largest inland fisheries catch (Figure 19.2) under both RCP2.6 and 8.5.

At the level of fishery subregions, considerable warming is projected to occur (Figure 19.1A), but marked differences exist in the scale of warming associated with the locations and the two different emissions scenarios, with far greater shifts in temperature projected with the high emissions scenario (RCP8.5). The most marked increases in air temperatures are seen in North America and the Russian Federation subregions, while the smallest are shown in the Oceania and American Islands subregions. One impact of the warming in the Russian Federation would be the creation of more potential habitat for inland fish because of warmer conditions and thawing of previously frozen tundra.

Projected changes in precipitation (Figure 19.1B) also vary considerably according to location and include reductions and increases in annual daily precipitation rates. Projected changes are most obvious in the Eastern Coastal Africa and the Russian Federation subregions under RCP8.5. Furthermore, there are several subregions that show little change under RCP2.6 but that show considerable projected reductions in precipitation under RCP8.5 (e.g. North America, Ssouthern Europe and Southern Africa).

FIGURE 19.1

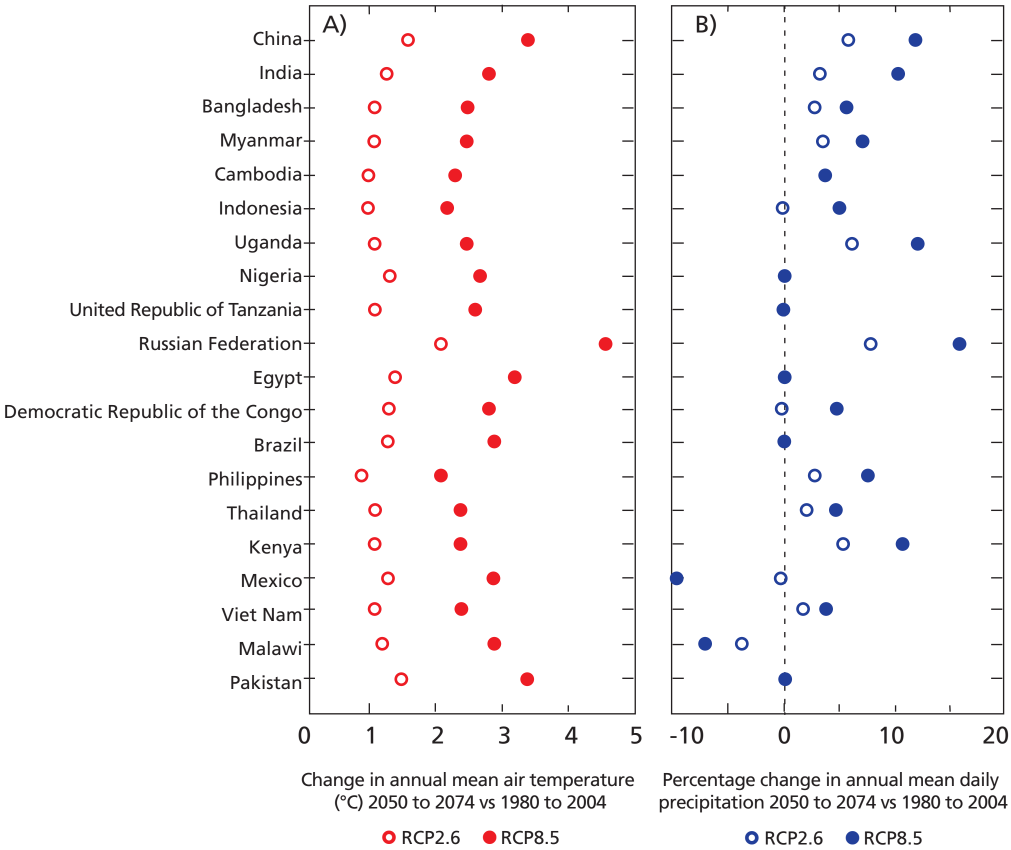
Variation in mean estimated change in A) annual mean air temperature (°C) and B) annual mean daily precipitation (%) projected for the period 2050 to 2074 under two CMIP5 scenarios (RCP2.6 and RCP8.5) relative to 1980 to 2004



Mean values are shown for the different FAO Inland Fishery Areas. Markers to the left of the vertical line in B) show a lowering in precipitation relative to the baseline period, those to the right show increased precipitation.

FIGURE 19.2

Twenty countries provided the bulk of global inland fisheries production (2015: more than 80 percent). Here, they are shown ranked by total catch (China first: Pakistan twentieth)

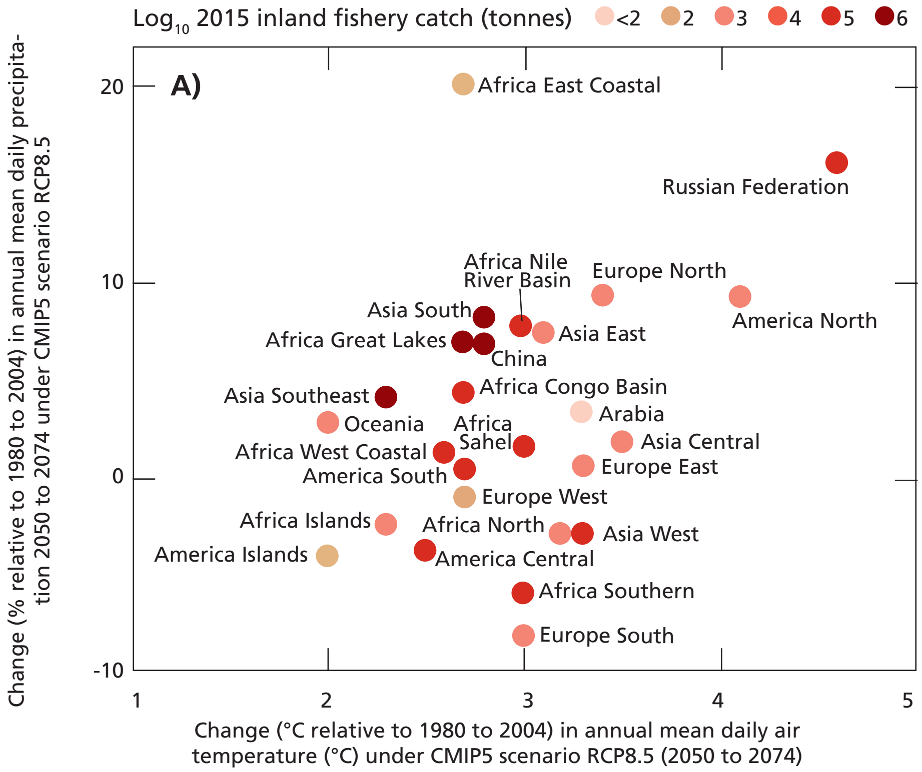


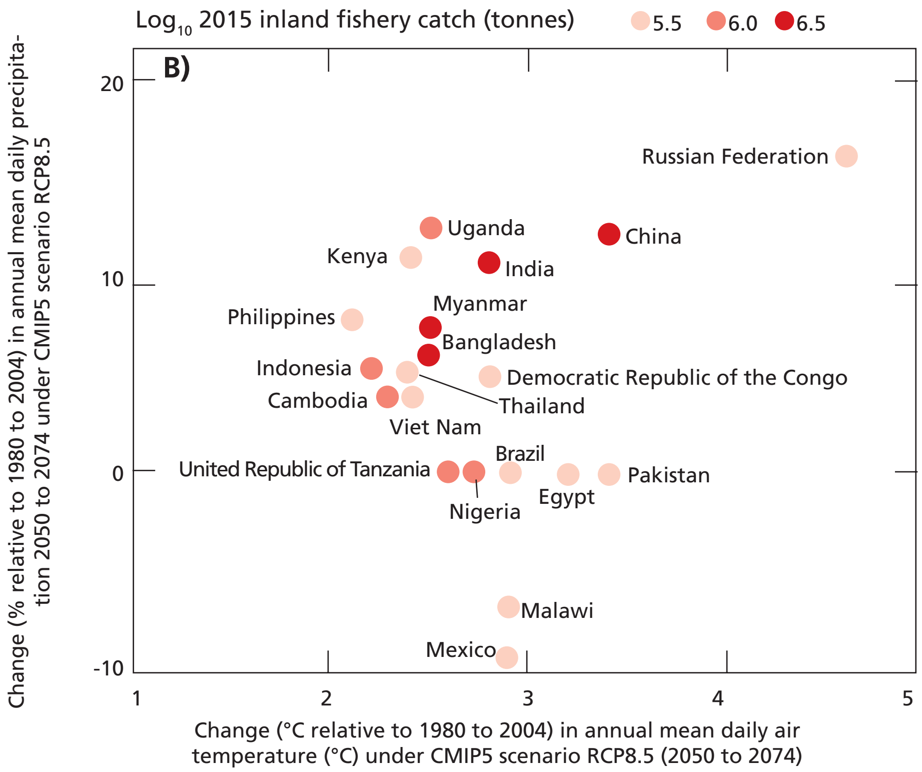
The Figure shows the variation in mean estimated change in A) annual mean air temperature (°C) and B) annual mean daily precipitation (%) projected for the different countries for the period 2050 to 2074 under two CMIP5 scenarios (RCP2.6 and RCP8.5) relative to 1980 to 2004. Markers to the left of the vertical line in B) show a lowering in precipitation relative to the baseline period, those to the right show increased precipitation.

At the level of the top 20 countries providing the bulk of inland fisheries production, there is a mean projected increase in air temperature of +1.2 °C under RCP2.6 and of +2.8 °C under RCP8.5 (Figure 19.2A). Projections for the Russian Federation, however, are notably higher under both scenarios. In terms of precipitation, most of these countries show increases under both scenarios (Figure 19.2B), with mean changes under RCP2.6 of +2.2 percent and under RCP8.5 of +4.5 percent, but precipitation is projected to either remain at baseline levels in several countries or even decrease markedly in the case of Malawi (RCP2.6 and RCP8.5) and Mexico (RCP8.5).

FIGURE 19.3

The A) regions and B) countries making the largest contribution to inland fishery catches (see marker colour intensity)





Note the different colour scales used to indicate $\log_{10}$ catch in the two figures. The differences in values shown for China in the two figures reflect the use of mean values in A) based on different regions of China.

The direct effects of temperature and precipitation changes have synergistic impacts on inland fisheries. The association between these two climate-related factors and the catches of inland fisheries was examined at the level of fishery subregion (Figure 19.3A) and for the 20 countries with the highest global inland fishery catch (Figure 19.3B).

A number of subregions (Southern Europe, Southern Africa, Central America, and Western Asia) will face reductions in precipitation, coupled to increased air temperatures. Most of these are not major contributors to global inland fisheries catch. There are two countries that appear to be most affected by reduced precipitation (Malawi and Mexico). Neither has substantial production from floodplains and rivers and the inland fish catch is derived from large lakes (Malawi) or lagoons and reservoirs (Mexico).

North America, China and the Russian Federation face increased precipitation as well as increased air temperatures. This warming may increase inland fishery availability in the case of Northern America and the Russian Federation, as waters warm and become more productive. This would however be characterized by changes in species, including possible invasives.

Many of the subregions that provide substantial contributions to global catch (South East Asia, African Congo, African West Coast and the African Sahel) are predicted to experience moderate increase in rainfall and temperature, indicating less extreme impacts. South Asia, the African Nile and African Great Lakes are also major contributors to inland fisheries but will experience slightly more extreme conditions.

19.3 THE RELATIVE IMPACT OF WATER STRESS, POPULATION INCREASE AND CLIMATE CHANGE STRESSES ON INLAND FISHERIES

It is important to recognize that climate change is just one of many factors that affect inland fisheries, but many of the drivers that affect inland fisheries are related to water, which itself is strongly influenced by climatic factors. Inland fisheries are subject to impacts from a range of drivers of global change, including human population change, demands on freshwaters from other sectors such as irrigation, industry and agriculture, and impacts on the connectivity of freshwater habitats and water quality through the construction of water storage dams, agricultural runoff and river regulation. To establish the present relative stresses on inland fisheries at country level and to understand the likely impact of climate change on inland fisheries in the context of other key drivers of global change, information on a range of relevant indicators was collected (Table 19.1).

TABLE 19.1
Indicators used to calculate current water, population and environmental stresses on inland fisheries

Stress indicator	Description	Source
Mean total baseline water stress for all sectors	Baseline water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percentage of the total annual available blue water in a country. A low score indicates relatively little water stress and therefore greater water availability for environmental flows and therefore is favourable for inland fisheries.	Gassert *et al.*, 2013
Mean flood occurrence	Flood occurrence is the number of floods recorded from 1985 to 2011. The incidence of flooding is taken as a proxy for the degree to which rivers and water in general, are regulated in a country. A low score (high frequency of flooding) suggests relatively little regulation and indicates conditions favourable to inland fisheries.	
Mean drought severity	Drought severity measures the average length of drought multiplied by the dryness of the droughts from 1901 to 2008. This is used as a proxy indicator for the extent to which water will remain in floodplains and the rate at which water bodies will dry out in dry seasons. A low score indicates infrequent drought and conditions favourable to inland fisheries.	
Mean water storage	Upstream storage measures the water storage capacity available upstream of a location relative to the total water supply at that location. A high score indicates that relatively little of the upstream flow is stored and is therefore available for environmental flow and can be considered favourable for inland fisheries.	
Current population density (2015)	Population density is a general indicator of overall pressures on the environment. A low score indicates relatively limited ability of humans to impact their surrounding environment through natural resource extraction. This will tend to be favourable for inland fisheries.	FAO Aquastat, 2016a
Percentage of country area under agriculture	The percentage of country area under agriculture provides a proxy for water quality pressures on inland fisheries from agriculture run-off and deforestation such as soil erosion, pesticides and nutrients. A low score indicates relatively little pressure on natural environments and is favourable for inland fisheries.	
Percentage of freshwater withdrawal by agriculture	In rural areas, the use of water by agriculture is one of the greatest pressures on water availability for inland fisheries. Any returning water will also have been modified through the agricultural system in terms of nutrients, pollutants and sediments. A low score indicates that the abstraction and return from agriculture is a low proportion of total water and thus impacts on flow are low and pollutant concentrations are diluted.	
Species richness	The number of fish species in a country. A low score indicates higher fish species richness; a high score indicates low fish species richness and that the inland fishery would be highly susceptible to change if even a few species were lost. A low score indicates greater ecosystem resilience (Oliver *et al.*, 2015) and therefore increased potential resilience of the fishery to environmental and fishing pressures.	FishBase: Froese and Pauly, eds., 2017

The potential impact of these factors on inland fisheries into the future is harder to establish. Projections of future water stress, population density and changes in precipitation and temperature (based on climate change models) were used (Table 19.2).

TABLE 19.2
Indicators used to calculate future climate, water and population stresses on inland fisheries

Stress indicator	Description	Source
Projected water stress	Used projected future country-level water stress for 2040 under business-as-usual (BAU) scenarios. Country projected water stress scores were averaged from weighted water stress scores presented for agriculture, domestic, and industrial sectors.	Luo, Young and Reig, 2015
Future population density	2050 population data were scored using the same cut-offs as were used for scoring the current population density. This allows the future population densities to be compared with current levels.	United Nations Population Division, 2017
Projected percentage change in precipitation	The percentage change in precipitation under the shared socio-economic pathway (SSP2) RCP8.5 scenario, from the baseline (1980 to 2004 average). Low scores indicate greater future precipitation, which is considered to be generally favourable for inland fisheries.	SSP2 RCP8.5
Projected change in temperature	The absolute change in surface temperature under the SSP2 RCP8.5 scenario, from the baseline (1980 to 2004 average). Low scores indicate lower future temperatures, which are considered to be generally favourable for inland fisheries.	SSP2 RCP8.5

The indicators used had established cut-off levels (e.g. the WRI Aqueduct datasets; Gassert *et al.*, 2013; and Luo, Young and Reig, 2015), or were ranked and the cut-offs were established by quintile. This provided a score between zero and four for each factor (Table 19.3). The total score (current and future) for a country was divided by the maximum possible score to provide the stress score (between zero and one). For the regional level, countries were aggregated into the subregional groupings used by FAO in its review (FAO, forthcoming) of the status of global inland fisheries.

TABLE 19.3
Cut off values for each of the indicators used

Current	0	1	2	3	4
Baseline water stress	Low (<10%)	Low to medium (10 to 20%)	Medium to high (20 to 40%)	High (40 to 80%)	Extremely high (>80%)
Flooding occurrence	Extremely high (>27)	High (10 to 27)	Medium to high (4 to 9)	Low to medium (2 to 3)	Low (0 to 1)
Drought severity	Low (<20)	Low to medium (20 to 30)	Medium to high (30 to 40)	High (40 to 50)	Extremely high (>50)
Upstream storage	Extremely low (<0.12)	Low (0.25 to 0.12)	Medium to low (0.5 to 0.25)	High to medium (1 to 0.5)	High (>1)
Population density (persons/km²)	<10	10 to 49	50 to 99	100 to 299	>300
Percentage of total country area under agriculture	<4	4 to 10	11 to 17	18 to 30	>31
Agricultural water withdrawal as percentage of total renewable water resources	<0.27	0.27 to 0.79	0.8 to 3.85	3.86 to 20	>20
Freshwater species richness	>315	314 to 135	134 to 81	80 to 49	<49
Future	0	1	2	3	4
Water stress (2040) BAU	Low (<10%)	Low to medium (10 to 20%)	Medium to high (20 to 40%)	High (40 to 80%)	Extremely high (>80%)
2050 future population (persons/km²)	0 to 9	10 to 49	50 to 99	100 to 299	>300
Future temperature (absolute change over baseline) (°C)	<2.4	2.4 to 2.6	2.7 to 2.9	3 to 3.2	>3.3
Future precipitation (% change over baseline)	+6.7 to 0	+1.2 to 0	0 to -2.4	-2.4 to -16.9	<-17

The current and future scores were then charted as bubble plots (Figure 19.4) to provide an indication of the current level of stress facing inland fisheries in each country or region. It also shows the potential future threat or stress which will be presented by climate change, population growth and water stress. The size of the bubble in each plot is the contribution of that country or region to the total global inland fishery catch using the inland fish catch (in tonnes) reported to FAO (FAO FishStatJ, 2017). The summary of these results is presented in Table 19.4.

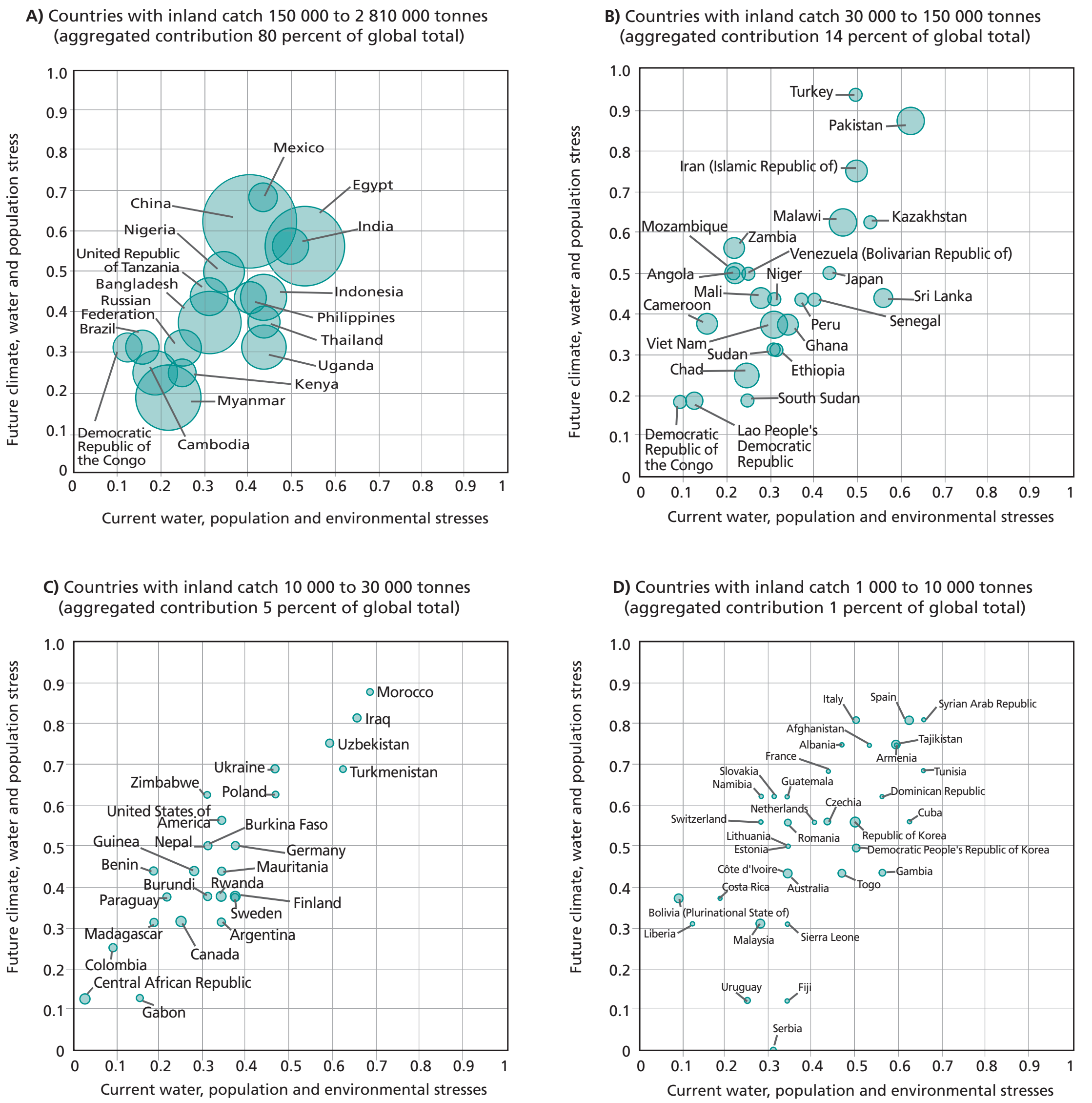
TABLE 19.4

Summary of the groups of countries and their contribution to inland fishery catch, organized by the degree of current and future stresses (V. High >0.75; High 0.6 to 0.75; Medium >0.25 to 0.6; Low ≤0.25)

Current	Future	No. of countries in group	Catch (2015) (tonnes)	% of global total	Countries in the group with inland fisheries catch >5 000 tonnes
High	V. High	8	179 810	1.6	Pakistan, Iraq, Morocco, Spain
Medium	V. High	4	39 266	0.3	Turkey
High	High	5	16 791	0.2	Turkmenistan
High	Low	1	65	0	-
Medium	High	24	2 798 622	24.2	China, Mexico, Malawi, Iran (Islamic Republic of), Kazakhstan, Uzbekistan, Ukraine, Poland, Zimbabwe, Armenia
Medium	Medium	60	5 429 440	46.9	India, Bangladesh, Indonesia, Uganda, Nigeria, United Republic of Tanzania, Egypt, the Philippines, Thailand, Viet Nam, Mali, Ghana, Sri Lanka, Ethiopia, Peru, Niger, Japan, Sudan, Senegal, Finland, Rwanda, Guinea, Nepal, Germany, Burkina Faso, Burundi, United States of America, Argentina, Mauritania, Sweden, Hungary, Republic of Korea, Côte d'Ivoire, Malaysia, Democratic People's Republic of Korea, Togo
Low	Medium	23	1 166 976	10.1	Russian Federation, Democratic Republic of the Congo, Brazil, Mozambique, Zambia, Cameroon, Angola, Venezuela (Bolivarian Republic of), Canada, Madagascar, Benin, Paraguay, Bolivia (Plurinational State of)
Medium	Low	7	7 093	0.1	-
Low	Low	17	1 831 394	15.8	Myanmar, Cambodia, Kenya, Chad, Lao People's Democratic Republic, Congo, South Sudan, Central African Republic, Colombia, Papua New Guinea, Gabon

It should be emphasized that the plot should be interpreted as the relative position of each country rather than the absolute value. Countries in the bottom left hand quadrant of the plot are those which are currently subject to the lowest stressors that negatively impact inland fisheries and which have the highest future precipitation change coupled to lowest projected population growth, water stress and temperature rise. Conversely, countries in the upper right hand quadrant are those facing existing pressures on their water and land resources, have high population densities and existing water stress. All of these will have negative consequences for inland fisheries. It is also important to note that the future stress may not necessarily lead to the loss of a fishery, but might change the system and lead to elimination of desirable/native species and their replacement with invasive species.

FIGURE 19.4
Current and potential future stresses on inland fisheries for individual countries



Eight countries are facing high current stresses and are projected to face very high stress in the future. Only four of these have any substantial inland fishery production (Pakistan, Iraq, Morocco and Spain) and the group contributes 1.6 percent of the total global catch. Swaziland is the only country that currently faces high current stress which is projected to reduce to low stress in the future, however the production from the inland fishery is only 65 tonnes.

Below this group there are four countries (contributing 0.3 percent of total global inland fishery catch) that are facing medium current stress and very high future stress. The only country with significant inland fisheries in this group is Turkey.

There are 24 countries that currently face medium stress but are projected to face high stress in the future. This group includes China, the largest inland fishery producer in the world, together with a number of minor inland fishery producing countries such as Mexico, Malawi, the Islamic Republic of Iran, Kazakhstan, Uzbekistan, Ukraine, Poland, Zimbabwe and Armenia (Figures 19.4c, 19.4d). Their combined contribution to global catch is 24.2 percent. China has heavily modified its rivers and has considerable water storage. It will face increasing pressures on water from population expansion although precipitation is expected to increase slightly overall. China already derives most of its inland fisheries catch from human-made water bodies rather than its rivers and floodplains. The aquaculture production in the country is also partially derived from culture-based fisheries. Many of the other countries in this grouping concentrate their inland fisheries in natural (e.g. Malawi, Kazakhstan) and human-made water bodies rather than rivers and floodplains. Malawi stands out with extreme projections for increasing temperature and reduced rainfall (Figure 19.3b). The situation of China is explored at sub-national level in the basin case study for the Yangtze (Section 19.4).

There are 60 countries which face medium current stress, and are projected to face medium future stress. This is the most numerous group and contributes most (46.9 percent) of the global inland fishery catch. It includes several of the world's largest producing inland fishery countries (*inter alia:* India, Bangladesh, Indonesia, Uganda, Nigeria, the United Republic of Tanzania), 30 of which have catches in excess of 10 000 tonnes. It is notable that many of the countries in this grouping have already heavily modified river basins and have developed considerable amounts of water storage, irrigation and damming to address their water needs. An exception is Uganda which derives most of its catch from Lake Victoria. The top countries also tend to have strong population and agriculture/land use pressures. Unsurprisingly much of the inland fish catch in these countries is derived from fisheries (and increasingly culture-based fisheries in the Asian countries) in human-made or natural water bodies as opposed to riverine and floodplain fisheries. Bangladesh is a notable exception, as nearly the entire country is a floodplain and it has considerable floodplain fisheries. These medium future stress scores in most of these countries are mainly the result of the projection of increasing rainfall and lower water stress in the future but overall, does not appear to be facing severe threats to inland fisheries in the future (Figure 19.4b). One surprising country is Bangladesh, with its high population densities and agricultural coverage. Its relatively unstressed position is indicative of its huge water resources, regular flooding and relatively low current and future water stress. There is a trend towards greater flood protection through poldering and this is fragmenting floodplains. The future stresses of population and water stress are likely to place greater strains on fish production in many of these countries and the top producing countries in the group already have well developed aquaculture production. The situation of India is explored at sub-national level in the basin case study for the Ganges-Bramaputra rivers basin (Section 19.5). The African Great Lakes (e.g. Uganda, Malawi, and the United Republic of Tanzania) are covered in case studies in Section 19.8.

Finland, and Sweden are exceptions in this group, as the specific threats facing those northern latitude countries are quite different to most of the other countries in this grouping, particularly in the effect of warming on cold adapted ecosystems. This is explored in the Finland case study in Section 19.6.

Another major group of countries (38) currently faces low stress and is projected to face medium stress in the future. This group contributes 10.1 percent of the global inland fishery catch and comprises several of the world's major inland fisheries (Russian reservoirs and lakes, Congo River, Amazon River, Zambezi River and La Plata River). These basins have varying degrees of water management, agricultural development and growing population densities, but their future water stress remains relatively low. The basins case studies for the Congo and La Plata rivers provide more detail in Sections 19.11 and 19.9 respectively.

Seven countries currently face medium stress which is projected to reduce in the future. The inland fisheries of these countries are minimal and contribute barely 0.1 percent of the global catch. Therefore these improving future conditions could be expected to provide more inland fish but the impact on increasing global inland fishery catch is likely to be negligible.

Seventeen countries are currently facing low stresses and are projected to face low stress in the future. This group contains several of the major inland fisheries countries of South East Asia and Africa and one in South America. Collectively they contribute 15.8 percent of the global inland catch. This group will face increasing population related stresses, but overall water stress, changing temperature and precipitation will be low compared with the previous groups. This is an important group, as it contains several countries that are most dependent upon inland fisheries. Seven of these countries (Cambodia, Myanmar, Chad, the Congo, the Lao People's Democratic Republic, Gabon and the Central African Republic) are in the top twenty countries with the highest per capita catch (a proxy for consumption) of all the countries in the world. This underscores how in relatively small countries, the low total catch from inland fisheries may appear globally insignificant, but could be of considerable importance to domestic food security.

Their low relative stress levels reflect relatively low levels of water management, low water stress and limited impacts from intensified agriculture. Some of these countries also have relatively low population densities, which, although they will grow, will still be far lower than more densely populated countries in the grouping above. The future scenario also indicates that inland fisheries will continue to provide an important future resource for nutrition and food security in these countries, emphasizing the need to sustain the integrity of these inland fisheries. This high dependence also underscores the need to take inland fisheries into consideration with planning and development, including climate adaptation (see Chapter 26). This group also represents a number of the world's major inland fisheries river basins (Ayeyarwady, Mekong, Congo, Lake Chad, and Upper Nile). The river basin case studies for the Congo (Section 19.11) and lower Mekong (Section 19.7) cover this in greater detail.

To illustrate some of these country level projections in more detail, the following sections provide eight basin and country case studies. These studies cover eight hydrological basins that span the major continents and cover the latitudes in which the major inland fisheries occur. Each of the examples also represents a basin which contributes a regionally significant volume of inland fish production and exhibits some dependency on inland fisheries. The case studies summarize the climate science and the known or likely impacts arising from interactions with the other drivers of global change that impact inland fisheries. The inland fisheries in each of these basins face distinct pressures alongside climate change, varying in the relative impacts of other forms of human-driven global change such as habitat modification and degradation, pollution, introduction of non-native species, over-extraction of water and over-exploitation of fishery resources. Although some of the basins examined are located within a single country (Finland's inland fisheries, Yangtze River basin), others are transboundary resources that extend either across catchments (i.e. African Great Lakes) or national boundaries (Amazon, the Congo, Ganges, and Mekong River basins). The data presented here provide information on fishery activities and human requirements, as well as the projected changes under future climate scenarios, providing outlines of basin-level climate change scenarios on stress and vulnerabilities.

19.4 YANGTZE RIVER BASIN

The Yangtze River (Chang Jiang) is the longest in China, and the third longest (6 300 km) river in the world. Its basin, draining an area of 1.8 million km^2 (Chen *et al.*, 2004), is equivalent to one fifth of the land area of China. The river has more than 3 000 tributaries and 4 000 lakes that, with their tributaries, form a complex riverine-lacustrine network (Fu *et al.*, 2003). Throughout the middle and lower sections of the river, many lakes are connected to the main channel, including Poyang Lake, China's largest lake (Dudgeon, 2010). Average discharge is very high (34 000 m^3/s), and there have been repeated catastrophic floods that have led to large-scale loss of human life and damage to agricultural land and urban and rural infrastructure.

19.4.1 Drivers and threats to the fisheries in the Yangtze River basin

Water management and other human activity in the basin have led to loss in connectivity, impacts on flow and deterioration in water quality (Yang *et al.*, 2005, 2011). There have been large-scale and destructive impacts on the hydrology of the Chinese river systems, and especially the Yangtze River basin. Since the 1950s, water withdrawal and consumption in China have increased approximately fivefold, reflecting a doubling of the population and increased irrigation and industrial activity (Yang and Lu, 2015). The Yangtze River is now highly modified (Nilsson *et al.*, 2005) and highly regulated, with more than 50 000 large and small dams built in the Yangtze River basin since 1950 (Cheng *et al.*, 2015; Li *et al.*, 2013; Xie *et al.*, 2007; Yang *et al.*, 2005, 2011).

The basin catchment is also highly modified by human agricultural and industrial activity, sustaining over 400 million people, more than 40 percent of gross domestic product (GDP) and more than two thirds of the total national rice production (Yang *et al.*, 2005). Water pollution is a major issue in China: by the beginning of the 2000s, about 80 percent of major rivers in China were too polluted to sustain life (Dudgeon, 2011). Major sources of pollution include urban areas, industry, mining activities and agriculture (Chen *et al.*, 2017; Dudgeon, 2011), as well as human sewage. Water quality issues in the Yangtze River drainage include: nutrient enrichment; biodegradable organic pollutants; heavy metals; persistent organic pollutants; pharmaceuticals and personal care products (Chen *et al.*, 2009, 2017; Dudgeon, 2011; Floehr *et al.*, 2013; Müller *et al.*, 2008).

Economic development is projected to continue into the future, albeit at a slower rate than in recent years (Green and Stern, 2017) and it is likely that there will be continued environmental impact in the Yangtze River basin. This, combined with rising water temperatures, and reduced flow, will undoubtedly have subsequent impacts on inland fisheries, constraining effective restoration of fisheries in the near future. More recently, policies have been implemented at a national level to ensure that future developments in the basin include sustainability considerations (Chen *et al.*, 2017).

The seasonal pattern of flow variation that has long driven the ecology of the River Yangtze basin, and the life cycles of key taxa, has been rapidly lost. Increasing shifts from the natural flow regime caused by dams, glacier melt, and increased seasonality of monsoonal rains have combined to alter profoundly the flow cycles to which the Yangtze biota are adapted and upon which they depend, thereby adding to the thermal stresses imposed by climate warming. This will increase in the future as climate change further impacts the system, and will also drive the construction of more dams in the basin for water storage and flood control, in order to enhance human water security (Dudgeon, 2010).

19.4.2 The inland fisheries of the Yangtze River basin

The Yangtze River traditionally supported the most developed inland fishery in China and historically accounted for about 60 percent of the total national freshwater catch (Chen *et al.*, 2004).

The fish fauna of the basin consists of more than 370 species, of which more than half are cyprinids. Less than 20 species are key species of economic concern and include: Chinese major carps (*Ctenopharyngodon idella, Hypophthalmichthys nobilis, H. molitrix*), black carp (*Mylopharyngodon piceus)*, Crucian carp (*Carassius carassius*), Common carp (*Cyprinus carpio*), bronze gudgeon (*Coreius guichenoti*), Reeves' shad (*Tenualosa reevesii*), tapertail anchovy (*Coilia nasus*) and the Japanese eel (*Anguilla japonica*; Chen *et al.*, 2009). In the Lower Yangtze, anchovy accounts for 50 percent of the catch, shad and eels 20 percent and major carps 30 percent (Chen *et al.*, 2009). The basin is the sole habitat of a number of endangered species, some of which are now functionally extinct (Chinese paddlefish *Psephurus gladius* and Yangtze sturgeon *Acipenser dabryanus*) (Zhao, Gozlan and Zhang, 2016).

There has been a continuous decline in fish catches on the Yangtze River from 400 000 tonnes in the 1950s, to about 70 000 tonnes/yr in 2014 (Lu *et al.*, 2016). Many traditional fisheries on the Yangtze River have disappeared or are in the process of doing so, following the loss of key fish species (Zhao, Gozlan and Zhang, 2016). Although the Yangtze River fishery is still globally significant, Chinese river fisheries now make relatively minor contributions to China's inland fish supply and most inland fish production (more than 90 percent) is derived from culture-based fisheries (in human-made and natural waterbodies) and pond aquaculture. There are an estimated 0.4 million full time fishers and 2.4 million fish farmers participating in Yangtze commercial fisheries and aquaculture activities (Ainsworth and Cowx, forthcoming).

19.4.3 The climate and future trend in the Yangtze River basin

Apart from some cold, high-altitude areas located in the Tibet Plateau, the climate of most of the Yangtze River basin is a subtropical monsoon climate with four distinct seasons, winter (December to February), spring (March to May), summer (June to August) and autumn (September to November) (Su, Jiang and Jin, 2006). The region is subject to two monsoons, one in winter and another in summer. Most precipitation falls during the summer monsoon season (Su, Jiang and Jin, 2006). The Yangtze River basin experiences long, hot and humid summers but in winter temperatures drop below 0 °C. The Yangtze is considered extremely vulnerable to climate change because of its large seasonal and interannual variability in precipitation, dense population and a rapidly developing economy. Climate warming may affect the intensity or the probability of the occurrence of extreme weather events including floods, which already have extremely serious impacts in the region (Su, Jiang and Jin, 2006). For example, floods in 1998 resulted in the loss of five million houses and the inundation of 21 million hectares of land (Piao *et al.*, 2010).

At a national level, air temperatures in China have warmed by 1.2 °C since 1964, but there is no consistent trend for precipitation over the same period (Piao *et al.*, 2010). At a basin level, air temperatures rose by 0.8 °C over the last century (Gu *et al.*, 2011). There has been a reduction in the number of warm days and increase in the number of warm nights in the middle and lower basin, as a result of increased summer rainfall (Qian and Lin, 2004). There is also a trend in the reduction in the number of frost days in the Yangtze River basin between 1960 and 2000, particularly in the lower basin (Qian and Lin, 2004).

Climate change has been associated with shifts in hydrological conditions in major water bodies in the Yangtze River basin (Chen *et al.*, 2017). Warming in the upland headwater areas of the basin has resulted in the loss of permafrost and a subsequent reduction in groundwater levels, with associated drying of wetlands and a fall in lake levels (Cheng and Wu, 2007). Jiang, Su and Hartmann (2007) examined recent (1961 to 2000) shifts in precipitation and showed evidence for a positive trend in summer precipitation, especially for extreme rain events in the middle and lower sections of the basin. This was associated with a positive trend in rainstorm frequency as well as a positive trend in flood discharges in the mid- and lower-basin over the 40-year period. Annual maximum streamflow increased in the middle basin between 1925 and 2000 (Zhang *et al.*, 2006).

Climate projections indicate that in the current century, the Yangtze River basin will undergo changes in temperature (increase), precipitation (increase) and discharge (decrease).

Climate modelling associated with the Fourth Assessment Report of the IPCC (Cruz *et al.*, 2007) indicated that China's average temperature is projected to increase by 1 °C to 5 °C by 2100, with greater increases in the north of the country and in the upland areas (Piao *et al.*, 2010). More detailed recent modelling suggests that these estimates are generally robust. Recent CMIP5 mean estimates for China (Alder, Hostelier and Williams, 2013; Chong-Hai and Ying, 2012; Taylor, Stouffer and Meehl, 2012) generated for the Fifth Assessment Report of the IPCC (AR5; Hijioka *et al.*, 2014) indicate that by the end of the twenty-first century, increases in mean annual air temperatures will be greater than the global average. Mean annual increases are projected to be between 2.5 °C (RCP4.5) and 5.1 °C (RCP8.5) relative to 1980 to 2004 (Taylor, Stouffer and Meehl, 2012) or 1986 to 2005 (Chong-Hai and Ying, 2012), giving increasing trends of between 0.24 °C (RCP4.5) and 0.62 °C per decade (RCP8.5). Projected changes in temperature are greatest in the north of China and in the Tibetan Plateau, the headwater region for the Yangtze. Birkinshaw *et al.* (2017) examined temperature and precipitation projections for the Yangtze River basin based on 35 different general circulation models from CMIP5 to examine the effect of climate change on river discharge for 2041 to 2070 for RCP8.5. They estimated that across the basin, mean air temperatures for the period 2041 to 2070 were projected to be 2.7 °C higher than 1981 to 2010. van Vliet, Ludwid and Kabat (2013) provided estimated changes in water temperatures for the end of the twenty-first century relative to 1971 to 2000. They projected that mean and 95th percentile water temperatures would increase by 1.8 °C.

At a national level, precipitation is projected to increase by 8.8 percent (RCP4.5) or 13.5 percent (RCP8.5), resulting in trends of +1.1 (RCP4.5) and +1.9 percent per decade (RCP8.5) (Chong-Hai and Ying, 2012). Huang *et al.* (2011) used a statistical downscaling approach with the B2 (low emissions) and A2 (high emissions) scenarios of the Hadley Centre Coupled Model version 3 to examine changes in precipitation at a basin level. Their results indicated that, compared to 1961 to 2000, precipitation in the basin would vary considerably both spatially and temporally, with differences between the upper, mid- and lower-sections of the basin, and also seasonally (reductions most marked in autumn) and through the future (2020s, 2050s, 2080s).

The A2 scenario predicts greater changes than the B2 scenario. Both predict a considerable decrease in precipitation over the short-term (by 2020s: A2 7.5 percent reduction, B2 only 4.7 percent reduction). The mid-term projection indicates that precipitation would be similar to the baseline (by 2050s: B2 0.24 percent reduction; A2 0.33 percent increase). In the long-term, both A2 and B2 scenarios predict increased precipitation (by 2080s: B2 5.3 percent increase; A2 13.1 percent increase). Huang *et al.* (2011) showed that under all the scenarios, precipitation would decline most markedly in the headwaters of the Yangtze River basin (decreasing by 15 percent to 20 percent). Birkinshaw *et al.* (2017) presented a multi-model basin mean for future precipitation in the Yangtze River basin showing a decline of 4.1 percent for 2041 to 2070 (RCP8.5).

Projections for future discharge are inconsistent. In their global analysis, van Vliet, Ludwid and Kabat (2013) estimated that mean discharge across the whole Yangtze basin would only change by -0.1 percent by the end of the twenty-first century relative to the period 1971 to 2000. They suggested that low (10th percentile) flows would fall by 18 percent, and that high (95th percentile) flows would increase by five percent. Conversely, Palmer *et al.* (2008) estimated that by the 2050s, mean annual discharge in the Yangtze River would increase by 17 percent under the A2 emissions scenario. More recent modelling focusing directly on the Yangtze basin provided a multi-model basin mean change in discharge of -11.1 percent (Birkinshaw *et al.*, 2017).

19.4.4 Impacts on inland fisheries in the Yangtze River basin

As in the recent past, the key future threats to the Yangtze fish community include over-exploitation, habitat degradation and pollution (Fu *et al.*, 2003). Dudgeon (2011) described the combination of these factors as a *perfect storm* (i.e. where a combination of threats combines to create a far larger hazard), to which the impacts of climate change (increased temperatures, reduced discharge) need to be added. Climate change has already changed physico-chemical conditions in the Yangtze River basin (0.8 °C increase in air temperatures in the last century), and as such, climate change has been acting on the fish community for the entire period of rapid regional development. However, the extent of any response is unclear, especially given the scale of other impacts. Apart from increased temperatures (projections suggest between +2 °C and +5 °C by the end of the century), the Yangtze River basin will see continued changes from the natural flow regime because of glacier and permafrost melt, more flow regulation as a result of dams and changes in seasonal precipitation. These problems will become increasingly compounded as hydropower is at the heart of China's strategy to reduce greenhouse gas emissions (Dudgeon, 2010).

In many warming river systems, cold- and cool-water adapted fishes have been seen to have shifted their distributions upstream (Comte and Grenouillet, 2013), but this option is limited in the Yangtze because of its great length, its east-west aspect, and the large number of dams and other instream barriers (Dudgeon, 2011). Given the inability of species to move to suitable habitats, the Yangtze fish community will become dominated by those species with more generalist habitat requirements, which likely include non-native species (Davidson, Jennions and Nicotra, 2011; Rahel and Olden, 2008), as the effects of warming and shifts in the flow regime strengthen in the future. Future management of inland fisheries in the Yangtze River basin will therefore face the issues of climate change on target species as well as the continued issues of pollution, habitat degradation and existing human over-exploitation.

19.5 GANGES RIVER BASIN

The Ganges River basin covers an area of about 1.7 million km^2 and extends across China (3.1 percent), India (79.1 percent), Nepal (13.5 percent), and Bangladesh (4.3 percent). The source of the Ganges River is glacial meltwater from the Gangotri glacier, located 6 000 metres above sea level in the Himalayas (Sanghi and Kaushal, 2014), and across the basin. Water is supplied by melting snow and monsoon rains. The basin consists of hilly terrains of the Himalayas with dense forest, sparsely forested Shiwalik hills and the fertile Ganga plains, resulting in habitats varying from high-gradient, cool-water upland streams in the short (about 300 km) mountain zone, warm water stretches in the Gangetic plains, including wetlands, oxbow lakes, and multiple interlaced channels along a section extending for 2 300 km, and finally deltaic habitats (Vass *et al.*, 2010). It is the most populous river basin in the world with 500 million people and a mean population density of 550 individuals/km^2, and up to 900 in the delta region (Sanghi and Kaushal, 2014). The basin plays a fundamental role in regional economies, e.g. providing more than 90 percent of wheat and 60 percent of rice in India.

19.5.1 Drivers and threats to the fisheries of the Ganges River basin

The Ganges basin population is highly dependent on the water resources, and demands on water will increase as the population grows. The overall population is predicted to rise by a mean rate of 14 percent (United Nations Population Division, 2017), with populations in India and Bangladesh to rise by 24 percent by 2050, resulting in India having the world's largest population (1.7 billion). About 33 percent of the land area of the Indian part of the Ganges basin is already under severe water stress (consumption exceeding 40 percent of the available water; Babel and Wahid, 2011).

Parts of the basin have traditionally served as a food bowls for the countries in the wider region, but development of the sector, to keep up with increasing demands, is limited by water access. During 2011 to 2040, rice and wheat yields are projected to undergo marked declines (by between 17 percent and 43 percent respectively) in the basin (Dulal, 2014). About 90 percent of all water abstractions in the basin are for agriculture, which is the mainstay of the economy. Some of the largest irrigation schemes in the world are found here (Jeuland *et al.*, 2013). An Indian plan to divert more than 174 million m^3 of water from water-rich to water-scarce basins, largely from the Brahmaputra through the Ganges and many of its distributaries to the drier southern and western parts of India, will possibly cause a decline in the already limited dry seasonal flow of the Ganges, threaten basin ecosystem integrity, and pose serious ecological and economic threats to downstream Bangladesh (Shahjahan and Harvey, 2012). There are more than 1 000 dams in the basin (Kelkar, 2014), and all tributaries in India are controlled by barrages, which divert water for irrigation (Payne *et al.*, 2004).

There are plans to build large storage dams at upstream sites in India and Nepal to capture part of the monsoon flows to mitigate flood intensities downstream, while augmenting dry season flows, and to generate 30 000 MW of hydropower to ease the energy crisis in the region. Hydroelectric power accounts for more than 96 percent of electricity generated in Nepal (FAO, 2016b). Embankments have been constructed to restrict flooding, but these prevent fishes from accessing flooded habitats to reproduce, feed and grow, and increase sediment deposition in riverbeds with lower flow and higher risks for embankment breach and flooding as a consequence (Babel and Wahid, 2011), and the spawning habitats of several fishes have been affected (Rahman, 2008).

From the headwaters to the delta, there are more than 30 major cities with more than 300 000 people, and the Ganges is now considered among the five most polluted rivers in the world as a result of the discharge of increasing quantities of sewage, industrial effluents and other pollutants from rapid urbanization, industrialization and agricultural growth (Kiumar, 2014). Some persistent chemicals are present in fish at higher concentrations than permitted in the United States of America, by the United States Environmental Protection Agency (Samanta, 2013). A further threat is posed by the ritual disposal of human bodies and cattle corpses in the river (Trivedi, 2010).

19.5.2 The inland fisheries of the Ganges River basin

There are at least 161 and possibly up to 380 fish species in the Ganges basin (Singh, Kumar and Ali, 2014). Fisheries in the basin involve professional, part-time and subsistence fishers and play an important role in nutrition, income and employment particularly in Bangladesh and India. There are also numerous medium and small lakes in Nepal heavily exploited for fish. Ainsworth and Cowx (forthcoming) estimate that at least 13 million people in Bangladesh are part-time fishers, while 142 000 men and 223 000 women are subsistence fishers in Nepal (Sharma, 2008). In 2009, Bangladesh had an estimated annual fish consumption of 19 kg/capita, which represents more than 60 percent of animal source food. Around 36 percent of the fish came from freshwater capture fisheries (Belton *et al*., 2011).

There are no reliable basin-wide catch statistics. Fish catches peak before and after monsoon floods. Upland habitats are dominated by cold-water-adapted cyprinids including *Schizothorax* species (snowtrout; 20 percent to 80 percent of the catch) and Tor species (Mahseer), and are exploited from below 1 800 metres above sea level (Payne *et al.*, 2004). The contribution of upland riverine fisheries to basin catches is low and less diverse compared with lowland fisheries. In the lower reaches of the Ganges, Indian and Chinese major carps make up 50 percent of the total catch, and anadromous hilsa (*Tenualosa ilisha*) also makes significant contributions to catches (Payne *et al.*, 2004). For subsistence fishers, small indigenous fish species are considered vitally important for maintaining household food security (Ainsworth and Cowx, forthcoming).

Fish landings in the upper and middle Ganges are dwindling, and catches of Indian major carps and hilsa have decreased (the latter likely because of the construction of the Farakka barrage in India in the 1970s), while the contribution of exotic fish increased (now 43 percent to 48 percent of the total catch). In the lower part of the basin, catches have increased, probably as a consequence of the growing population. However, the catch of spawn from wild major carps in Bangladesh declined from 17 241 kg/yr in the 1980s to 2 255 kg/yr in the 2000s (Rahman, 2008). Several non-native fish species have been introduced, mostly for aquaculture, including salmonids, a variety of carp species (including Chinese carp), Mozambique tilapia (*Oreochromis mossambicus*) and Pangasius catfish (*Pangasianodon hypophthalmus*) and make major contributions to fisheries.

Fishing communities are marginalized and socio-economically impoverished, with low levels of education making them particularly vulnerable to negative impacts of climate change. As a response to growing population density and more intense competition for resources, fishers move from lowland to highland areas (Kumar, 2017).

19.5.3 The climate and future trend in the Ganges River basin

The climate of the Ganges River basin varies from semi-arid to humid, and is extremely variable both spatially and temporally. Precipitation is low in the northwest of its upper region, and extremely high in the Ganges Delta (FAO, 2016b). Precipitation in the basin is mostly associated with southwesterly monsoon winds (July to October), but is also generated by tropical cyclones originating in the Bay of Bengal between June and October (FAO, 2016b). Very little precipitation falls in December and January. In the upper Gangetic plain, mean annual rainfall ranges between about 750 mm and 1 000 mm, in the middle Gangetic plain between about 1 000 mm and 1 500 mm, and in the Ganges Delta between about 1 500 and 2 550 mm, and Bangladesh has one of the wettest climates in the world. Temperatures vary significantly between locations, ranging between less than 0 °C to more than 26 °C (Jeuland *et al.*, 2013). The mean maximum temperature across the basin is 30.3 °C in summer and 21.1 °C in winter (GRID-Arendal, 2017a): the pre-monsoon season is the hottest in the Ganges basin with an average temperature of 31.4 °C. June is the hottest month in the upper basin, and May in the lower basin, while January is the coldest month across the basin.

The run-off pattern, and its timing and intensity vary greatly with the precipitation quantity and distribution varying according to seasonality and with the snowmelt in the Himalayas. The Ganges system is characterized by low base flow during the dry season and extremely high discharges following the monsoonal rains. About 80 percent of the flow in the Ganges occurs in the monsoon months (June to September), and very little during the dry season (Babel and Wahid, 2011; Shahjahan and Harvey, 2012). The relative strength of the monsoon varies markedly between years, with significant impacts on the livelihoods of people in the Ganges River basin that include major floods and shifts in the river channel through to droughts and crop failure (Rasul, 2015).

Several authors have reported similar trends of increasing air temperatures in the Ganges River basin of about +0.6 °C/decade (Das *et al.*, 2013; GRID-Arendal, 2017a; Nepal and Shrestha, 2015). Das *et al.* (2013) showed that the annual mean water temperature increased in the upper cold-water section of the Ganges River by about 1 °C in 20 years (1980 to 2009), and that this was associated with an upstream shift in the distribution of warm-adapted fishes. They also showed that the mean minimum water temperatures from aquaculture pools situated in the lowland plains increased by between 0.2 °C and 0.7 °C over the same period.

Downstream sections of the basin suffer from an excess of water during the monsoon months causing floods in many areas, but often experience severe water shortages causing drought. These two extremes cause socio-economic and environmental disasters almost on an annual basis (Shahjahan and Harvey 2012; Trivedi, 2010). There is no evidence of any general large-scale change in precipitation across the Ganges River basin (GRID-Arendal, 2017a; Nepal and Shrestha, 2015), but this is complicated by the considerable interannual variation in monsoon intensity.

Climate models predict an increase in air temperature of 2 °C to 5.0 °C for the Ganges River basin by the end of the twenty-first century (GRID-Arendal 2017b; Jeuland *et al.*, 2013). Increases are projected to be more marked in winter than summer, resulting in a shortened winter and an extended growing season. Models using both RCP4.5 and RCP8.5 scenarios indicate that air temperatures will increase significantly by 2050 across the Ganges basin in summer by about 2 °C, with mountain areas warming by up to 3 °C (GRID-Arendal, 2017b). Winter temperatures are projected to increase between 2 °C to 3 °C across the basin, and up to 4 °C in high altitude areas. van Vliet, Ludwid and Kabat (2013) predicted that at a whole catchment level, mean water temperature would increase by 1.2 °C by the end of the twenty-first century relative to the period 1971 to 2000. Over the same period, they estimated an increase in mean flow of 65 percent, no significant change in low flows, and 78 percent increase in high (95th percentile) flows.

Such warming in upland areas has the potential to affect the glaciers and associated snow that provide the initial inputs that form the Ganges River basin: they also provide base-flow during low precipitation periods (Vass *et al.*, 2010). The contribution of snow and glacier melt to streamflow in the Ganges basin is estimated at about 10 percent. In general, the glacier melt contribution is high in upstream areas because of the relatively small catchments and higher melt runoff, and low in the lower elevation areas, where runoff from rainfall is much higher (Nepal and Shrestha, 2015). Under a warming climate, the volume of glaciers in the eastern Himalayas (Nepal) will decline over the twenty-first century, despite increasing precipitation, as a result of less precipitation falling as snow as well as increased ablation (Wiltshire, 2014). Jeuland *et al.* (2013) suggested that summer glacial melt initially will result in increased summer flows, but that future dry season flows could be reduced by 10 percent to 24 percent.

For the period 2046 to 2065 under the A1B scenario, a decrease of 18 percent in mean upstream water supply is projected for the Ganges basin, with the reduction in melt runoff partly compensated for by increased upstream rainfall (+8 percent; Nepal and Shrestha, 2015). A recent analysis using the RCP4.5 and RCP8.5 scenarios (GRID-Arendal, 2017b) showed that summer rainfall was projected to increase by between 10 percent and 25 percent across most of the basin by 2050, and may even exceed 25 percent over the central northern part of the basin. Both scenarios project a decrease in winter precipitation by up to 10 percent in high altitudes. Monsoonal rainfall is projected to increase by about 15 percent under both scenarios (GRID-Arendal, 2017b).

An overall increase in monsoon precipitation of 12.5 percent (A1B scenario) and 10 percent (A2 scenario) is projected for the Ganges basin, with a decrease during the pre-monsoon and increase during the post-monsoon seasons (Nepal and Shrestha, 2015). Other projections for future precipitation in the Koshi catchment in Nepal based on ten general circulation models (GCMs) under three scenarios (A1B, B1 and B2) indicated an increase in summer, autumn and annual precipitation, but a decrease in spring precipitation (Nepal and Shrestha, 2015).

Palmer *et al.* (2008) estimated that the discharge of the Ganges River would increase by 17 percent by the 2050s. van Vliet, Ludwid and Kabat (2013) predicted that at a whole catchment level, by the end of the twenty-first century mean flow would increase by 65 percent relative to the period 1971 to 2000, but they saw no significant change in low flows. However, high (95th percentile) flows increased by 78 percent. Mirza *et al.* (2003) examined the implications of climate change for river discharge and floods in Bangladesh based on climate change scenarios from four GCMs, and concluded that the peak discharge in the Ganges River would increase substantially, leading to significant changes in extent and depth of inundation.

19.5.4 Implications for fisheries in the Ganges River basin

Given the demands for water in the Ganges River basin and the potential for climate change to affect the availability and quality of water, it is likely that climate change will affect inland fisheries and the ecosystem services on which they rely (Das *et al.*, 2013). Given issues with sea level rise and saline intrusion this may be particularly apparent in the lower part of the basin.

People in the Ganges River basin have always adapted to environmental change, showing potential inbuilt capacity to adapt to climate change. However, human population increases may be so large that adaptive scope is overwhelmed, and there is a marked lack of the infrastructure, information and institutions required to permit successful climate change adaptation in the basin (Dulal, 2014). Allison *et al.* (2009) found that Bangladesh was the 12th most vulnerable country globally in terms of climate impacts on fisheries.

Changes in hydrology (as well as loss of connectivity and deteriorating environmental conditions), have been largely responsible for the decline in fisheries and provide a useful indicator of the impacts of future climate change. Reduction by 7 percent in total rainfall during the peak breeding period of Indian major carps, the target of the most important commercial fishery in the river, compounded by the over-abstraction of water has resulted in loss of the flow and turbidity required for reproduction and recruitment of Indian major carps in the River Ganga (Das *et al.*, 2013). This highlights the need to maintain a minimum baseflow to allow the river to function. If precipitation increases are as projected, high flows will also need to be managed to allow fish to utilise flooded habitats e.g. during the monsoon period (June to September).

An apparent shift occurred in the distribution of some fishes from the Ganges (Sarkar *et al.*, 2012), with several fish species previously only reported from the warmer middle and lower sections of the Ganges in the 1950s, now being recorded from upper sections of the river, following the warming of mean minimum water temperature (Haridwar, India) from 13 °C to 15.5 °C, between the period 1975 to 2005 (Vass *et al.*, 2010). This indicates that there will likely be a restructuring of the fish community, with impacts on the ecosystem function and the fishery itself. Increases in water temperature in lower sections of the river may be such to stress existing members of the fish community, and there may be a switch from “white fish” to “black fish” species in impacted areas (Das *et al.*, 2013).

It is most likely that future changes in water demand in the Ganges River basin associated with increased human populations will drive impacts on inland fisheries in the region. Maintaining ecological flows in the river will become increasingly difficult as human populations grow in the basin in view of the conflicting and competing uses of the water. If future resource management strategies are not sensitive to the environmental requirements of fish, it is likely that there will be major impacts on the fishery and that these will be enhanced by the impacts of climate change.

19.6 FINLAND

Finland has rich freshwater resources with lakes, rivers and wetlands making up 15 percent of its surface area (Eurostat, 2017; Putkuri, Lindholm and Peltonen, 2013). A quarter of the country lies above the Arctic Circle and the country is heavily forested (68 percent of total cover), with a relatively limited amount of farmland (10.3 percent) (Eurostat, 2017). A 2013 ecological assessment of surface waters accorded good or high status to 85 percent of the surface area of Finnish lakes, and 65 percent of rivers (Putkuri, Lindholm and Peltonen, 2013), although many small lakes in the south suffer from eutrophication (Putkuri, Lindholm and Peltonen, 2013). The Finnish population is relatively small and is highly urbanized.

19.6.1 Drivers and threats to the inland fisheries of Finland

Most inland fisheries in Finland are on lakes, which reflects the large-scale ecological damage caused to rivers associated with the early uptake of hydroelectricity in Finland (Karlsson and Karlström, 1994). Rivers were also regulated for flood defence and water storage, and to provide water for the burgeoning forestry and paper industry. Dredging and removal of rapids was undertaken for downstream transportation of logs (Hildén and Rapport, 1993; Jonsson and Jonsson, 2016). Many Finnish lakes are also regulated for hydropower, flood protection and recreation (Veijalainen *et al.*, 2010). The river modifications had large and catastrophic impacts on migratory fishes (*Salmo salar, S. trutta, Coregonus lavaretus*) and their once extremely productive inland fisheries (Autti and Karjalainen, 2012; Hildén and Rapport, 1993; Nilsson *et al.*, 2005). These river fisheries were very important for local part-time subsistence and artisanal fisheries, and provided an important economic, nutritional and cultural role, the loss of which is still felt in local communities today (Autti and Karjalainen, 2012).

19.6.2 The inland fisheries of Finland

Inland fisheries in Finland are important and provide a useful case study for other temperate or boreal fisheries operating in similar latitudes such as those in northern North America and the Russian Federation. There are relatively few Finnish freshwater fish species (about 40), reflecting the recent glacial history of the region (Jonsson and Jonsson, 2016).

Freshwater fish are exploited heavily in Finland providing income and food to commercial fishers, recreational fishers and subsistence fishers (Jurvelius and Auvinen, 2001). The inland fishery is significant involving 28 percent of the total population (34 percent of Finnish males and 19 percent of Finnish females), with a total yield of 29 317 tonnes, representing 65 percent of the total inland fishery catch of Northern Europe (FAO FishStatJ, 2017). Finnish inland fisheries involve different groups ranging from professional commercial fishers, to household fishers who combine recreational and subsistence fishing, often using gillnets, as well as recreational sports fishers (who in Finland typically eat their catch). Although lakes are covered by ice for between four and seven months according to latitude, ice fishing methods allow catches throughout the year.

Full-time commercial fishing in Finnish inland waters is a relatively recent phenomenon, dating from the 1960s and 1970s and has largely targeted the small pelagic coregonid *Coregonus albula* (Jonsson and Jonsson, 2016; Jurvelius and Auvinen, 2001; Luke, 2018). Large amounts of fish (typically cyprinids) are also removed through so called management fisheries where fish stocks are reduced in order to improve lake water quality through biomanipulation (Luke, 2018). In the space of two decades there has been a marked reduction in the commercial catch from Finnish inland fisheries (Luke, 2018) but a considerable increase in the recreational and subsistence catch over the same period. Overall the inland fishery catch has declined with increases in consumption of farmed rainbow trout. This highlights that future implications of climate change on fisheries will also be related to the willingness of people to adapt to new fish species which may have quite different characteristics.

19.6.3 The climate and future trend in Finland

The Finnish climate is cold relative to much of Europe, but is moderated to a degree by the influence of the North Atlantic Drift. Climate varies considerably within the country, reflecting its length which covers latitudes between 60 °N to 70 °N. Finland undergoes large seasonal climatic shifts, with lowest temperatures being recorded in winter (December to February), when significant snowfall can occur, and daytime temperatures in Southern Finland can reach -20 °C, or -30 °C in the north. In winter, all lakes and even coastal water in the Gulfs of Bothnia and Finland freeze. Spring falls between March and May. Summer (June to August), with air temperatures reaching 20 °C in the south of Finland, and about 15 °C in the north, is reflected in the surface temperatures of lakes and rivers. Winter in Northern Finland extends for about 200 days, with snow and ice cover extending from about mid-October to early-May. Summers in the north are short (two to three months) but quite warm, and given the existence of the midnight sun, represent a period of considerable growth opportunities for fish.

Mean annual rainfall is between 600 mm and 700 mm, depending on location. In Northern Finland, mean annual precipitation is 600 mm, but approximately 50 percent falls as snow (compared to 30 percent in the south). There is considerable seasonal variation in precipitation, with spring being the driest period (summer and autumn are the wettest). Excluding the drier coastal regions, in Finland, on average precipitation falls on more than 50 percent of all days (Irannezhad, Marttila and Kløve, 2014).

The average mean air temperature in Finland has increased by about 1 °C since the 1850s. Warming has been most marked in the spring, and mean temperatures in March to May are about 2 °C higher than in the middle of the nineteenth century (Marttila *et al.*, 2005). There has been a rapid change in temperatures since the 1970s, especially in winter months (Marttila *et al.*, 2005). Recent decades have seen significant increases in air temperature between 1971 and 2011 in subarctic Finland (Hayden, Harrod and Kahilainen, 2014). Given that air and water temperatures are tightly correlated (Hayden, Harrod and Kahilainen, 2014), it is likely that lakes in the region have also warmed over the same period. Recent climate change has been associated with some quite rapid shifts in the dynamics of ice cover and thickness (Lei *et al.*, 2012).

Global projections show that climate change will be most marked in the north of the northern hemisphere (IPCC, 2014b), and this is clearly apparent from projections for Finland (Marttila *et al.*, 2005 and see Climateguide.fi website[2]). The Finnish Meteorological Institute estimates that by 2080 the average air temperature could rise by 4 °C to 6 °C and the average precipitation would grow by 15 percent to 25 percent. (Marttila *et al.*, 2005). Under the moderate RCP4.5 emissions scenario, average mean air temperatures in Finland are projected to increase by 3.6 °C by 2080 (Ministry of the Environment and Statistics Finland, 2013). Projections using the more extreme RCP8.5 emissions scenario indicate that by 2080, mean annual air temperatures will increase by 5.8 °C. The temperature increase in Finland is expected to be more than one and a half times as large as that seen at a global level (Ministry of the Environment and Statistics Finland, 2013).

Mean annual precipitation is projected to increase by between about 12 percent (RCP4.5) and 20 percent (RCP8.5). Increases in temperatures and precipitation rates will be larger in winter than in summer. Under the RCP8.5 scenario, January mean temperatures are projected to increase by 4 °C to 12 °C, and precipitation by ten percent to 60 percent by the end of the twenty-first century (Ministry of the Environment and Statistics Finland, 2013). Predictions indicate that heatwaves will become longer and more frequent, but severe cold spells will gradually lessen in intensity. Heavy summer rainfall events will increase, while the number of winter days with precipitation will increase, meaning increases in snow, where temperatures are suitable. This will result in increased river flows (van Vliet *et al.*, 2013; van Vliet, Ludwid and Kabat, 2013), as seen in many northern rivers. The significant future increases predicted for temperature, mean that the snow season will become shorter and the amount of water held in the snow will decrease, a pattern most marked in Southern Finland, where snow cover

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[2] https://ilmasto-opas.fi/en/datat/mennyt-ja-tuleva-ilmasto

may even be lost (Ministry of the Environment and Statistics Finland, 2013). Warmer winters with increased precipitation will lead to increased thawing periods and winter floods with a decrease in spring floods (which are typically driven by snowmelt). Palmer *et al.* (2008) estimated that by 2050 mean annual discharge in the Kemijoki River would increase by 21 percent under the A2 emissions scenario. Summers will become drier, with a longer summer season and increased evapotranspiration and lake evaporation.

Finland has a history of flooding, and the probability of large-scale floods will increase with subsequent impacts across sectors including water supply, agriculture, power supply and fisheries, where impacts may be negative (e.g. reduced water quality) or positive (e.g. increased spawning and nursery habitat). Any droughts arising from reduced summer precipitation and increased temperatures have the potential to impair fisheries through reduced supply and quality of water.

19.6.4 Implications for inland fisheries in Finland

The scale of the temperature increases projected for Finland are such that there can be confidence that they will have extremely significant impacts on freshwater fisheries through their influence at a catchment level, including loss of permafrost in the north (Instanes *et al.*, 2016; Prowse *et al.*, 2006). These changes will affect the function and physio-chemistry of freshwater habitats (Nilsson, Polvi and Lind,, 2015), and their biological communities (Heino, Virkkala and Toivonen, 2009), including fish (Lehtonen, 1996; Reist *et al.*, 2006) and ecosystem function (Jeppesen *et al.*, 2010). Changes in ice cover may mean that fishing methods will have to change.

Increased temperatures and a longer growing season will lead to increased fish growth in those situations where they are currently temperature limited, assuming that other factors such as dissolved oxygen concentrations, food, parasites or interactions with non-native species do not become limiting. Fish species that are currently unable to spawn or that show sporadic recruitment because of a lack of suitable spawning cues and conditions may encounter improved conditions in the near future (Lehtonen, 1996). From a point of view focused on maximizing fisheries production, this is generally considered a positive outcome of climate change. However, many of the economically valuable cold-adapted species that currently thrive in cool conditions will encounter stressful temperature conditions as freshwaters warm. Vulnerable species are the vendace and other whitefish (*Coregonus* spp.), Arctic char (*Salvelinus alpinus*), brown trout (*Salmo trutta*) and burbot (*Lota lota*) (Lappalainen and Lehtonen, 1997).

Increased water temperature may be such that gonad development is reduced and spawning is inhibited in cold-adapted species (Cingi, Keinänen and Vuorinen, 2010). Although these changes will have negative implications for cold-adapted fish, conditions will improve markedly for cool-water and warm-water fishes (Lappalainen and Lehtonen, 1997). This will be manifested through improved recruitment success for species that are currently limited by water temperature e.g. through relaxation of factors preventing spawning, by improved summer feeding (Mills and Mann, 1985) or by relaxation of overwintering mortality (Griffiths and Kirkwood, 1995; Lappalainen *et al.*, 2000).

Northern fish communities are depauperate and dominated by cold-adapted salmonids, while southern communities are more diverse and are dominated by cool-water and warm-water percids and cyprinids (Jurvelius and Auvinen, 2001; Lappalainen and Lehtonen, 1997; Lehtonen, 1996). There has been a gradual shift north of cool-water-adapted fishes and warm-water species (Hayden *et al.*, 2013), associated with recent shifts in climate that have resulted in longer, warmer summers (Rolls, Hayden and Kahilainen, 2017) and reduced periods of winter ice cover (Lei *et al.*, 2012). Cold-water adapted species may become rare or even lost in the south of Finland (Lappalainen and Lehtonen, 1997). At a national level, fish communities will undergo a homogenization, as northern lakes become more like their southern counterparts. This is likely to have implications for fisheries as many of the cool- and warm-water species are of considerably lower value than cold-water species both economically and in terms of preference for consumption (especially cyprinids). As Finnish waters warm, they may become increasingly at risk to invasion by non-native fishes, with unknown consequences for inland fisheries (Rolls, Hayden and Kahilainen, 2017; Walther *et al.*, 2009). Further biotic and abiotic effects of future climate change on Finnish inland fisheries include possible increases in parasite transmission (Lõhmus and Björklund, 2015; Marcogliese, 2001), which may affect fish population dynamics and even the quality of the catch (Tolonen, Rita and Peltonen, 2000).

Climate change will mean that future inland fisheries in Finland will likely be more productive than they are currently, but will be quite different to those of today. The ecological knowledge held by fishing communities, and the gears they currently use may not be as relevant in the future (Ford, Smit and Wandel, 2006). There will be a need for adaptive fisheries management to allow successful adaptation to climate change in Finland (Brander, 2007), as the impacts of climate change on Finnish fishing communities are likely to be as fundamental as the loss of fisheries for migratory Atlantic salmon seen across newly regulated rivers in the twentieth century (Autti and Karjalainen, 2012).

19.7 LOWER MEKONG RIVER BASIN

The Mekong basin has a total area of about 800 000 km^2 and is the 22nd largest river basin in the world. Its catchment is comprised of China (21 percent of total catchment), Myanmar (3 percent), the Lao People's Democratic Republic (25 percent), Thailand (23 percent), Cambodia (20 percent) and Viet Nam (8 percent).

The hydrology of the Mekong River basin is characterized by marked and predictable seasonality. The annual monsoon results in a single annual peak in flow, which sees a 20-fold increase in discharge. The dry season discharge is about 30 times less than monsoon season and coincides with maximum demand for water for production of irrigated rice. The inflow from left bank tributaries (the Lao People's Democratic Republic) of the Mekong provides the bulk of the wet season peak discharge and the floods that characterize the system. Some all year round flow is derived from snowmelt from the Tibetan plateau.

Wetland and floodplain habitats extend across about 185 000 km^2 in the lower Mekong basin and include the Tonle Sap system, one of the world's greatest inland fisheries. The Mekong River basin is a biodiversity hotspot for fish, birds, molluscs and plants, and includes between 780 and 900 fish species.

19.7.1 Drivers and threats to the inland fisheries of the lower Mekong River basin

A rapid increase in population over the past 50 years is associated with increased exploitation of the fisheries, extraction of water for agriculture and habitat modification. This development of a largely agricultural population has led to accelerated land use change with deforestation and development of reservoirs and irrigation systems for agriculture and plantations. These can affect fisheries by degrading habitats, increasing siltation and inputs of agricultural chemicals including fertilizers and pesticides (Meynell, 2017).

Water demands from agriculture impact the water supply for fisheries, and extraction of water from the Mekong River is considered to have the largest hydrological impact on the Mekong River system. There are about 25 000 small irrigation reservoirs in the lower Mekong basin region and there has been an estimated 78 percent conversion of original wetland habitat; mainly for rice cultivation.

The loss of connectivity in river and floodplain systems through the construction of dykes as flood defences, all-weather roads, river training and channel modification all have impacts on fisheries. The basin also includes more than 370 constructed hydropower or multipurpose dams. There are approximately 100 more dams that are either under construction or planned throughout the basin. Further dam construction and regulation of flow will see a reduction in the duration and impact of the dry season, and reduction in flooding associated with the wet season.

19.7.2 The inland fisheries of the lower Mekong River basin

Mekong basin is home to some of the world's poorest people. Rural dwellers are heavily dependent on inland fisheries and for the poorest, fishing may be the main source of food and income throughout the year. Estimates of the number of inland fishers range between 7.6 million and 20 million. Estimates of the total catch of the fishery range between 1.2 million and 2.6 million tonnes per year.

This is probably the largest subsistence inland fishery in the world and in parts of the basin, per capita consumption of fish can be up to 50 kg/yr, providing up to 80 percent of animal protein in the diet. Non-fish aquatic species can make significant contributions (about 25 percent) to catch (Hortle, 2009). The annual value of the wild-capture fisheries in the lower Mekong basin is estimated at approximately USD 11 billion (2015). There has been a systematic expansion of fisheries associated with increasing population density, with a concomitant increase in the use of modern fishing gear (Hortle, 2009).

19.7.3 Climate change and future trend in the lower Mekong basin

Climate change is recognized as a major issue for the lower Mekong basin (MRC, 2009, 2010) but possibly less controversial than that of water management. In terms of impacts on fisheries, Allison *et al.* (2009) identified Cambodia's economy as the 30th most vulnerable to climate change impact on fisheries, reflecting the very high (about 50 percent) per capita reliance on fish as a source of protein (Baran, 2010). The basin is included in the IPCC AR5 as a case study (Hijioka *et al.*, 2014). Those authors state that over the past 30 to 50 years in the lower Mekong basin, there is evidence of increases in air temperature, that rainfall in the wet season has increased, but decreased in the dry season (Hijioka *et al.*, 2014). They also note an intensification in flood and drought events, as well as sea level rise in the Mekong Delta. Apart from this, there is little published work on observed changes in climate in the lower Mekong basin, reflecting the remote nature of the basin and the political situation over the last century.

United Nations Development Programme Climate Change Country Profiles (McSweeney *et al.*, 2010) are available for Cambodia and Viet Nam. These show that mean annual air temperatures have increased between 1960 and 2003 (Cambodia: +0.8 °C; Viet Nam: +0.4 °C). The frequency of hot days (Cambodia: +46; Viet Nam: +29) and nights (Cambodia: +63; Viet Nam: +49) per year increased over the same period. There was no measurable change in precipitation in either country. Although Thoeun (2015) observed an increase in temperature over the period 1950 to 2002 for Cambodia (0.8 °C), they also reported a small reduction of 0.18 percent per year in precipitation. Zhang *et al.* (2007) examined changes in water temperature differences between the upper and lower parts of the basin over time. On average, lower basin temperatures are higher (wet season: +2 °C; dry season +5 °C) reflecting differences in latitude and altitude. However, Zhang *et al.* (2007) suggested that the differences between the upper and lower catchment lessened between 1985 and 2000 in both wet and dry seasons.

A series of assessments of future climate change in the region have been conducted in the primary literature (McSweeney *et al.*, 2010; Nijssen *et al.*, 2001; van Vliet *et al.*, 2013) and as reports published by the Mekong River Commission (MRC) (Hoanh *et al.*, 2010; MRC, 2009, 2010) or other international agencies (Eastham *et al.*, 2008; ICEM, 2012, 2013; IRG, 2010) including summaries by the IPCC (Hijioka *et al.*, 2014). Results of predictive modelling suggest that at a basin level, climate change will affect the Mekong River by reducing the dry season discharge from the Tibetan Plateau, and also by strengthening the southwest Monsoon that drives the annual floods. The MRC estimate that by 2050, air temperatures will increase by +0.8 °C in the lower Mekong basin, but that increases will be greater in the colder northern parts of the basin at +0.9 °C (Hoanh *et al.*, 2010). Precipitation at the whole basin scale is predicted to increase by 13.5 percent (+200 mm) in the wet season. Dry season precipitation is predicted to increase in both parts of the basin (upper by 28 percent; lower by 2.6 percent). Hoanh *et al.* (2010) suggest that these changes will result in an increase of 21 percent in total annual run-off and will result in increased flooding in the basin, with greatest impacts seen in downstream catchments of the main-stream of the Mekong River.

In an independent study comparing several major rivers, van Vliet *et al.* (2013) estimated that a basin level, average discharge in the whole lower Mekong River basin is predicted to increase by three percent by the end of the twenty-first century relative to 1971 to 2000. High flow is predicted to increase by seven percent, which given the volume of water in the system at peak discharge, means this may have significant impacts on conditions in the main channel and the extent of flooding. Low flows are predicted to decrease by 22 percent. In the same study, they predicted that changes in water temperatures would be relatively minor, 0.9 °C, for both mean and high (95th percentile) forecast temperatures. Palmer *et al.* (2008) estimated that by 2050 mean annual discharge in the Mekong River would decrease very slightly, by one percent, under the A2 emissions scenario.

19.7.4 Implications for fisheries in the lower Mekong basin

The Mekong system has evolved against a background of extremely predictable annual floods (Adamson *et al.*, 2009), and even minor shifts in low flows or the timing of the wet season may affect the ecology of the river and the ecosystem services it provides to humans, including inland fisheries. The projected increases in flow during the wet season shown by both studies will likely result in increased flooding, e.g. in Tonle Sap. This will potentially be a positive for fish, expanding spawning, nursery and growth habitat, with likely positive effects for the fishery. Extreme flooding, however, may be catastrophic for human populations.

The projected reductions in flow during the dry season (van Vliet *et al.*, 2013) are of concern, as they will extend the period spent by fish in refuge pools, and the severity of conditions in the pools (Ficke, Myrick and Hansen, 2007). Any reductions in dry season precipitation will also lead to increased demands for water for irrigated rice, which grows during the dry season (Pech, 2013).

In many of the world's main inland fisheries, future population increase represents a major threat to the long-term management of inland fisheries. In the lower Mekong basin, the picture is less clear because projected population changes differ between countries (United Nations Population Division, 2017). At a national level, Thailand is projected to see a five percent reduction by mid-century, while populations in Viet Nam (+20 percent), the Lao People's Democratic Republic (+34 percent) and Cambodia (+38 percent) are set to increase considerably (United Nations Population Division, 2017). The development of urban areas close to key fisheries like the Tonle Sap system may represent a potential threat (Campbell, Say and Beardall, 2009).

Xing (2013) highlighted five major potential land-use changes that are likely to affect the lower Mekong River basin (and its fisheries) up to 2050: the expansion of mainstem dams, water diversion, expansion of large-scale rubber plantations and transnational transport infrastructure. They predicted that about 2.3 million ha of forest will be converted to plantations, irrigation will be extended to 851 000 ha of farmland and 12 000 ha of riparian farmland will become permanently flooded following dam construction. They also note that as infrastructure develops, it is likely that urban areas will expand. They foresee a future where natural landscapes in the region will be fragmented by human-made landscapes such as dams, mines, plantations and transport infrastructure.

Climate change will likely result in an increase in rainfall during the growing season for several key crops (rain fed rice, upland rice, sugarcane, and maize) across much of the lower Mekong River basin, even in the dry season (Eastham *et al.*, 2008). However, climate change is predicted to result in higher evaporation rates and reduced growing season rainfall across most of the lower Mekong basin region. As such, water requirements for irrigated rice (grown during the dry season) will increase (Eastham *et al.*, 2008), with obvious implications for fisheries. Increased future reliance on pump-irrigation may result in reduced natural fish production in rice fields because of decreased inputs of fish eggs and larvae relative to those provided by flood irrigation.

Climate change will increase vulnerability to poverty and food insecurity in the lower Mekong River basin, and the area is considered as one of the world's most vulnerable regions to climate change (IRG, 2010), especially because of its importance as a rice growing region and the risk of extreme weather events such as drought and flooding.

Climate change is expected to affect air and water temperatures, precipitation, agricultural yields and practices and the volume and flow of the river, affecting the fish and other taxa that support one of the world's largest inland fisheries that, in turn, plays a major role in the nutrition of the population of the lower Mekong basin. The MRC Council study projected that drier conditions in the lower Mekong basin would reduce fish yields by at least 15 percent. Modelling results indicate that the impact of 78 proposed tributary dams would further reduce the biomass of migratory fishes by 19 percent (Barlow *et al.*, 2008; Ziv *et al.* (2012). Furthermore, given the importance of fish protein to human populations in the lower Mekong basin, the loss of fish through construction of dams means that an additional 6 percent to 17 percent of water and 19 percent to 63 percent of land will be required to raise livestock to replace the protein previously supplied by the fishery (Orr *et al.*, 2012), without considering the reduction in health benefits compared to the consumption of fish.

This will require the formulation of adaptation strategies that work both in individual countries and across the region (MRC, 2009, 2014b). However, it is likely that the direct effects of climate change on inland fisheries in the region, at least by the end of the twenty-first century, will be secondary to more pressing direct human impacts, including dam building (which impacts flow regulation and creates barriers to fish migration) and agricultural development (affecting water extraction and leading to habitat degradation). It is important that policymakers in the region fully recognize the crucial role of fisheries in maintaining food security in the region (Orr *et al.*, 2012).

19.8 AFRICAN GREAT LAKES SUBREGION

The Great Lakes Region of Africa encompasses parts of Burundi, Kenya, Malawi, Rwanda, the United Republic of Tanzania and Uganda and includes several of the world's largest lakes, as well as numerous smaller lakes. The region also includes several significant river and wetland systems (including seasonal floodplains), and some reservoirs that provide important inland fisheries. The region is recognized as a centre of fish diversity. However, several of the indigenous species, such as the Nile perch (*Lates niloticus*), Nile tilapia (*Oreochromis niloticus*) and the small pelagic Tanganyika lake sardine (*Limnothrissa miodon*) have been introduced in water bodies outside of their natural range, and now make major contributions to the region's fisheries, that are of global significance.

19.8.1 Drivers and threats to inland fishery resources in the African Great Lakes subregion

The human population of Africa is growing at an average rate of approximately 2.5 percent per annum (Marshall, 2016) but the rate is notably higher in landlocked countries that are particularly reliant on inland fisheries as a protein source. The populations of the countries of the Great Lakes region are predicted to undergo considerable increases in the next three decades (median increase 2017 to 2050 of 130.5 percent). These changes will see increased population densities across the region greatly increasing demands on water and land for living space, food supply, industrial development and power generation, with subsequent detrimental effects on water quality and fish stocks. Although most people live in rural areas, there are several large urban (Lake Victoria) and industrial (Lake Tanganyika) areas located close to the lakes that have marked effects on water quality through the discharge of untreated sewage or pollutants. However, urban dwellers also rely on rural ecosystem services for their water and food supply, electricity, heating and cooking fuel, further impacting freshwater systems (Seimon, Ingram and Watson, 2012).

Human activities in the region threaten the long-term health of the region's freshwaters as a result of many factors including over-exploitation of fish, introduction of aquatic and terrestrial exotic species, river regulation, siltation (arising from deforestation), habitat degradation, eutrophication, industrial and agricultural pollution and over-extraction of water (Odada *et al.*, 2003). Some of these impacts have led to rapid changes to the lakes themselves (Marshall, 2016), as well as rivers, highlighted by reduced spawning success in some important migratory fishes (Tweddle, 1992). Water extraction and diversion has been a particular issue in Lake Turkana (Odada *et al.*, 2003).

Sáenz *et al.* (2012) noted the presence of more than ten large hydropower dams in the region (95 percent of electricity in Malawi is from hydropower). According to the global dam database there are more than 40 dams in the region. Although there are indications that dams have negative effects on fisheries (Odada *et al.*, 2003), their overall number and hence impact is relatively limited, compared to other regions with major inland fisheries where riverine fisheries have been seriously impacted by water regulation.

The development of fisheries in the African Great Lakes has coincided with large and negative shifts in many key stocks (Odada *et al.*, 2003). Apparent declines in both fish yield and diversity (Ainsworth and Cowx, forthcoming), and average size of key target species (Marshall, 2016) are likely the result of over-exploitation and size-selective fishing. However, the change in fishing methods (Sarvala *et al.*, 2005) and target species (e.g. development of fisheries for small pelagic species), makes it difficult to associate changes in fish stocks with overfishing or other factors such as climate change, pollution, changes in lake level and invasive species (Niang *et al.*, 2014).

19.8.2 Inland fisheries in the African Great Lakes subregion

Fisheries have taken place in the region for at least 90 000 years (Yellen *et al.*, 1995), and demand for fish is high in the region. According to FAO (forthcoming), 1 053 694 tonnes was landed from inland fisheries in the region in 2015, equivalent to nine percent of global production from inland fisheries. Ainsworth and Cowx (forthcoming) estimated catches in the region at 1 426 893 tonnes, but noted that this was likely an overestimate. The fishery is based on a range of native species including small pelagic species, cichlids, catfishes, cyprinids and characiforms (Marshall, 2016).

Marshall (2016) suggested that Lake Victoria is probably the world's largest inland fishery providing food for eight million people along its shores, while more than one million people rely on the fisheries of Lake Tanganyika (FAO, forthcoming). Ainsworth and Cowx (forthcoming) estimated that 258 000 people are directly involved in fisheries in the region, and larger numbers of people (probably mainly women) are working along the whole value chain. There are also significant fisheries for ornamentals in Lakes Malawi and Tanganyika (Odada *et al.*, 2003).

19.8.3 The climate and future trend of the African Great Lakes subregion

The climate of the African Great Lakes region reflects its geography, and climate varies locally driven by variation in topography, latitude and altitude, and has driven patterns in biodiversity and human activities in the region. Climate seasonality and the amount and timing of precipitation in the wider region is a function of the Intertropical Convergence Zone. The northern and southern parts of the region encounter a single wet season phased six months apart each year, while the areas between them experience two distinct wet seasons, i.e. the so called “long rains” (March to May) and “short rains” (September to November) (Seimon, Ingram and Watson, 2012), with an area of Kenya encountering a third wet season (Odada *et al.*, 2003). In addition, local precipitation patterns are extremely complex, and vary between years, driven both by landforms and land-cover, as well as variation in sea surface temperatures in the Indian, Atlantic and Pacific Oceans, with the El Niño Southern Oscillation (ENSO) and the more local Indian Ocean Dipole (IOD) combining to drive climate variability in the region (Seimon, Ingram and Watson, 2012). Temperature in the region varies largely as a function of elevation, but given the volume of the Great Lakes themselves, there can be a strong lake effect on local temperatures.

Differences in catchment geometry and hydrology, and regional differences in rainfall seasonality, cause individual lake basins to respond differently to climatic variation (Seimon, Ingram and Watson, 2012). The larger lakes (e.g. Victoria, Malawi and Tanganyika) are largely fed by rain falling directly on the lake surface, with losses via evaporation, while, for example, Turkana relies on riverine inputs to maintain water levels (Odada *et al.*, 2003). Wetland and river floodplain fisheries vary widely in scope depending on water levels (FAO, forthcoming). Climate data summaries are available for several of the countries in the region[3] (McSweeney *et al.*, 2010).

The African Great Lakes region has experienced warming of both air (Funk, Michaelsen and Marshall, 2012) and water temperatures (Tierney *et al.*, 2010, Vollmer *et al.*, 2005) over the last 50 to 100 years, and evidence strongly suggests that this is consistent with anthropogenic climate change (Niang *et al.*, 2014; Seimon, Ingram and Watson, 2012). Multiple lines of evidence indicate that precipitation has decreased over the last three decades across the region (Funk, Michaelsen and Marshall, 2012; Niang *et al.*, 2014; Seimon, Ingram and Watson, 2012; Tierney, Ummenhofer and deMenocal, 2015). During the last 30 to 60 years, extreme precipitation events (e.g. droughts, heavy rainfall) have increased in the region (Niang *et al.*, 2014).

Future trends in the climate of the African Great Lakes region will reflect variation in three components: 1) secular (anthropogenic greenhouse gas emissions); 2) changes in large-scale atmospheric-oceanic circulation patterns (ENSO, IOD); and 3) changes in land use, all of which are significant drivers of climatic change at a local level and have a large aggregate effect at a regional level (Seimon, Ingram and Watson, 2012). The recent IPCC 5AR provided a summary of predictions of future climate indicating that warming will occur faster in Africa than for the globe as a whole, and it is likely that, even under relatively low impact emissions scenarios, air temperatures will increase by more than 2 °C by the middle and end of the twenty-first century (Niang *et al.*, 2014) in the Great Lakes region.

Predictions for precipitation are more uncertain, but increased precipitation is predicted for the African Great Lakes Region in the mid-twenty-first century under a range of scenarios with more intense wet seasons and less severe droughts (Niang

[3] http://www.geog.ox.ac.uk/research/climate/projects/undp-cp/

et al., 2014). However, this forecast does not extend to the whole region, and some predictions indicate that precipitation will decline in some parts of Uganda, Kenya and the United Republic of Tanzania (Niang *et al.*, 2014) and some authors suggest that drying will be very marked in the region (Tierney, Ummenhofer and deMenocal, 2015).

19.8.4 Impacts on inland fisheries in the Great Lakes subregion

Climate change has been reported to have had marked effects on fisheries productivity in the region, and represents a key case study used by the IPCC to demonstrate the observed effects of climate change on ecosystem services. Here climate change was identified as a causal factor (O'Reilly *et al.*, 2003), driving an approximately 30 percent reduction in fisheries production in Lake Tanganyika. O'Reilly *et al.* (2003) reported that the increased temperatures and reduced wind velocity had weakened lake mixing, with a subsequent reduction in nutrient availability. However, Sarvala *et al.* (2005) suggested that the decline in catch likely reflects changes in the fishery and challenge the link with climate change.

The greatest threat to fisheries and the supply of fishery products in the region is likely to be changes in human populations, a threat that will interact with the effect of climate change.

As pressures increase to improve the supply of food (Funk *et al.*, 2008), agricultural development will likely result in large-scale land-use changes, including intensified deforestation at higher altitudes and the use of river floodplain habitats for agriculture such as rice and biomass fuel crops (Marshall 2016). This will in turn have impacts on basin hydrology (run-off, evapotranspiration) and water quality (sedimentation, agricultural chemicals, eutrophication), affecting the climatic, physico-chemical and biological characteristics of the region's inland waters and their capacity to maintain food security. Water stress is currently limited in most of the region (Gassert *et al.*, 2013), but where it does occur it is typically the costs rather than a physical lack that limit access to suitable volumes of water. Future population increases, combined with some aspects of climate change will likely result in water stress increasing greatly across the region (Vörösmarty *et al.*, 2000, 2010), with likely subsequent impacts on inland waters and their fisheries.

19.9 LA PLATA RIVER BASIN

The La Plata River flows for about 4 850 km and the basin is the fourth largest in the world. It is formed by three sub-basins: the Paraná, Paraguay and the Uruguay River basins and occupies most of central-southern South America (3 million km^2) across five countries: Bolivia (Plurinational State of) (7 percent), Brazil (46 percent), Paraguay (13 percent), Argentina (30 percent) and Uruguay (5 percent). The La Plata River flows through a variety of different ecosystems including upland streams, main stem, floodplain, oxbow lakes, storage reservoirs, wetland and delta habitats, which are reflected in the large fish diversity with approximately 920 species, of which 444 (48 percent) are endemic and four are introduced (Reis *et al.*, 2016). The Pantanal wetlands, in the upper Paraguay River, is one of the largest (140 000 km^2 to 300 000 km^2) freshwater wetlands in the world and crucial for regulating the hydrology of the system (Coronel and Menéndez, 2006). Other key ecosystems include the Chaco, an arid area drained by several rivers, Yungas forest, the Pampas, the Cerrado, the forested Mata Atlantica, and the internal delta of the Parana in Argentina, with an area of about 15 000 km^2.

19.9.1 Drivers and threats to the La Plata River basin inland fishery

More than 110 million people inhabit the La Plata River basin, and it accounts for about 70 percent of the regions GDP, producing much of the region's food, energy and exports. The population density is relatively low with 35 individuals per km^2. However, some of the largest urban and industrial centres in South America are located within the basin, including the capitals of Argentina, Brazil, Paraguay and Uruguay, with high demands for water and marked impact on water quality. The average predicted increase in population for the five basin countries is 23 percent by 2050 (United Nations Population Division, 2017). Urbanization is a major driver of change, and in the last half of the twentieth century, the proportion of urban dwellers rose from 45 percent to almost 90 percent (World Water Assessment Programme, 2009).

Agriculture and mining are important activities. Cattle ranching has changed from being a seasonal to a permanent activity increasing organic pollution and habitat deterioration, and the forestry sector is being developed by draining wetlands (Baigún *et al.*, 2008). There were approximately 75 dams in place in 2012, mostly for hydropower generation (FAO, 2016c), but also for water storage and flood defence. Hydropower is responsible for about 75 percent of all power generation in the region (Palomino Cuya *et al.*, 2013), and all five countries are strongly reliant on the availability of water. The catch of potamodromous fish now frequently declines to well below 50 percent of the total catch. Fisheries mostly take place in reservoirs where they target non-migratory smaller species with short lifespans and low commercial value; and non-native species have become important for both commercial and recreational fisheries. River regulation and fragmentation is not uniform across the basin: some areas such as the Pantanal wetlands, lower Paraná and La Plata rivers still support large floodplains and wetlands and have undisrupted main channels (Barletta *et al.*, 2016), making sediment of Andean origin available for essential nutrient loading in the lower Paraguay and the middle Paraná River. In the less developed riverine axis Paraguay–middle Parana–Rio de la Plata, large migratory fish remain present in the catch (Quirós, 2004).

Boat transportation is an important means of communication in the La Plata River basin, and a Paraguay-Paraná-Uruguay waterway (the *Hidrovía*) has been proposed to speed up movements of goods and people throughout the region. However, the project has been associated with a range of potential negative impacts on the basin ecosystem.

In the Paraná Delta, overfishing has produced marked changes in fish stocks and fish assemblages. The abundance of piscivores is in decline, and the size of the migratory stock and the mean individual length of most important commercial species are decreasing too. A further threat to inland fisheries in the basin is the introduction of non-native species (*Oreochromis niloticus, Cyprinus carpio, Colossoma macropomum, Cichla* spp., *Micropterus salmoides*) for aquaculture and recreational purposes through official stocking programmes and illegal activities (Barletta *et al.*, 2016).

A shift to recreational fishing tourism in Brazil and Argentina that started in the 1980s, with, for example strong restrictions on artisanal fisheries in the Brazilian Pantanal, resulted in a downturn in professional fishing. In 2012, 37 percent of the registered 345 000 sport fishers in Brazil declared a preference for fishing in the Pantanal region (Barletta *et al.*, 2016).

19.9.2 Inland fisheries in the La Plata basin

The La Plata basin fisheries can be grouped into subsistence, recreational, commercial and industrial sectors. Most of them are multi-species, highly seasonal, and use diverse gears. Both artisanal and recreational fisheries are mostly supported by large characiforms (Bryconidae, Anostomidae, Prochilodontidae) and catfishes (Pimelodidae, Doradidae) undertaking potamodromous migratory movements upstream for spawning during spring and summer and downstream to the lower areas (Pantanal floodplain, lower Paraná, lower Uruguay and La Plata rivers) for feeding.

Reviews of the fishery are provided by Quirós (2004) and Barletta *et al.* (2016). Quirós (2004) suggested that fishing pressure is relatively low in the La Plata basin compared to other tropical and subtropical floodplain fisheries, which may partially explain the low productivity. With a mean per capita consumption of 10 kg per year, fish play a moderate role in the diet of people in the basin (Ainsworth and Cowx, forthcoming). Quirós (2004) estimated that some 60 000 tonnes/yr of fish (mainly the detritivorous *Prochilodus*) are captured in the middle Parana, much of which is for export. In the early 2000s, about 40 000 families relied on fish either as subsistence or commercial fishers in the Paraná River catchment, Argentina (World Water Assessment Programme, 2009).

19.9.3 The climate and future trend in the La Plata basin

The climate of the La Plata basin is very variable, both regionally and seasonally, reflecting the geographical variation found in the basin. Regional variation in climate is largely driven by differences in precipitation, and to a lesser degree by temperature (Caffera and Berbery, 2006). Climatic conditions include tropical areas at the sources of the Paraná and Paraguay Rivers (mean air temperature of 25 °C to 30 °C), subtropical in parts of Argentina, Brazil and Paraguay (20 °C to 25 °C), warm temperate in parts of Argentina and Uruguay (15 °C) and arid, high altitude areas in the Plurinational State of Bolivia sub-Andean region (5 °C to 15 °C)[4].

At a whole basin level, mean precipitation is 1 100 mm/yr, of which only approximately 20 percent reaches the sea as surface water (FAO, 2016c; Mechoso *et al.*, 2001). Mean annual precipitation decreases from north to south, and from east to west, and there is a notable decrease in the amplitude of the annual precipitation cycle from north to south. In the northern part of the basin, there is a well-defined annual cycle with maximum precipitation during summer (December to February). The central region (Northeast Argentina/Southern Brazil) has a more uniform seasonal distribution, with maxima during spring and autumn. Given that the major rivers in the basin run from north to south, this rainfall regime contributes to the attenuation of the seasonal flooding cycle downstream (Caffera and Berbery, 2006). The La Plata basin has undergone periods of markedly high and low precipitation associated with ENSO, resulting in historical high and low flows with significant ecological and socio-economic impacts throughout the basin (Berbery and Barros, 2002; Coronel and Menéndez, 2006).

The most obvious recent climatic change observed in the La Plata basin has been large increases in precipitation and in the frequency of heavy rainfall (Báez, 2006; Barros, Clarke and Silva Dias, eds., 2006; IPCC, 2014a). This has led to increased runoff (+10 percent to +20 percent) and increased discharge in the basin in the second half of the twentieth century (IPCC, 2014a). Báez (2006) examined data from nine stations from the centre and west of the basin in Paraguay and Argentina, collected from various points between 1951 and 2001 (record period differed by station). Across these locations, there was a mean positive trend in air temperature of +0.12 °C/ decade. During the same time, evapotranspiration increased by 27.2 mm/decade and precipitation increased by 53 mm/decade (Báez, 2006).

Marengo *et al.* (2012) using the A1B scenario, predicted an increase in mean annual air temperature of +2.5 °C to +3.5 °C by the year 2100, and a +20 percent increase in precipitation across the La Plata basin by the year 2100. They also predicted that this would result in a +10 percent to +20 percent increase in runoff. Palmer *et al.* (2008) estimated that by 2050 mean annual discharge in the La Plata River would increase by +6.2 percent under the A2 emissions scenario. Cabré, Solman and Nuñez (2010) predicted that by 2050, daily precipitation would increase by +0.5 mm/day to 1.5 mm/day; and that air temperature would be +1.5 °C to +2.5 °C warmer than today. Using the intermediate RCP4.5 scenario, Mourão, Chou and Marengo (2016) recently predicted that mean precipitation at a whole basin level will fall relative to present

[4] http://hypeweb.smhi.se/laplatahype/long-term-means/)

conditions during summer, but by the end of the twenty-first century, precipitation will increase in the winter. They further predicted that mean air temperatures across the basin would increase from current values by +3 °C in 2011 to 2040, +3.5 °C in 2041 to 2070, and +4 °C in 2071 to 2099.

Climate predictions are available for the La Plata basin via the HypeWeb project[5]. These show the potential impacts of climate change on water resources based on a modelling chain, where different climate change scenarios (RCP4.5 and RCP8.5) are projected through a global climate model, a regional climate model, a bias correction method, and the HYPE hydrological model applied on the La Plata basin. These suggest that under the RCP4.5 scenario, by the 2080s mean annual temperatures will increase by about 1 °C relative to 1981 to 2010 in the south of the basin and by about 2 °C in the north of the basin. Under the RCP8.5 scenario, the extent of warming increases, with a predicted increase of 5 °C to 6 °C in the northwest of the basin, decreasing to an increase of 1 °C to 2 °C around the La Plata estuary. Projections for precipitation under the RCP4.5 scenario show a marked regional difference, with increases ranging from one percent to 50 percent to 100 percent relative to 1981 to 2010 in the north of the La Plata River basin and decreases from -5 percent to -50 percent in the south of the basin. This pattern is repeated under the RCP8.5 scenario, but includes more heterogeneity across the basin and an area of reduced precipitation in the northeast of the basin. These patterns are paralleled by projections for river discharge, which under both scenarios show marked increases in the north of the basin, and reductions in the south.

19.9.4 Impacts on fisheries in the La Plata basin

The largest likely future impacts on the fishery will probably be a result of river regulation and increased agricultural, urban and industrial development and associated changes in human populations. However, these factors will interact with climate change in a way that will affect inland fishery production.

As seen in other basins, increased temperatures will reduce the suitability of low-oxygen habitats for the more sensitive species, but for those species that can withstand the increase in temperature, growth may increase, potentially increasing yields.

If precipitation increases (as predicted in the majority of climate models produced to date) and discharge also increases, connectivity between habitats and the scale of fisheries-relevant habitats may increase, resulting in improved recruitment, production and fish yield. Increased availability of water will also provide the opportunity to reduce flood pulse disruptions by incorporating hydro-ecological criteria in dam regulation programmes (Baigún *et al.*, 2008), which may help to minimize the impacts of at least some increases in temperature and would likely result in increased fish production. Conversely, if precipitation is reduced under future climatic conditions, we can expect an intensification of the ecological impacts associated with recent drought conditions (e.g. 2008), especially if demands for water from other sectors increase, as expected. This will most likely result in a marked reduction of the fisheries potential of the La Plata basin over the long-term and will require careful management.

Given the existence of a positive relationship between discharge and catch of *Prochilodus lineatus*, an important fisheries resource, in the Pilcomayo River, a tributary of the Paraguay River (Smolders *et al.*, 2000; Stassen *et al.*, 2010), climate change is very likely to have impacts on the inland fishery, and its capacity to support food security and the provision of jobs and income in the region.

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[5] http://hypeweb.smhi.se/laplatahype/climate-change/

19.10 AMAZON RIVER BASIN

The Amazon River basin is the world's largest catchment (6.8 million km^2) encompassing parts of the Plurinational State of Bolivia (11.2 percent), Brazil (67.8 percent), Colombia (5.5 percent), Ecuador (1.7 percent), Guyana (0.1 percent), Peru (13 percent), and the Bolivarian Republic of Venezuela (0.7 percent). The river is 6 400 km long, and has a discharge of 210 000 m^3/s to 219 000 m^3/s, surpassing the combined discharge of the next nine largest rivers.

The climate in the central basin is hot and humid and the mean annual temperature is 26.6 °C. Annual precipitation is 5 000 mm/yr in the Andean foothills, where the river rises. The central basin receives 2 500 mm/yr, falling on a flat landscape creating a large network of freshwater habitats that may represent up to approximately 30 percent of the total surface area of the basin. Precipitation falls to 1 000 mm/yr to 1 500 mm/yr in the archaic shields, formed by the northern (Guyanas) and southern (Central Brazil) uplands of the central basin, and the contrast between the dry and wet seasons becomes more pronounced. The principal source of rain is via the Western Atlantic, and 65 percent is lost to evapotranspiration.

The region is a biodiversity hotspot and much of the basin remains in near-natural conditions because of the low densities of resident human populations. Approximately 2 500 fish species have been described from the Amazon basin, of which 45 percent are endemic, and it is estimated that more than 1 000 new fish species remain to be discovered. Half of the species occur in large rivers and their floodplains, while the remainder live in small tributaries, where endemism is very high because of geographic isolation.

The basin contains a wide diversity of habitats including permanently or seasonally flooded areas such as rivers, streams, lakes, floodplains, marshes and swamps, representing between 14 percent and 29 percent of the total basin. The Amazon River and its large tributaries exhibit predictable monomodal flood pulses in response to dry and rainy seasons, and there are considerable fluctuations in water level (6 m to 12 m). Amazonian large-river wetlands are classified by water colour (white waters, black waters, and clear waters) which reflect varying sediment and nutrient loads, which in turn reflect catchment geology and hydrology, and drive differences in productivity. The basin provides a wide range of valuable ecosystem services to human populations, and many people in the basin rely on freshwater for transport, drinking water and resource extraction, including fish.

19.10.1 Drivers and threats to the fisheries of the Amazon River basin

Amazonian freshwater ecosystems are subject to escalating impacts from: increasing levels of deforestation, pollution, dam construction, river regulation, mining and overharvesting of animal and plant species, all of which threatens their capacity to provide important goods and services.

Population density is currently low in the Amazon basin, although the population for the Amazonian nations is expected to increase by a mean of up to 24 percent by 2050. The loss of habitat to pastures and croplands is thus expected to continue in the near future. One of the most serious threats to freshwater habitats (and therefore fisheries) is the large-scale transformation of natural vegetation by increasingly agrarian populations on the slopes of the Andean hills, and by agro-industries (palm oil and soybean) in the Amazon lowlands. Many headwaters are heavily stressed by the degradation of riparian and in-stream habitats caused by deforestation, cattle trampling and stream regulation. Illegal logging increasingly damages the habitat quality of rain forest streams and threatens the stocks of fruit-eating fish species that move into flooded forests during the wet season.

In the Amazon basin there are currently 142 dams in operation or under construction and at least 160 new dams have been proposed (Anderson *et al.*, 2018). Major environmental changes related to hydropower expansion in the basin may negatively affect some preferred commercial fish species, disproportionately affecting fisheries and food security in fishing villages and even in major cities. Impacts of these dams would extend well beyond direct effects on rivers to include forced relocation of human populations and expanding deforestation associated with new roads. Large dams on the Xingu River and in the Madeira River are likely to affect fisheries that rely heavily on migratory fishes, such as Matrincha (*Brycon* spp.) and Dourada (*Brachyplatystoma rousseauxii*). Dam projects in the southern and eastern portion of the basin are already embedded within the infamous Amazonian "Arc of Deforestation", the aggressively expanding agricultural frontier. The negative synergistic interaction between dam building and development could also drive deforestation and forest fire dynamics, with far-reaching consequences for biodiversity loss and the potential for future regional economic stagnation as river flows decline and power output decreases.

19.10.2 The inland fisheries of the Amazon basin

Fish constitute a key source of protein for the Amazon populations, especially indigenous people, who consume up to 0.4 kg–0.8 kg fish per capita per day (Barletta *et al.*, 2016). The basin currently supports more than 170 000 professional fishers and about 200 000 subsistence fishers, as well as 200 000 indirect jobs related to fisheries. Besides food fisheries, some 150 fish species are used in the ornamental trade employing 10 000 people in Brazil and 3 000 in Peru. Commercial, artisanal and subsistence fisheries focus on about 250 species, in particular migratory species of the orders Characiformes and Siluriformes. Most stocks (70 percent) are considered underexploited, but some larger bodied species with high market value have been over fished. In 1989, Bayley and Petrere Jr. (1989) estimated fisheries yield across the whole basin as approximately 200 000 tonnes per year. They estimated a potential yield of more than 900 000 tonnes per year, indicating that there was considerable scope for increased exploitation. Recreational fishing associated with tourism is an increasingly important source of employment and income and by 1998 it was already estimated that the value of recreational fisheries was more than USD 400 million.

19.10.3 The climate and future trend in the Amazon River basin

The Amazon basin has long been subject to heavy floods and droughts, and Junk (2013) notes that recent occurrences are unlikely to have been a response to climate change. However, a number of observed shifts in climate recorded from the Amazon basin have been associated with climate change (Magrin *et al.*, 2014), including reduced rainfall across the region (-0.32 percent over 28 years), and a delay in the onset of the rainy season by a month between 1976 and 2010. Projected rainfall in central and Eastern Amazonia is expected to decrease by between 20 percent and 30 percent, while in Western Amazonia it is predicted to increase by 20 percent to 30 percent by the end of the twenty-first century.

There are no systematic records showing changes in air temperature, but air temperature in all regions is projected to increase by between 5 °C and 7 °C for both summer and winter by the end of the twenty-first century (Marengo *et al.*, 2012). There is medium confidence that droughts will intensify during the twenty-first century in some seasons and areas as a result of reduced precipitation and/or increased evapotranspiration in the Amazon basin (Magrin *et al.*, 2014).

There is no clear long-term trend in streamflow for the whole Amazon River (Magrin *et al.*, 2014), but discharges are projected to increase by 3.5 percent in the high-water season, but decrease by 9.9 percent in the low-water season (Nakaegawa, Kitoh and Hosaka, 2013; Sorribas *et al.*, 2016). Palmer *et al.* (2008) projected decreases in discharge of 18.6 percent by 2050 under the A2 scenario[6]. These projections conflict with the projected stream flow values for the end of the twenty-first century developed by van Vliet (2013), which suggest an overall increase at mean flow of 21 percent, no significant change at low flows, and an increase of 23 percent at high flows.

The precipitation–evaporation difference in the A1B downscaled scenario (also an IPCC SRES scenario) suggest water deficits and river runoff reductions in the eastern Amazon, making this region susceptible to drier conditions and droughts in the future (Marengo *et al.*, 2012). Mean water temperatures in the main channel are predicted to increase on average by 0.5 °C by the end of the century (van Vliet *et al.*, 2013). These main channel habitats have been considered less important for fisheries production beyond that of piscivorous fishes (Bayley and Petrere Jr., 1989) but the main channel provides a migration corridor for the most important commercial species. Temperature changes in the more productive floodplain habitats are likely to increase by a higher amount, given the projections for air temperatures reported above. This suggests that the impact on fishes and fisheries may be notable, especially to sensitive species or life stages.

The Amazon River basin is especially prone to the ecological impacts of future climate change (Castello and Macedo, 2016). Frederico, Olden and Zuanon (2016) estimated that more than one-third of threatened freshwater fish species in the Amazon, Tocantins and Araguaia river basins may be lost if the most pessimistic scenarios of climate change are realized. As seen above, future predictions suggest that the Amazon will face warmer and dryer conditions, with less predictable rainfall and more extreme events (e.g. droughts and floods) in the future (Magrin *et al.*, 2014). A study combining modelling the impacts of climate with dam hydrological impacts, predicts an 18 percent reduction in discharge for the Amazon basin by the year 2050, however, withdrawals will remain low enough to prevent water stress (Palmer *et al.*, 2008).

19.10.4 Implications for fisheries

Knowledge regarding Amazonian fish communities remains limited, which complicates their management and protection. Despite the clear importance of freshwater fisheries to human populations in the region, especially of indigenous peoples, governments and agencies typically fail to recognize this and to develop strategies and methods for sustainable management of resources (Cooke *et al.*, 2016a; Pelicice *et al.*, 2017).

All Amazonian countries are developing and food security is a major concern especially in rural areas; hence, declining fisheries have serious economic and social consequences. Most of the conservation problems, including those of the main river basins, need to be addressed on a multinational basis, and harmonized management of transboundary waters is a necessity (Barletta *et al.*, 2016; Pelicice *et al.*, 2017), a possible future area for the Amazon Cooperation Treaty Organization to consider.

Large interconnected distribution areas confer upon the fish fauna a certain amount of resilience in the face of local environmental changes. About half of the basin's fish species, however, are restricted to headwaters and small tributaries or specific habitats, such as rapids. This limited distribution makes them very vulnerable to habitat degradation (Junk, 2007), but also reduces their contributions to fishery production at a basin level. However, many of the large-bodied commercial catfishes (*Pimelodidae* spp.) spawn in the headwaters, and some migrate from the estuary to the headwaters of tributaries.

Low concentrations of dissolved oxygen occur naturally in the Amazon basin (Barletta *et al.*, 2016), and many species have evolutionary and behavioural adaptations to cope with these conditions (so called black fish, which are largely fished for subsistence; Welcomme, 1979). However, increased temperatures in shallower waters

[6] One of the higher emission SRES scenarios used for the 3rd and 4th Assessment Reviews of the IPCC.

are expected to lead to stronger and more persistent oxygen depletion in the future, leading to chronic stress for many fish species. Climate change is likely to reduce hydrological connectivity within rivers and this impact on fish dispersal may ultimately determine their ability to respond to deteriorated conditions (Frederico, Olden and Zuanon, 2016).

Climate-induced changes in water quality are considered a greater threat to species persistence than potential changes in water quantity. Expert survey results also suggest that threatened fishes in the basin exhibit high sensitivity to changes in temperature and dissolved oxygen, and moderate to high sensitivity to changes in high-flow (i.e. flood) and low-flow (i.e. drought) regimes (Frederico, Olden and Zuanon, 2016). The estimated sensitivity of species to climate change shows no relationship to their ability to disperse. This indicates that protected areas may serve as important refugia for those species unable to migrate or shift their range as climate change occurs. Despite this, the number and size of protected areas in Brazil have decreased over the past decade, largely to support the exploitation of hydropower and mining. Strategic conservation planning that involves the maintenance of existing and the development of new protected areas for those fish species most at risk from climate change is warranted (Castello *et al.*, 2013; Frederico, Olden and Zuanon, 2016).

Climate-driven shifts in the magnitude, duration and timing of ecologically critical flow events will have direct consequences for the breeding, migration and persistence of fish species in the Amazon River basin. This will be of particular importance for migratory species that rely on habitat connectivity and are among the most fished (Castello *et al.*, 2013; Hallwas and Silvano, 2016).

Two economically important species that responded negatively to severe drought events deserve notice. Silver arowana (*Osteoglossum bicirrhosum*) is valued in both the aquarium trade and as a food fish. Tucunare´ (*Cichla monoculus*) is also commercially important, mainly to the sports fishing industry but also as a locally important food source for riverine communities (Freitas *et al.*, 2013). It is therefore possible that more frequent and/or more pronounced droughts, which are predicted to occur with increased frequency in the future, will degrade the floodplain fisheries, which would exacerbate the negative effects on many exploited species of increasing fishing pressure, and habitat degradation caused by agriculture and hydropower development, (Alho, Reis and Aquino, 2015; Freitas *et al.*, 2013; Pelicice *et al.*, 2017).

As Junk (2013) noted, although climate change will have marked impacts on the Amazon, the principal threats facing the region are human population growth and economic development, and their associated consequences. Human populations in the region are expected to continue to grow in the short-term, albeit at a pace that is closer to potential GDP growth, helped by internal demand as the middle class becomes stronger and as credit becomes increasingly available. As such, in the face of population growth, continued land use change and climate change, there is an urgent need to develop Amazonian resource management, broadening its current forest-centric focus to better encompass the freshwater ecosystems that are vital components of the basin and that feed and employ many people. This is possible by developing a river catchment-based conservation framework for the whole basin that protects both aquatic and terrestrial ecosystems (Castello *et al.*, 2013).

19.11 CONGO RIVER BASIN

The Congo River (4 700 km) is the second longest river in Africa, and the seventh longest in the world. Its basin (3 789 053 km^2), discharge (mean 45 000 m^3/s) and freshwater species diversity are ranked second in the world after the Amazon River (Ainsworth and Cowx, forthcoming; FAO, forthcoming; Harrison, Brummett and Stiassny, 2016). The basin extends across ten different countries (core countries in italics): Angola, Burundi, Cameroon, the *Central African Republic*, the *Democratic*

Republic of the Congo, the *Congo*, *Rwanda*, South Sudan, the United Republic of Tanzania and Zambia. The Congo basin provides about 30 percent of Africa's freshwater resources and supports more than 75 million people (Harrison, Brummett and Stiassny, 2016). The population of the Congo basin relies heavily on freshwater habitats and the associated forests to provide food, energy (hydropower, wood), water and transport. Population density is low but diverse, with over 150 different indigenous groups living in the Congo basin.

The Congo basin is predominately forested, with more than 30 percent of forested area in the Cuvette Centrale region being classified at flooded habitat (Bwangoy *et al.*, 2010), there are also extensive wetlands. The Congo incorporates a large number of different and contrasting ecoregions and habitats (Harrison, Brummett and Stiassny, 2016). These are comprised of the main headwaters (Luapula, Lufira and Lualaba rivers) which drain shallow lakes located in Northeastern Zambia and extensive wetlands. The middle Congo flows through the Cuvette Centrale Congolaise, a 190 000 km^2 wetland and is joined by a series of large rivers. The short lower Congo falls 280 m over a series of cataracts entering the Eastern Atlantic Ocean.

19.11.1 Drivers and threats to the fisheries of the Congo River basin

Political instability and conflict in the region and poor communications have constrained rapid development, and the usual impacts on water and fisheries which accompany this. Open access to the fishery means that changes in political or economic circumstances may result in people opportunistically switching to fishing (Béné *et al.*, 2009). Low population densities mean that over-exploitation of fish stocks in the Congo basin is less of a problem than in other African inland fisheries (Harrison, Brummett and Stiassny, 2016). Fishing impacts are reported in the middle Congo, close to areas of high population density and this is also associated with the use of illegal and harmful fishing practices such as dynamite and fine-meshed nets, which are a threat to fish stocks (Ainsworth and Cowx, forthcoming).

The region is a centre for commercial logging and there are other activities that also result in deforestation and degradation of riparian habitat, including mining, agriculture, clearing of land for human habitation and the felling of trees for charcoal production. A recent switch to oil palm cultivation has spread to the upper Congo (Harrison, Brummett and Stiassny, 2016). These activities as well as human settlements and industry result in increased sediment and pollutant loads to the river. Although major dams do exist in the Congo basin (Harrison, Brummett and Stiassny, 2016), their impacts are considered moderate (Nilsson *et al.*, 2005), suggesting that they do not yet have major impacts on inland fisheries.

19.11.2 The inland fisheries of the Congo River basin

Although there are reports of the importance of fish to the Congo region, there are limited sources of information on these fisheries and there seems a tendency to overlook the role and vulnerability of fisheries with preference given to the forests. Approximately 20 percent of the population living in the forests are involved in fisheries, with 90 percent of the catch coming from artisanal or traditional fisheries, most of which is done part-time or seasonally (Béné *et al.*, 2009). The inland fishery is important, with fish providing almost 50 percent of the animal protein requirement of the population; and up to 65 percent of income in some areas (Béné and Heck, 2005; Béné *et al.*, 2009). Fish may be seasonally important to households during the "lean season" (when food from agricultural production is lowest), because this period coincides with the end of the dry season when rivers are low and fishing conditions improve. Ainsworth and Cowx (forthcoming) suggest that there are more than 1 000 species of fish in the Congo basin, of which approximately 625 are endemic, and nine are introduced. Total reported fishery production of the Congo region (the Republic of the Congo, the Democratic Republic of the Congo and the Central African Republic) is 287 000 tonnes (FAO FishStatJ, 2017), but there are several lines of evidence that suggest that fishery production in the Democratic Republic of the Congo is markedly under-reported (FAO, forthcoming), thus the importance and dependence on fish may be greater than currently acknowledged.

19.11.3 The climate and future trend in the Congo basin

The equatorial Congo basin receives rainfall throughout the year, with a mean annual precipitation between 1 500 mm/yr and 2 000 mm/yr. Between 75 percent and 95 percent of the region's rainfall is generated by local evapotranspiration. Mean annual air temperature is relatively constant (24.9 °C), and the few reliable data that are available indicate that air temperatures have recently increased. Detailed analyses of predicted climate change scenarios for the Congo basin, as well as impacts on temperature, precipitation, and hydrology, and future options for adaptation were recently conducted by the German Climate Service Centre (Haensler *et al.*, eds., 2013), based on low and high emission/concentration scenarios. Results showed that predicted future temperatures for the end of the twenty-first century varied by scenario but were generally uniform across the basin (Haensler, Saeed and Jacob, 2013). Predicted increases by the end of the twenty-first century were between +1.5 °C and +3 °C for lower emission scenarios, rising to +3.5 °C and +6 °C for higher emissions scenarios (Haensler, Saeed and Jacob, 2013). Predicted annual average precipitation levels were similar to contemporary values under low emissions scenarios, and increased by less than ten percent under higher emissions scenarios. However, when predictions were examined at a seasonal level, it became apparent that there are likely to be both regional and seasonal differences in precipitation: central areas of the basin will likely only see changes (increases) in precipitation under the high emissions scenarios. In southern parts of the basin, precipitation is predicted to decrease during the dry season under both low and high emissions scenarios, but these reductions will be most marked under the high emissions scenario. Conversely, in the north of the basin, precipitation levels are predicted to increase during the northern dry season (December to February). Extreme events both in terms of cold and hot days/nights and extreme precipitation events were also modelled. The frequency of cold days and nights is predicted to decrease across the basin, and under all scenarios by about ten percent. Hot days and nights will increase under both low and high scenarios, with a greatest increase under the high scenario (25 percent by the end of the current century). Projected increases are particularly marked in the central part of the basin (50 percent under low and 70 percent under high emissions scenarios). Extreme precipitation events are predicted to increase by up to 25 percent under both scenarios.

Analyses of predicted hydrological changes in the Congo basin (Beyenne, Ludwig and Franssen, 2013) indicated that by the end of the twenty-first century evaporation will increase throughout the basin under both low (eight percent) and high (ten percent) emissions scenarios. Run-off was predicted to increase by ten percent by mid-century and 23 percent by the end of the century under the low emissions scenario. Under the high emissions scenario, run-off was estimated as 15 percent higher by mid-century and 27 percent higher by the end of the century. There were notable spatial differences in estimated changes in run-off, with run-off being most notable in the central and western parts of the basin. Predicted increases in run-off would mean that river discharge will also increase. Beyenne, Ludwig and Franssen's (2013) modelled estimates (low emissions scenario increasing by 27 percent; high equal to 38 percent) are similar to those predicted by van Vliet *et al.* (2013), where mean flows by the end of the twenty-first century were estimated as increasing by 20 percent. Conversely, Palmer *et al.* (2008) suggested that by 2050, mean annual discharge would fall by about six percent.

Assessment of impacts of climate change in the Congo basin by the Climate Service Centre have largely focused on hydropower, agriculture and forestry (Ludwig *et al.*, 2013) with little attention to the possible effects on fisheries. It has been noted that increased water availability would have a positive impact on hydropower generation, but that this could also increase flood risk. The effect on fisheries has not been evaluated. Impacts on forest growth represent a balance between factors promoting growth (increased CO_2 concentrations) and reducing growth (increased air temperatures), and Ludwig *et al.* (2013) predict that carbon storage will increase and that, unlike the Amazon, it was unlikely that there would be a predicted widespread loss of forest habitat. Rain-fed agriculture represents an important source of income and food in the Congo basin and Ludwig *et al.* (2013) suggested that there was unlikely to be any marked impact of climate change, in marked contrast to countries in West, East and Southern Africa.

19.11.4 Impacts on fisheries in the Congo basin

Allison *et al.* (2009) ranked the Democratic Republic of the Congo as the second most vulnerable national economy globally to climate change driven impacts on fisheries, largely because of its current nutritional dependency on fish (45 percent of animal protein being derived from fish) rather than projected climate change impacts. Predicted changes in precipitation and air (and hence water) temperature associated with climate change may affect the capacity of fisheries in the Congo basin to support human populations (e.g. if sensitive species or life stages encounter water temperatures that are outside their tolerances, or flooded areas and wetlands are increasingly regulated). From the combined stress projection (Figure 19.4a), the Congo Basin seems to face relatively limited threats compared with the rest of the world. There may still be issues with increased precipitation, as increased river flows may paradoxically reduce the catchability of fish, even if overall flooding of wetlands increased the potential fish production. Human population in the region is predicted to double by the end of the twenty-first century, suggesting that the primary threats to the fishery will be driven by intensified degradation of habitat from deforestation for agriculture and increased demands for fish as food. The seasonality of flow and duration of flooding also have a significant role to play in the dynamics of inland fisheries and this highlights the need for downscaled evaluations of the impacts on fisheries according to the different water bodies and fisheries within a basin system.

19.12 CONCLUSION - GLOBAL IMPLICATIONS FOR FOOD SUPPLY

Using a case study approach, this chapter has revealed that the regions and the countries supporting inland fisheries are going to undergo considerable changes because of human-derived climate change, with large-scale increases in air (and water) temperature, shifts in the amount and timing of precipitation (both negative and positive) and discharge.

It is projected that China and India, major inland fishery producers, are likely to face considerable stressors affecting their inland fisheries in the future, but that a large group of countries that produce around 60 percent of global inland fisheries are projected to face medium or relatively low future stress and will not to be subject to the most extreme impacts of climate change. Even those countries with low future stress will be exposed to an array of other anthropogenic drivers of change and these can impact the capacity of fisheries to maintain food supply as much as, or even more than, climate change itself. These include overfishing, over-extraction of water, introductions of non-native fishes and other taxa, and the modification, degradation and loss of key habitats.

Inland fisheries continue to provide access to high-quality protein and fatty acids to consumers worldwide, and this will likely continue even under continued climate change. In some cases, fish yields could increase, but the combination of climate change and other global change drivers will potentially reduce the quality or quantity of fishery yields, with subsequent impacts on those most vulnerable to the reduction in access to food supply. This is most important to the group of countries that face the lowest future climate stress, but which have the highest national dependence on inland fish for food security. This highlights the need for effective incorporation of inland fisheries into development planning, high quality data and routine monitoring at the level of individual water bodies and fisheries when examining the perceived and future impacts of climate change (Harrod, 2016).

The demand for fishery products and access to fisheries as a food source, as well as for employment and recreation, will change because of climate change (Badjeck *et al.*, 2010). It will also see shifts because of the continued patterns of economic growth, urbanization and changes in human populations that will drive future changes in food preferences. Currently, many of the major global inland fisheries target traditional (often low trophic level) species: this may change as human diets become more cosmopolitan and selective (Gerbens-Leenes, Nonhebel and Krol, 2010). Any shifts in fishing pressure will affect fish stocks and it is likely that new species will be introduced to satisfy customer demand, with subsequent impacts on native fishes.

If climate impacts and other developments strongly affect the ability of existing commercial fish populations to reproduce, interventions in the form of stocked fisheries may become more common place. This is already a strong trend in the human-made water bodies of Asia, as well in some riverine and lake salmonid fisheries in North America. The extension to other regions may become attractive under the right economic circumstances, but may simply be bypassed with a direct move towards aquaculture systems (such as cage and pen aquaculture) in large water bodies. Again, there are already developments in this direction, unrelated to climate change and simply the result of increasing demand for inland fish not being met by inland fisheries catches or resulting from the decline of inland fisheries because of environmental perturbations. This is also seen clearly in the expansion of freshwater aquaculture in such countries.

In countries where economic development sees increasing urbanization combined with increased time (and income) available for recreation, inland fisheries may shift from providing a key source of food, to supporting recreational fisheries. This may coincide with stronger environmental regulation, efforts to halt or reverse the biodiversity losses in inland waters and the need to improve water quality and storage for drinking water supplies. Recreational fisheries can provide valuable new sources of income and employment (Cooke *et al.*, 2016b; Cowx, 2008; Gupta *et al.*, 2015), outside of traditional fishery livelihoods, but can lead to conflicts where there are still dependent fishing communities (Cooke and Cowx, 2004).

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Chapter 20: Effects of climate change on aquaculture: drivers, impacts and policies

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KEY MESSAGES

- Growth of aquatic food supplies to meet demand will come mainly from aquaculture for the foreseeable future; it is therefore essential that we understand the effects of climate change on the sector from the broad to the finest spatial scales.
- Countries considering aquaculture in their Nationally Determined Contributions are mostly located in the developing countries, especially in Africa.
- Direct and indirect climate change drivers may result in favourable, unfavourable or neutral changes in aquaculture, in the short- or long-term and at different spatial scales. Unfavourable changes are likely to predominate in the developing countries, adversely affecting investment and sector growth.
- Several adaptation measures are already available to mitigate impacts of negative changes or increase resilience. They must be considered in accordance with multi-sector National Adaptation Strategies.
- Knowledge gaps in science, institutional and socio-economic change and policies hamper more effective adaptation of aquaculture, especially in the developing countries.

20.1 INTRODUCTION

Although capture fisheries continue to play a major role in the livelihood, food security and nutrition of millions around the world (FAO, 2016c), most global aquatic products now come from aquaculture (Chapter 3). By supplying an increasing amount of fish, crustaceans and molluscs, the sector not only contributes to meet growing demand for the foreseeable future, but also helps dampen price rises (Béné *et al*., 2016). It is thus paramount that we understand the likely interactions between climate change and aquaculture – for both mitigation (Chapter 27) and adaptation – and help to build resilience and adaptation, especially among the many small-scale practitioners who still account for most of the production by the sector.

Despite its long history (Beveridge and Little, 2002), for the most part aquaculture must be considered a modern industry – indeed, in 1950 aquaculture accounted for only 3 percent of global aquatic products supplies (Fishstat, FAO[1]). The difficulties of farming

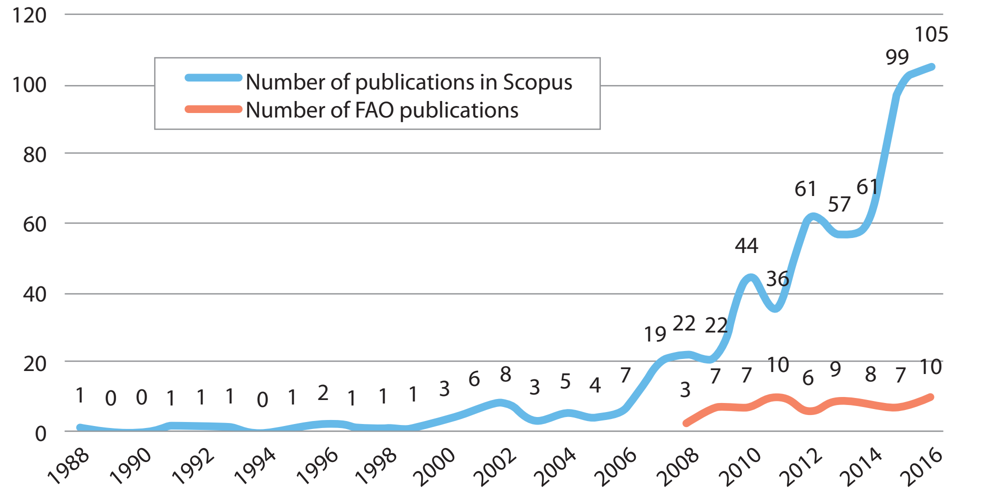
[1] http://www.fao.org/fishery/statistics/en

aquatic environments, exposed as they are to the vagaries of waves, storms and flooding, are argued to have been a major disincentive to the wide-scale uptake of aquaculture, at least until recently when modern materials and designs became available.

The first mention of research on climate change and aquaculture in the scientific literature was at the end of the 1980s[2] but it took more than 15 years after that for researchers to invest significant effort on the topic (Figure 20.1). The uncertainties related to climate change – aquaculture interactions are likely one of the reasons why it was not prioritized earlier. To date, the climate-related issues considered in research have included global and marine/fishery models, impacts on fish and shellfish biology, disease, habitat changes (temperature, acidity and salinity) as well as livelihoods, resilience and sustainability assessment.

FIGURE 20.1

Numbers of published scientific papers per year dealing with aquaculture and climate change in Scopus and FAO databases, as a proxy of interest in the issue



The terms aquaculture and climate change were searched for in the title and/or abstract. The Scopus database includes peer-reviewed papers published in scientific journals, books and conference proceedings. The FAO database includes all publications released by the organization.

The Intergovernmental Panel on Climate Change also highlighted a number of potential impacts of climate change on aquaculture as early as 1990 (Tegart, Sheldon and Griffiths, 1990), but it was only in 1995 that for the first time the sector merited a dedicated chapter (Watson, Zinyowera and Moss, 1995). After the Fourth Assessment Report, released in 2007, the issue became truly mainstreamed in global discussions (Parry *et al*., 2007).

During the twenty-seventh session of its Committee on Fisheries in March 2007, FAO was requested to undertake a scoping study to identify the key issues, to initiate a discussion on adaptation, and to take a lead in informing stakeholders and policy-makers. As a result, in 2008, the FAO Fisheries and Aquaculture Department held an Expert Workshop to provide the FAO Conference with a comprehensive overview of the fisheries and aquaculture climate change issues. This resulted in the publication of the FAO Fisheries Report No. 870 (FAO, 2008), followed by the release of an overview of the scientific knowledge (Cochrane *et al*., 2009).

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[2] The oldest paper in the Scopus database is **Sherwood, J.E.** 1988. The likely impact of climate change on south-west Victorian estuaries. *In* G.I. Pearman, ed. *Greenhouse: planning for climate change*. CSIRO, Melbourne, Australia. pp. 456–472.

20.2 IMPACTS OF CLIMATE CHANGE DRIVERS ON AQUACULTURE

Direct and indirect climate change drivers can be responsible for changes in aquaculture, whether in the short- or long-term. Examples of short-term impacts include loss of production or infrastructure due to extreme events, diseases, toxic algae and parasites; and decreased productivity due to suboptimal farming conditions. Long-term examples include scarcity of wild seed, limited access to freshwater for farming, limited access to feeds from marine and terrestrial sources, decreased productivity due to suboptimal farming conditions, eutrophication and other perturbations. These are well described by De Silva and Soto (2009), Santos *et al*. (2016) and FAO (2017a). Tables 20.1 and 20.2 list some of the likely impacts at different scales, from modification of the metabolism of aquatic organisms to those operating at global scales. Note that there may also be location-specific positive effects, potential complex interactions between drivers (e.g. mutual cancellation or amplification), or new drivers emerging from adaptive strategies, which are not considered here.

TABLE 20.1

Direct climate change drivers, possible overall impacts on aquaculture and adaptations at different scales. For a given scale: green = overall favourable impact, yellow = potentially both positive and/or negative, red = overall unfavourable change

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Warming	Potential impacts	• Increased metabolism and growth rate	• Increased production, improved feed conversion and shorter production cycles should translate into a more profitable sector and higher income	• Increased farm production • Improved feed conversion efficiency for species with higher thermal tolerance • Shift to shorter production cycle aquaculture; intensified production	• Need for informed spatial planning, which, among others, would also reduce potential conflicts with other sectors and contribute to the effective management of aquaculture zones.	• New areas become favourable to aquaculture (higher altitude), while others become unfavourable • Increased monitoring of environmental variables	• New areas favourable to aquaculture (higher latitude), others become unfavourable • The most resilient species may develop on a large scale
		• Increased plankton respiration and proliferation • Changes in mollusc spatfall • Changes in reproduction and sex ratios • Increased/decreased transmission of some diseases	• Relocation of some farming facilities (e.g. seaweed, finfish, shellfish) to cooler/deeper areas in the sea may create new safety risks • Moving facilities may affect livelihoods and increase production cost	• HABs may force farm movement/closure or installation of depuration facilities • Effects of increased jellyfish blooms on marine farms • Lower feed conversion efficiency for species subjected to increased stress	• Increased stratification in lentic systems • Changes in nutrient circulation		
		• Species with a narrow thermal range may no longer be farmed • Increased sensitivity to other drivers (e.g. acidification, pathogens) • Increased Harmful Algal Blooms (HABs)			• Some areas may become unfavourable to farming • Changes in the performance of the supply of ecological services to aquaculture • Increased local eutrophication		
	Adaptation measures	• Farm species and/or strains with higher thermal tolerance • Move farming facilities to cooler/deeper offshore or inland areas	• Adopt guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Selective breeding for thermal tolerance • Adjustment in farming calendar/practices • Change of farmed species • Climate-smart facilities (e.g. deeper ponds, etc.)	• Closure and relocation of production sites • Spatial planning for determining new favourable and unfavourable areas • Risk-based siting	• Closure and relocation of production sites • Spatial planning to determine new favourable and unfavourable areas	• Spatial planning to determine new favourable and unfavourable areas

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Acidific-ation	Potential impacts	• Seaweed sequestering excess dissolved CO_2 may benefit, possibly also contributing locally to some impact mitigation • Changes in bivalve reproduction • Slower growth rates in shell-bearing organisms and corals • Weakened $CaCO_3$ shells and skeletons • Changes in pearl formation in oysters • Impaired growth in some marine finfish, especially embryonic and larval stages • Eutrophication exacerbates ocean acidification	• Some shellfish farming may have to be discontinued or moved to more favourable sites, creating new safety risks • Moving facilities may affect livelihoods	• Spat may have to be bought from new sources • Selective breeding for acidity tolerance • Shellfish hatcheries relying on natural marine water may have to move to more favourable areas	• Reduced spat availability in some areas • Changes in the ecosystem supplying ecological services to aquaculture • Fish production relevant for aquafeeds may be negatively impacted	• Lower shellfish production • Mass die-offs of oyster larvae in hatcheries • Pearl culture in deeper waters/ new sites	• Seaweed farming may develop
	Adaptation measures	• Shift in farmed species or strains, especially of shell-bearing organisms and corals • Move farming facilities to new areas offshore or inland	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Move farming facilities to new areas offshore or inland	• Move farming facilities to new areas offshore or inland	• Closure and relocation of production sites	• Mainstream spatial planning
Hypoxia	Potential impacts	• Species and/or strains with higher tolerance should be less affected • Increased mortality • Reduced growth • Higher sensitivity to other drivers (e.g. pathogens)	• Relocation of some farming facilities to better oxygenated areas may create new safety risks • Moving facilities may affect livelihoods and add to costs	• Lower carrying capacity of ecosystems • Increased aeration costs • Reduction in the number of annual crops when hypoxia is seasonal (e.g. stratification cycles in lakes)	• Lower carrying capacity of ecosystems • Some aquaculture areas may become unfavourable • Changes in ecological services to aquaculture	• Lower production resulting from lower carrying capacity	• New areas become favourable to aquaculture, others become unfavourable
	Adaptation measures	• Shift to more tolerant farmed species or strains	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016c)	• Relocate farming facilities to new areas offshore or inland	• Move farming facilities to new areas offshore or inland • Mainstream spatial planning and ecosystem approach	• Mainstream spatial planning and ecosystem approach	• Mainstream spatial planning and ecosystem approach

[3] Aquaculture management areas (Aguilar-Manjarrez, Soto and Brummett, 2017).

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Distribut-ional shifts	Potential impacts	• Changes in plankton distribution may affect production of filter feeders • Poor growth of stock if natural feed availability is reduced	• Changes in labour availability due to climate-driven migrations • Relocation of some farming facilities to more favourable areas may create new safety risks	• Changes in plankton distribution may change production of filter feeders • Reduced availability of natural seed	• Lower productive capacity for filter feeders of the ecosystems in areas where plankton abundance decreases • Changes in ecosystem services	• Drop in national production if ecosystem integrity is compromised and productivity is decreased	• Changes in production of fish oil and fishmeal and consequences on markets
	Adaptation measures	• Move farming facilities to new areas	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Shift to commercial feed formulation for carnivorous species currently using low-value fish directly as feed • Farmed stocks adjusted to the new productive capacity	• Move farming facilities to new areas • Spatial planning	• Move farming facilities to new areas • Spatial planning	
Sea level rise	Potential impacts	• Higher salinity in affected areas may induce: • lower growth • higher mortality • greater sensitivity to other drivers	• Damage to properties • Complex socio-economic effects (e.g. changes in access/ownership rights and rights to use of ecosystem services)	• More marine and brackish water aquaculture • Less freshwater aquaculture • Loss of areas providing physical protection • Increased exposure of infrastructure and impacts on value chains • Increased exposure to disasters (e.g. tidal surge)	• New opportunities for aquaculture in coastal areas • Loss of intertidal area for freshwater aquaculture • Coastal erosion • Flooding of coastal rivers • Saline intrusion upstream of river systems	• New opportunities for aquaculture in coastal areas • Loss of coastal areas • Disruptive shift in activities to upstream or inland • High adaptation costs • Complex socio-economic effects (e.g. integration of farms in the overall agriculture landscape etc.)	• New opportunities for aqua-culture in coastal areas globally • Increased pressures on coastal aquaculture by other sectors
	Adaptation measures	• Shift toward natural or selected saline-tolerant freshwater species or strains • Shift toward euryhaline (e.g. estuarine) or marine species	• Mainstream ecosystem approach to aquaculture (FAO, 2010) • Support the development of local governance and conflict resolution schemes, in which aquaculture stakeholders are involved	• Investment in protection infrastructure		• Investments in new infrastructure (dams, dikes etc.) to reduce salinity intrusions • Mainstream spatial planning and ecosystem approach	

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Water currents, circulation & winds	Potential impacts	• Sudden changes in stratification may induce mass mortality, reduced growth and/or higher sensitivity to other drivers, but can also result in beneficial flow of oxygen rich waters	• Land-based farming systems (e.g. recirculation systems) should develop, reducing hazards to workers currently operating in the sea • Increased hazards to workers with more frequent storms and bigger waves for farming systems sited offshore	• Changes in stratification may affect aquaculture in floating cages (through upwelling of low dissolved oxygen waters or the release of toxic gases such as H_2S) • Increased exposure to tidal surges and waves	• Changes in the direction and strength of circulation and winds may alter transport/retention of contaminants and nutrients for seaweeds and filter-feeders • Increased risk of fish escapees	• Mainstreaming of spatial planning and management • Development of contingency plans	• Changes in dispersal of eggs/larvae
	Adaptation measures	• Shift toward species with wider water quality tolerance	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Greater investments in stronger cage and mooring systems and in other equipment			

Drivers		Aquatic organisms	People	Farming system	Land-Seascape/AMA[3]	Country	Global
Extreme events (e.g. droughts, floods	Potential impacts	• Changes in reproductive cycle for rain-dependent species in capture-based aquaculture systems • Drought may induce low water quality, mass mortality, reduced growth and/or higher sensitivity to other drivers	• Increased hazards to workers from sudden extreme events • Increased damage/ destruction to properties • Loss or disruption of livelihoods	• Supply of inputs such as wild seed or plant-based feed ingredients may be disrupted • Stock losses to floods/ sea storms/extreme temperatures • Higher adaptation costs	• Increased risk of fish escapes as a result of flooding, overspills and facility destruction • Eutrophication of water bodies • Pollution of freshwater resources by heavy rainfall runoff • Erosion and/or silting-up of mollusc-growing areas	• Increased competition for, and potential conflicts over, freshwater	• Short or long disruption of aquaculture value chains (supply, production, post-harvest, markets, supporting services)
	Adaptation measures	• Shift to species with higher tolerance to poor water quality	• Follow guidelines on decent work in aquaculture (e.g. FAO, 2016b)	• Shift to shorter production cycles • Shift to indoor or Recirculating Aquaculture Systems (RAS) • Invest in water efficient technologies • Invest in stronger facilities • Relocate farms to less exposed areas (e.g. upstream, protected bays)		• Certification by countries of the design, construction and environmental standards of farming facilities allows the industry to operate with stronger equipment, more resilient to extreme events (Chapter 21) • Increased investments in mitigation measures, such as mainstreaming of spatial planning and management, contingency plans, emergency/ disaster responses	
Disease & harmful algal blooms (HABs)	Potential impacts	• Accumulation of residues and toxins affecting flesh quality (off-flavour) product safety, growth and survival, especially of filter feeding species • Increased mortality • Lower market value (off-flavour)	• Increased risks to human health • Increased use of anti-microbial drugs • Increased risk of anti-microbial resistance	• Increased cost to protect stock • Higher production cost arising from depuration • Increased occurrence of diseases • Impact of HABs on caged stocks may be particularly deleterious	• May prompt closure of growing sites and relocation of cages	• Will require higher investments in biosecurity frameworks at national level and contingency plans	
	Adaptation measures	• Increase environmental, food safety and quality monitoring	• Mainstreaming at farm level of methods such as Hazard Analysis and Critical Control Points (HACCP)	• Investment in depuration facilities and controlled environments production systems (RAS, ponds, etc.)	• Increased surveillance and monitoring costs	• Increased surveillance and monitoring costs	

TABLE 20.2

Other climate change-related drivers leading to possible impacts and adaptation measures at different levels/scales of impact. For a given level: green = overall favourable impact, yellow = both positive and negative, red = overall unfavourable change, white = no foreseen impact

Drivers		Aquatic organisms	People	Farm	Land-Seascape /AMA	Country	Global
Gaps in knowledge and uncertain-ties on specific climate change impacts	Potential impacts	• The variability of the future environment may differ from the spectrum of tolerances of species available	• People make ill-informed aquaculture choices, increasing the risk of maladaptation and further livelihood losses, especially for the most vulnerable	• Farm facilities may not be adapted to the average or range of variability of the future environment • Higher cost of adaptation if maladaptation options are chosen first	• Individual maladaptation may have a cumulative impact on the local aquaculture or economy	• Higher risk of national maladaptation strategies	• Small- and medium-scale farmers have limited resources and access to technical assistance to cope with uncertainties • Increased cost of risk management/ increased insurance premiums
	Adaptation measures	• Selecting species with a wide spectrum of tolerance (e.g. euryhaline, eurythermal) to cope with a wide range of uncertain environmental variations • Diversifying farmed species and systems to cope with a wide range of uncertainties	• Social protection strategies • Development of new tools for coping with uncertainties (e.g. complex adaptive systems, etc.) • Need for building increased resilience • Need for increasing local knowledge	• Modified insurance schemes • Facility designs that can be adapted to a certain range of conditions	• Better monitoring and early warning systems • Diversified production • Development of new tools for coping with uncertainties (e.g. complex adaptive systems, companion modelling etc.)	• Better monitoring and early warning systems • Focus research to fill the gaps and reduce uncertainties • Diversified production	• Focus research to address complex uncertainties (e.g. overlap and synergies amongst different drivers)
Water shortage	Potential impacts	• Farmed aquatic products contaminated by polluted water • Water stress may induce low water quality-mass mortality, reduced growth and/or higher sensitivity to other drivers	• Water stress • Aquaculture may not be prioritized for water use	• Reduce production efficiency	• Competition for water resources • Reduce production efficiency	• Water stress • Competition for water resources	• Some territories with limited freshwater such as the small island developing states may invest in marine aquaculture
	Adaptation measures	• Promotion of new species tolerant to low water quality	• Include multisectoral adaptation priorities into aquaculture adaptation plans (e.g. choose between local food production vs. export, etc.) • New governance schemes that ensure equitable access to water, especially during water shortage periods	• Promotion of new water-saving practices (no water renewal, water recirculation, etc.) • Building of climate-smart facilities for water storage • Promotion of climate-smart agriculture, including aquaculture	• Aquaculture may benefit from integrated farming • Aquaculture may benefit from collective water storage • Aquaculture may benefit from multiple use of water schemes • Aquaculture must be included in collective water management schemes • Need for spatial planning	• Need for National Adaptation Plans (see below)	• Promote mariculture where possible

Drivers		Aquatic organisms	People	Farm	Land-Seascape /AMA	Country	Global
Climate change impacts on fisheries[4]	Potential impacts	• Change in the availability of fish oil and fishmeal for feed • Survival and growth of some species, especially marine, may be affected by fishmeal/oil-free feed • Fishmeal/oil-free feed impact flesh composition and may reduce nutritional value, in particular with regards to n-3 polyunsaturated fatty acids (PUFAs)	• Reduced profitability if feed cost increases	• Additional restrictions on feedstuffs and seeds for capture-based aquaculture may create new constraints where commercial feeds are not available • Higher feed cost if resource becomes scarce	• Increased cost of feed	• Increased aquaculture potential as alternative provider of food and livelihood • Reduced aquaculture investment interest	• Aquaculture market development and demand likely to be positively driven by stagnation of fisheries • Aquaculture development could be negatively driven by stagnation of capture fisheries, feed shortage and higher costs
	Adaptation measures	• Use of species more efficient at using feed, especially at lower trophic levels • Selective breeding for strains efficient in using plant feed, especially for species at higher trophic levels • Focus research to reduce negative side effects of terrestrial feedstuffs • Develop new feeds	• Need for capacity building on efficient feed use • Farmers may look for alternative livelihoods	• Better on-farm feeding practices and performance	• Cluster approach to access better feed • Cluster approach to improved feed management	• Increase incentive to consume and farm non-fed species • Increase research investment on better feeds and feeding	• Increase incentive to consume and farm non-fed species • Increase research investment on better feeds and feeding • Increase research on feed-efficient species
Climate change impacts on agriculture	Potential impacts	• Increased competition for freshwater may result in lower water quality and subsequent impacts on survival, growth and/or sensitivity to other drivers or flesh contamination	• Adaptive measures, e.g. integrated/agro-ecological aquaculture will mitigate impacts of risks on the farming system • But they may also create new burdens for farmers (such as increased workload, restrictions on pest/disease treatments etc.)	• Decreased availability and higher cost of terrestrial ingredients for fish feed • Limited availability of land for new farms	• New constraints on the availability of land and water resources inland and in coastal areas. • Increased competition for freshwater • Increased competition for land and water use	• Adaptation in agriculture such as creation of water reservoirs may open an opportunity for cage farming (e.g. Brazil) • Reduced space and water availability for aquaculture growth	• Spatial competition between crops used for human food security and for producing aquaculture feed
	Adaptation measures	• Selective breeding for species more efficient in using feed • Need for species adapted to integrated farming and/or agro-ecological farming	• Integrated/agro-ecological aquaculture to cope with freshwater and land use competition may create benefit to people, e.g. higher income, higher productivity of rice crops etc.	• Better feed management practices • Integrated farming, aquaponics	• Integrated aquaculture-agriculture (e.g. irrigation-aquaculture, rice-fish farming, aquaponics etc.) • Building of irrigation facilities as an adaptive answer to climate change may create new opportunities for aquaculture	• Appropriated freshwater use governance schemes • Spatial planning and management	• Promote integrated water and land uses considering aquaculture potential to provide opportunities for the sector

[4] Reduced catches of marine fish will restrict availability of fishmeal and fish oil even further.

Drivers		Aquatic organisms	People	Farm	Land-Seascape /AMA	Country	Global
Distal drivers[5]	Potential impacts	• New diseases and algal blooms (Table 20.1) • New invasive species may create new risk for farmed species	• Competition for space and resources in some regions such as coastal or peri-urban areas, making them inappropriate for aquaculture • Aquaculture may provide employment and livelihoods • Need for more stringent collective action for multi-users of common resources	• Higher cost of energy, resources, feed etc. may lower farm profitability • Urban aquaculture systems (e.g. aquaponics) may develop	• Recycling of food by-products/organic wastes through aquaculture in support of a circular economy • Aquaculture land may usefully serve other purposes, including by hosting solar panels, in addition to aquatic production • Extractive aquaculture may contribute towards removing nutrients and organic loads in some areas	• Need for increased monitoring for water quality, disease outbreaks, etc. • Demography and demand for aquatic products drive aquaculture development • New information and communication technology tools allow for upscaling aquaculture development	• Aquaculture development driven by demography and growing demand for aquatic products • Globalization and inter-regional trade may help to cope with regional imbalance in fish availability • Growing pressures will require planning of aquaculture development as part of integrated multi-sectoral planning • Several distal drivers will make aquaculture impossible or non-profitable in some areas with high human or environmental pressures
	Adaptation measures	• Conduct vulnerability assessments • Spatial and integrated multi-sectoral planning • Local, regional and national adaptation strategies must consider other changes that have the potential to modify the drivers of climate change					
National Adaption Plans (NAP)	Potential impacts	• New farmed species promoted by NAPs	• Creation of new opportunities for aquaculture within the NAPs	• Aquaculture may have to overcome additional constraints to meet the priorities set for other sectors in the NAP	• Aquaculture may have to overcome additional constraints to meet the priorities set for other sectors in the NAP	• Aquaculture may have to comply with additional constraints to cope with the priorities set for other sectors in the NAP	• International cooperation on NAPs
	Adaptation measures	• Mainstream spatial planning and management • Ensure aquaculture is included in NAPs • Ensure aquaculture is included in multisectoral approaches (e.g. Blue Growth (FAO, 2017b) etc.)					

20.3 OVERVIEW OF SOME CLIMATE CHANGE ADAPTATION POLICIES: NAPAS, NAPS, NDCS

Established in 2001 by the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the National Adaptation Programmes of Action (NAPAs)[5] are intended for least developed countries (LDCs) to coordinate and communicate priority actions that allow access to adaptation funding mechanisms (Vadacchino, De Young and Brown, 2011). By June 2017, 51 NAPAs had been received by the Secretariat, of which 21 include actions in relation to aquaculture. Six countries have also prioritized projects directly addressing aquaculture. These focus on developing small-scale farming (Cambodia, Myanmar), rehabilitating aquaculture sites (Mali), increasing fish production and preservation of fish (the Gambia), adaptation to new climate-induced environments, including increased salinity (Bangladesh), and spatial planning of land use practices (Zambia).

Ten years after the launch of the NAPAs, the National Adaptation Plans (NAPs) from developing countries[6] were established by the Parties to the UNFCCC (FAO, 2017d). Unlike NAPAs, NAPs are not explicitly linked to a funding source; moreover, all developing countries, not only LDCs, are encouraged to develop NAPs. Of the seven NAPs from developing countries available on the UNFCC website in June 2017, six include measures relating to aquaculture. Priority areas include the vulnerability of aquaculture (Brazil, Cameroon), implementation of best practices (Burkina Faso), upscaling of aquaculture (Kenya), adaptation to salinity and wastewater reuse (Sri Lanka) and building resilience (Sudan).

The Paris Agreement entered into force on 4 November 2016 (FAO, 2016a). It stipulates that each party shall prepare, communicate and maintain successive Nationally Determined Contributions (NDCs) to the global response to climate change[7] that it intends to achieve. In June 2017, of the 197 Parties to the Convention, 142 had already submitted their first NDCs, and 19 make reference to aquaculture or fish farming, of which nine focus on adapting aquaculture to climate change (Cambodia, Cameroon, Chile, Madagascar, Mexico, Nigeria, Peru, Sri Lanka, Viet Nam) while a further ten propose agro-ecological or conventional aquaculture development as an adaptation and/or mitigation measure (Belize, Central African Republic, Chad, Congo, Côte d'Ivoire, Equatorial Guinea, Gambia, Mauritania, Morocco, Zambia).

20.4 KNOWLEDGE AND POLICY GAPS AND THEIR IMPLICATIONS

The impacts of a warmer, less predictable and more extreme climate are not evenly distributed across the globe. Some regions will experience potentially detrimental changes, such as increased drought or flooding, while others may find that conditions for aquaculture improve (De Silva and Soto, 2009; FAO, 2017a, 2017c; Chapters 1 and 21). Increased scientific knowledge may contribute to a reduction in uncertainties and improve the adaptive capacity of poor and small-scale aquaculture producers and value chain actors. In order for aquaculture to adapt to climate change, relevant research is required and regions and countries need to work on common issues.

Research gaps include:

- knowledge of synergistic interactions between stressors (e.g. acidification and increased water temperature);
- understanding of bioclimatic envelopes of species tolerance to extreme weather events, or a combination of stressors;

[5] http://unfccc.int/adaptation/workstreams/national_adaptation_programmes_of_action/items/4583.php
[6] http://www4.unfccc.int/nap/Pages/national-adaptation-plans.aspx
[7] http://www4.unfccc.int/ndcregistry/Pages/Home.aspx

- realistic scenarios for aquafeed resulting from the increasing diversion of crop-based feedstuffs for the production of biofuels and/or to other animal husbandry sectors (Troell *et al*., 2014, 2017a; Troell, Jonell and Henriksson, 2017b);
- better feeds and feeding practices; further reduction in use of fishmeal and fish oil; disease susceptibility, new diseases and preventive treatments; evidence of the impacts of climate change on the post-production food chain;
- understanding of the relationship between species and habitat based on optimal thermal limits and salinity levels; the impacts of climate change on public health risks for consumers of farmed fish (e.g. HABs);
- the consequences of combined climate change impacts on resources, physical assets, livelihoods and health; and
- understanding of how climate change impacts on food systems in general and economics may lead to changes in demand and in market prices.

Research to enhance the adaptation to climate change of farming households, farming communities and industry includes: analyses of the social and economic consequences of climate change; reporting on adaptation strategies at all levels of the value chain; and developing and strengthening integrated monitoring systems to provide information on environmental variables and diseases that fish farmers can use to make decisions.

Information gaps and capacity building requirements must be identified and addressed through networks of research, training and academic institutions. Research to inform policy includes:

- the recommendations of physical assets, social and institutional options to enhance the sustainability of livelihoods and the resilience of poor people to multiple climate change impacts;
- improved assessment of the interactive effects of different climate variables (for example, the identification and improved understanding of pathways between climate effects and aquaculture impacts at various scales i.e. including effects on other food systems and human development) so as to better inform strategies that aim to mitigate adverse impacts and encourage adaptation to change; and
- improved understanding of the gender dimensions of adopting climate-smart smallholder aquaculture innovations (Morgan *et al*., 2015).

Regional adaptation plans are also needed for transboundary water bodies (e.g. Mediterranean Sea and Mekong, Lake Victoria and Amazon basins).

Potential adaptation measures could be built on a sustainable livelihoods framework and the ecosystems approach to aquaculture, supported by risk assessment and management along the value chain, and guided by a feasibility assessment.

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Chapter 21: Climate change and aquaculture: vulnerability and adaptation options

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KEY MESSAGES

- Vulnerability assessments of aquaculture to climate change show that a number of countries in both high and low latitudes are highly vulnerable.
- In general, vulnerability is directly associated with governance, from national to farm level.
- Global assessments of vulnerability must be complemented by investigations at more localized levels, where specific aquaculture practices, environmental conditions and interactions with stakeholders and communities are taken into account.
- Longer-term climate-driven trends, e.g. increases in temperature and salinity, are more readily addressed than increasing climate variability and extreme events. With regard to the former, there is time to plan and implement adaptation measures (e.g. development and adoption of strains better adapted to increasing salinity conditions) while it is more difficult to plan for surprises and short-term events, such as storm surges. Adaptation strategies must, however, encompass the short-term, which also facilitates understanding, and use inclusive, bottom-up approaches involving stakeholders.
- Vulnerability reduction depends on broader adaptation measures beyond the aquaculture sector and there is a strong need to integrate aquaculture management and adaptation into watershed and coastal zone management.
- Ultimately, it is at the farm level where vulnerability reduction efforts converge; vulnerability assessments should be as fine-grained as resources allow in order to be relevant to farmers.
- Capacity building in addressing vulnerability and improving adaptation to climate change, especially among target stakeholders, is an investment that more than pays for itself.
- Specific measures to reduce aquaculture vulnerability in accordance with the ecosystem approach to aquaculture include:
  - improved management of farms and choice of farmed species;
  - improved spatial planning of farms that takes climate-related risks into account;
  - improved environmental monitoring involving users;
  - improved local, national and international coordination of prevention and mitigation actions.

21.1 INTRODUCTION

Climate change brings about both challenges and opportunities for global food systems and those engaged in them. The challenges are principally experienced by the global poor in low latitudes while the opportunities in general are realized at higher latitudes (IMF, 2017). This applies to aquaculture as much as to any other food sector, whether it is viewed in isolation, as a livelihood component or as an element of a landscape level food production system.

21.2 MODELLING AND FORECASTING

21.2.1 Introduction to models and aquaculture vulnerability

Vulnerability of aquaculture to climate change can be equated to short- or long-term risk and a variety of indices are available to enable evaluation of the likely response of aquaculture systems and the industry to the probable effects of climate impacts (FAO, 2015). Assessment of the vulnerability of aquaculture and associated industries in the value chain, including the many dependent livelihoods, can be considered at a range of scales from single farms or small areas - typically at a high spatial resolution - to global assessments where resolution may be at the scale of countries or features such as drainage basins. Given the uncertainties about future developments and data limitations, broad scale more generalised assessments of vulnerability often aim to show relative differences between geographic areas in terms of ranked vulnerability scores rather than attempting to quantify results. In addition to providing useful tools for decision-makers, such broad vulnerability assessments (VAs) can be an objective starting point for guiding further and more detailed research in specific areas.

For aquaculture, models designed to assess vulnerability need to take into account multiple drivers including relevant aspects of the physical environment, chemical environment, infrastructure, access to goods and services and economic factors. Importantly, societal factors are also key to VA and in consequence assessments should be interactive and collaborative, involving stakeholders and end-users. Having identified factors leading to high vulnerability, responses to climate change must centre on boosting adaptive capacity and resilience, of both the communities and the ecosystems on which they depend.

Vulnerability (V) can be expressed as a function of exposure to climate change (E) and sensitivity to climate change (S), and adaptive capacity (AC), as in the following equation:

$$V = f(E, S) - AC \qquad \text{[equation 21.1]}$$

where better adaptive capacity can mitigate the negative effects of exposure and sensitivity. This method was implemented in the Intergovernmental Panel on Climate Change (IPCC) third assessment report (McCarthy *et al*., 2001) with similar approaches being used in a range of vulnerability studies (e.g. Allison *et al*., 2005, 2009; Metzger, Leemans and Schröter, 2005; O'Brien *et al*., 2004; Schröter, Polsky and Patt, 2005).

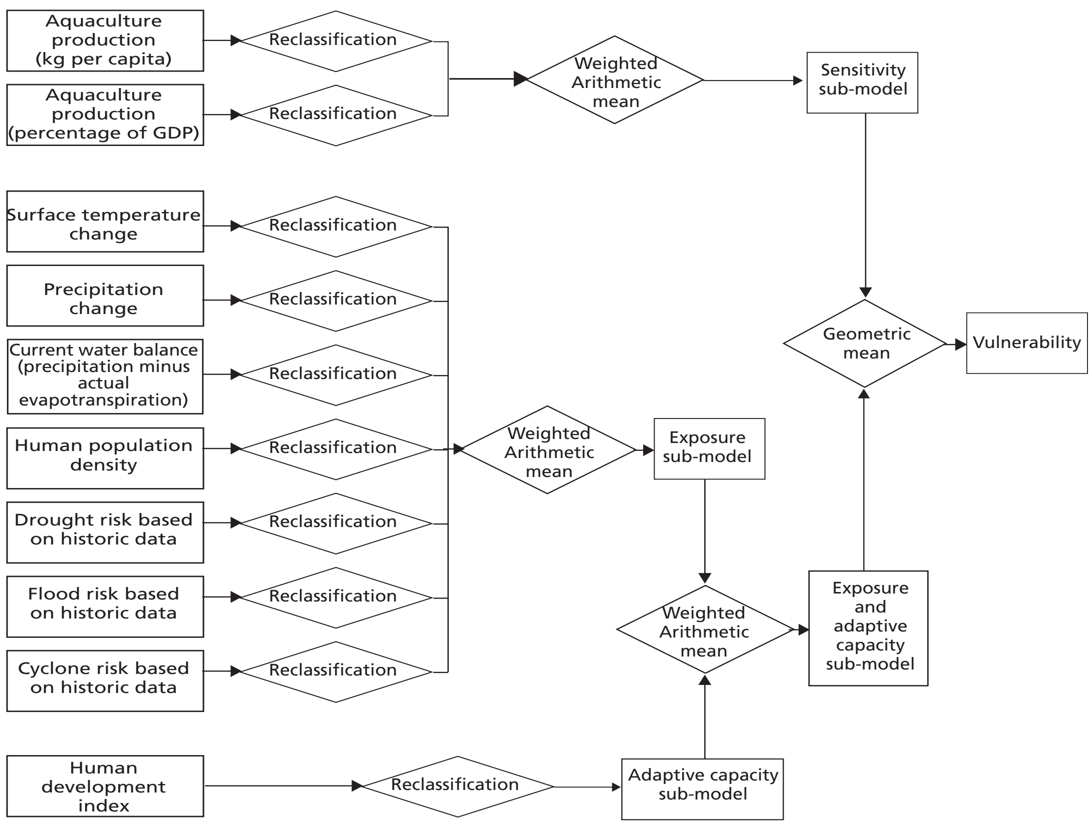
21.2.2 Modelling aquaculture vulnerability at the global scale

To date there have been few attempts to compare vulnerability between regions at the global scale in relation to the aquaculture or fisheries sectors. Allison *et al*. (2005, 2009) used a range of indicators to rank nations in terms of vulnerability of livelihoods dependent on capture fisheries to climate change. Rather than representing key variables using only simple numerical indices, and recognising that vulnerability is location specific, Handisyde *et al*. (2006) used geographic information systems (GIS) to represent and combine qualitative and quantitative data spatially for aquaculture at the global scale. In addition to allowing for visual interpretation of results and intermediate stages of the modelling process, GIS enables the combination of multiple key variables available at varied resolutions and scales while maintaining as much detail as possible.

Handisyde, Telfer and Ross (2017) developed a significantly improved hierarchical model structure to that of 2006 in which a range of indicators was pooled to represent the sensitivity, exposure and adaptive capacity components, which were then combined to indicate vulnerability. A schematic overview of the model structure and potential input variables is provided in Figure 21.1. Not all inputs are necessarily used in every scenario as choice of inputs and weightings (level of influence within the model) vary depending on the aquaculture environment (fresh, brackish or marine) being evaluated. When considering aquaculture trends and adaptive capacity, Handisyde, Telfer and Ross (2017) considered that extrapolation of future scenarios over a time period relevant to climate change would be likely to introduce considerable inaccuracies into the modelling process. The authors therefore used current indicators of adaptive capacity in association with future climate scenarios to provide the best proxy when comparing vulnerability at a broad scale.

FIGURE 21.1

Schematic representation of model used by Handisyde, Telfer and Ross (2017). Primary variables (leftmost column) were standardised to a continuous 0-1 scale with higher numbers representing greater vulnerability, greater exposure, greater sensitivity or lower adaptive capacity. This results in a continuous series as opposed to the assignment of a number of distinct classes (see Handisyde, Telfer and Ross, 2017, for further details)



Sensitivity

In the model developed by Handisyde, Telfer and Ross (2017) sensitivity is represented at a national scale and indicates the importance of aquaculture to people within a country and thus how sensitive their livelihoods may be to climate impacts on the aquaculture sector. Two metrics are used; aquaculture production quantity (kilograms per capita) and aquaculture production as a percentage of gross domestic product (GDP), in both cases excluding aquatic plants. The quantity of aquaculture products per capita represents the physical size of the aquaculture sector within a country assuming that, generally, nations with a high per capita production of aquaculture products are likely to have a greater percentage of their population whose livelihoods' are either directly or indirectly linked to aquaculture production. Consideration of the value of aquaculture production as a percentage of GDP gives an indication of its importance to the economy, which is dependent on the scale of aquaculture production within a country in terms of physical quantity, the relative value of the aquaculture products and the size of the national economy. In richer countries it is likely that not only will aquaculture make a smaller contribution to overall wealth but also people are more likely to have economic alternatives and thus be more able to adapt to potential impacts and change.

Exposure

Exposure to climate change in the model is viewed as the relative extent of change in climate drivers between locations rather than attempting to quantify changes. Future changes in annual mean temperature and precipitation are considered while water balance (precipitation minus actual evaporation) is used as a proxy for current water availability. The inclusion of population density assumes that higher population densities may exacerbate the potential impacts of climate change through mechanisms such as increased requirements for resources including water (Murray, Bostock and Fletcher, 2014), and greater environmental pressure, e.g. through increased pollution.

The frequency of past climate extremes in the form of cyclones, drought and flood events is used as a proxy for future risk on the assumption that any increases in the intensity or frequency of these extremes are likely to be particularly significant in areas where they are already common (Handisyde *et al*., 2006; Islam and Sado, 2000). The global mean warming used for the model was 2 °C, derived from multiple global circulation models and based on a year 1990 base point. Data from an increasingly large number of climate models are now available and when operating at the global scale, the combined results from an ensemble of climate models typically show greater skill in reproducing the spatial details of climate when compared to a single model. The authors considered that multiple warming scenarios were not relevant to this assessment as the aim was to show relative differences between global areas, rather than quantify vulnerability in relation to a given amount of warming.

Adaptive capacity

Adaptive capacity was based on the United Nations Human Development Index (HDI) (Malik, 2013), which is a globally complete and consistent data set based on the combination of health (life expectancy at birth), education (a combination of mean years of schooling and expected years of schooling) and living standards (gross national income per capita). The components of the HDI are transformed to a 0–1 scale before being combined as a geometric mean. Gall (2007) undertook an evaluation of global indices in relation to social vulnerability and, while generally critical of many indices, concluded that the HDI outperforms the others examined despite being based upon a smaller number of variables.

21.2.3 Forecasting aquaculture vulnerability at the global scale

Handisyde, Telfer and Ross (2017) show images of the model assessments of overall vulnerability as well as sensitivity, exposure and adaptability separately for each culture environment (Figure 21.2a, b, c). The greatest variability is seen between countries as a result of the more strongly weighted sensitivity and adaptive capacity components where data are available at the national level. Variability within countries results from the exposure component and provides a useful indication of where the effects of changing climate may be most extreme. Handisyde, Telfer and Ross (2017) also showed combinations of exposure and adaptive capacity giving an indication of vulnerability that is independent of the scale of a region's aquaculture production. While those results are not shown here, examination of the exposure and adaptive capacity components in isolation is useful when considering all countries involved in aquaculture, regardless of current extent, and is potentially valuable when considering nations where aquaculture production is currently low but where an indication of vulnerability is needed. It is also possible that where aquaculture is less significant countries may be less able, or prepared, to invest in adapting to impacts on production.

The vulnerability of freshwater aquaculture is greatest in Asia, with its large aquaculture sector. Viet Nam is the most vulnerable country followed by Bangladesh, The Lao People's Democratic Republic and China (Figure 21.2a). Within the Americas, Belize, Honduras, Costa Rica and Ecuador appear most vulnerable. Uganda is indicated as the most vulnerable country in Africa followed by Nigeria and Egypt. It is worth noting that while African countries are ranked quite low in the overall VA because of relatively low current levels of aquaculture production, many also have low levels of adaptive capacity.

For brackish water production, Viet Nam, again, has high vulnerability scores, as does Ecuador. Egypt with its aquaculture production within the Nile delta and Thailand with its significant brackish water production of crustaceans also feature strongly (Figure 21.2b). When considering adaptive capacity alone in relation to countries currently engaged in brackish water aquaculture at any level, Senegal, Ivory Coast, Tanzania and Madagascar score highly (indicating low adaptive capacity) in Africa, as do India, Bangladesh, Cambodia and Papua New Guinea within Asia.

The highest vulnerability in relation to marine aquaculture was recorded for Norway and Chile, perhaps unsurprising because of the large relative size of their respective industries (Figure 21.2c). Interestingly, in terms of per capita aquaculture production and contribution to GDP, the Faroe Islands is significantly above Norway and Chile but could not be included in the assessment because of lack of data. Within Asia, China is most vulnerable in terms of mariculture production, followed by Viet Nam and the Philippines. In Africa, Madagascar is most vulnerable, while in the Americas, Peru emerges most strongly after Chile. Mozambique, Madagascar, Senegal and Papua New Guinea all emerge as countries involved in mariculture but with low adaptive capacity (Figure 21.2c).

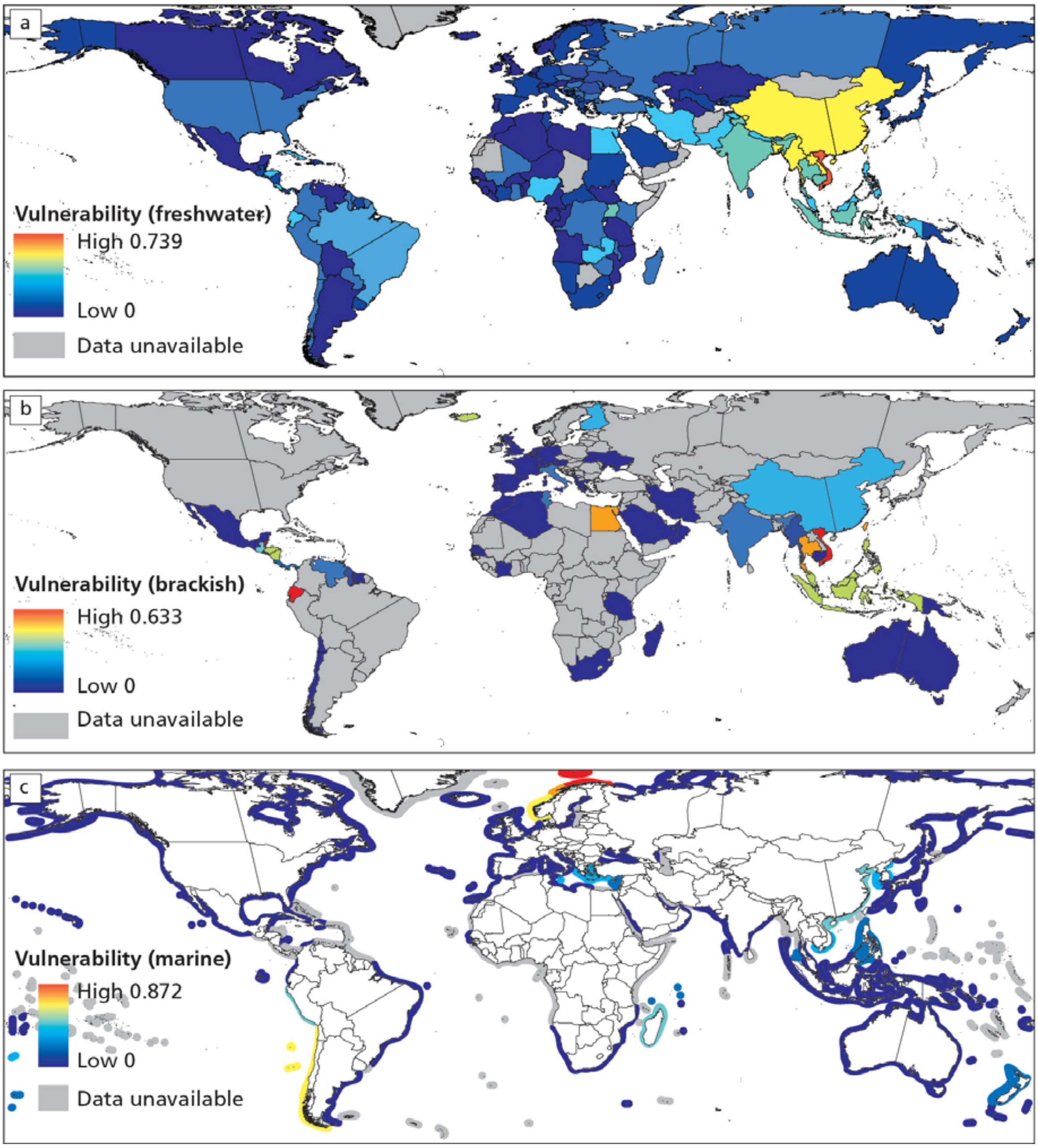
Table 21.1 shows the averaged scores for the 20 most vulnerable countries for each culture environment along with their sensitivity, exposure and adaptive capacity drivers. The values are relative rather than absolute and no direct comparison of values can be made between different culture environments because of the varied data used in the respective models. However, a high ranking of countries for more than one environment is significant. Due to their substantial aquaculture industries, a number of Asian countries, Viet Nam, The Lao People's Democratic Republic, Bangladesh and to a lesser extent China, were considered most vulnerable to impacts on freshwater aquaculture production. Viet Nam along with Ecuador was also ranked as highly vulnerable in terms of brackish water production. Norwegian and Chilean mariculture were indicated as most vulnerable to climate change influenced by the extremely high per capita levels of production and despite both being well developed countries. Other locations with high mariculture vulnerability include China, Viet Nam, the Philippines, Thailand, Greece and Madagascar. Viet Nam is notable in achieving high vulnerability scores across all three culture environments.

Handisyde, Telfer and Ross (2017) improved on the only previous global evaluation of vulnerability of aquaculture-related livelihoods to climate change (Handisyde *et al*., 2006), notable advancements being the application of a more sophisticated set of climate change projections in the form of a multi-model ensemble of data and improvements in data processing by using a geometric rather than arithmetic mean to reduce the likelihood of countries with very small aquaculture sectors (low sensitivity) being considered as highly vulnerable in situations where metrics for exposure and adaptive capacity scored highly. In addition, the impacts of exposure and adaptive capacity could be considered in isolation to give insights into vulnerability, irrespective of the size of the national aquaculture industry.

Global assessment of vulnerability provides a highly valuable indication of where aquaculture-related climate change effects may occur and where further research would be valuable. Clearly, global studies should be complemented by investigation at a more localized level where specific aquaculture practices and environmental conditions can be considered, as well as taking into account specific interactions with stakeholders and communities. While locally focused studies may identify potential negative impacts, they are also better able to evaluate positive benefits arising from changing climate on specific aquaculture practices, thus guiding future development and adaptation within the sector.

FIGURE 21.2

Relative vulnerability† of aquaculture to climate change at global level††; a) in freshwater, b) in brackish water, c) in the marine environment (shown as a 50 km buffer zone from coasts). From Handisyde, Telfer and Ross (2017)



† The colour range indicates vulnerability relative to other areas within the same culture environment and is not intended to be a quantitative means of comparing vulnerability between culture environments.
†† In some cases no data is available on aquaculture production, at any scale, in FAO FishStatJ (2013) statistics.

TABLE 21.1

Average vulnerability values (V) highest to lowest), sensitivity (S), exposure (E) and adaptive capacity (A) for the 20 most vulnerable countries in relation to the freshwater, brackish and marine environments. (see equation 21.1)

Freshwater[1]					Brackishwater[2]					Marine[3]				
	V	S	E	A		V	S	E	A		V	S	E	A
Vietnam**	0.690	0.999	0.395	0.519	Ecuador	0.558	0.950	0.277	0.355	Norway	0.307	0.809	0.357	0.000
Lao People's Democratic Republic	0.561	0.583	0.358	0.633	Vietnam**	0.557	0.664	0.368	0.519	Chile	0.273	0.486	0.045	0.209
Bangladesh*	0.544	0.498	0.436	0.676	Belize*	0.524	0.758	0.312	0.389	China**	0.160	0.068	0.347	0.393
Myanmar	0.514	0.462	0.318	0.702	Egypt	0.483	0.528	0.426	0.450	Madagascar	0.156	0.044	0.194	0.725
China**	0.504	0.616	0.452	0.393	Taiwan*	0.460	0.267	0.383	1.000	Vietnam**	0.123	0.036	0.232	0.519
Taiwan*	0.404	0.207	0.363	1.000	Thailand**	0.457	0.536	0.356	0.407	Malta	0.112	0.077	0.152	0.166
Uganda	0.342	0.181	0.408	0.767	Nicaragua	0.358	0.278	0.293	0.547	Peru	0.111	0.045	0.152	0.329
Cambodia	0.334	0.201	0.406	0.633	Philippines**	0.332	0.258	0.360	0.462	Philippines**	0.096	0.023	0.283	0.462
Thailand**	0.322	0.254	0.409	0.407	Honduras*	0.325	0.236	0.349	0.496	Greece	0.095	0.058	0.179	0.146
India	0.293	0.153	0.455	0.616	Indonesia*	0.308	0.236	0.209	0.501	Korea, Republic of	0.095	0.052	0.378	0.071
Indonesia*	0.268	0.172	0.250	0.501	Iceland*	0.265	0.554	0.232	0.075	Seychelles	0.090	0.042	0.118	0.229
Belize*	0.253	0.172	0.343	0.389	Malaysia*	0.241	0.223	0.211	0.286	New Zealand	0.085	0.119	0.073	0.055
Honduras*	0.241	0.125	0.403	0.496	Guatemala	0.222	0.100	0.337	0.575	Thailand**	0.077	0.019	0.148	0.407
Philippines**	0.239	0.134	0.351	0.462	Bangladesh*	0.207	0.075	0.379	0.676	Croatia	0.069	0.021	0.222	0.230
Costa Rica*	0.224	0.173	0.308	0.280	Panama	0.171	0.116	0.222	0.269	Japan	0.069	0.028	0.379	0.066
Nepal	0.213	0.071	0.416	0.756	Finland	0.142	0.107	0.373	0.097	Cyprus	0.068	0.026	0.201	0.164
Malaysia*	0.213	0.164	0.264	0.286	Costa Rica*	0.125	0.058	0.250	0.280	Turkey	0.066	0.014	0.216	0.358
Republic of Moldova	0.206	0.088	0.545	0.453	China**	0.111	0.032	0.391	0.393	Iceland*	0.064	0.026	0.317	0.075
Nigeria	0.199	0.062	0.438	0.743	Guam	0.109	0.015	0.449	1.000	Canada	0.063	0.022	0.396	0.068
Iran	0.195	0.095	0.542	0.327	Brunei Darussalam	0.103	0.064	0.186	0.154	Mozambique	0.061	0.005	0.165	0.965

[1] For freshwater, gridded vulnerability values are averaged over the entire land area of each country.
[2] For brackish water, vulnerability values are averaged over land area within 50 km inland of the coast.
[3] For mariculture, vulnerability values are averaged over each country's coastal waters for an area extending 50 km offshore.
** = countries appearing in the most vulnerable 20 for all three culture environments.
* = countries appearing in the most vulnerable 20 for two of the three culture environments.

21.3 VULNERABILITY ASSESSMENTS IN PRACTICE: SELECTED CASE STUDIES AT NATIONAL, LOCAL AND WATERSHED LEVELS

21.3.1 Introduction

Quantitative or semi-quantitative VAs are as yet rare for food systems *let alone* aquaculture. The sector is often assessed together with fisheries or agriculture and in coastal or watershed-based studies. Nonetheless, an increasing number of studies describe various elements of vulnerability of some aquaculture species and systems that should contribute to more formal assessments. Kais and Islam (2017) describe the main climate-related threats to shrimp farming in Bangladesh and some approaches to reduce exposure of farming systems and reduce sensitivity. Doubleday *et al*. (2013) describe an aquaculture exposure assessment carried out in Southeast Australia based on experts' views of risks from climate change biophysical hazards and Pimolrat *et al*. (2013) describe climate change risks of tilapia farms in Thailand at different altitudes. Both studies focus on exposure and analyse elements to reduce risks but do not delve into social and economic dependency or the consequences of the risks to communities. Soliman (2017) describes the threats to aquaculture in Egypt, underscoring the impact of climate change on freshwater availability as one of the major risks for the sector. Lydia *et al*. (2017) describe stakeholder perceptions of climate change risks to aquaculture in Nigeria and Egypt, supporting Soliman's findings. Studies in China address a number of the vulnerability components. For example, Li *et al*. (2016) constructed a province-level dataset to estimate the profitability and productivity of Chinese aquaculture under climate change. They noted that aquaculture production "has heterogeneous responses to climate change".

The climate change VAs reviewed here are of different geographical areas and scopes, in different agro-ecological environments, and of different targets with different livelihood resources. They aim to provide an overview of the range of purposes, stakeholder engagement strategies, assessment frameworks, methodologies and tools, and results and lessons. The assessments include a country's aquaculture sector, a national aquaculture commodity industry, i.e. salmon in Chile, fisheries and inland aquaculture in the Lower Mekong Basin (although only aquaculture is discussed here), and a mix of livelihood resources that includes fishing, aquaculture, crop and livestock farming and non-agriculture options in four coastal districts in South Sulawesi, Indonesia.

21.3.2 National assessments

a. Aquaculture sector of Chile

González *et al*. (2013) assessed the vulnerability of Chile's aquaculture sector in 2012, covering all the geographical sites and the main aquaculture resources, following the methodology of Allison *et al*. (2009). They used national climate change forecasts embodied in a model developed in 2006. It provided a good coarse-grained framework to estimate exposure in the coastal marine environment over shorter time scales (2011–2030; 2046–2065 and 2066–2100) under the IPCC scenario A2[1]. There was some confidence in the forecasts that ocean temperatures will increase, but perhaps the most relevant factor, particularly with regard to the main aquaculture areas, is the projected decrease in precipitation that results in less freshwater flowing into fjords and inner seas. The authors concluded that salmon and scallop farming were more vulnerable than other systems but that in general Chilean aquaculture had a low vulnerability to climate change. This result was strongly influenced by the high values used for indicators of adaptation capacity, such as governance. Unfortunately, the assessment

[1] See http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=94.

was rapidly shown to be misguided by the El Niño-related massive harmful algal blooms (HABs) in 2015 and 2016, because a number of critical governance tools, including monitoring, early warning, preventive measures and mitigation measures were not sufficiently in place to be effective (FAO, 2017a). Another problem is that the models used for forecasting were low resolution and did not allow for finer, local-level assessments of exposure. Finally, the models predicted trends in the mid- and long-term i.e. 20, 30 and 50 years, and they do not yet incorporate surprise changes or synergistic effects of overlapping phenomena such as a climatic trend and a short-term cyclical event such as El Niño.

b. Aquaculture and fisheries in shared marine waters

Martinez-Ortiz and Bravo-Moreno (2013) used the IPCC model adapted from Allison *et al.* (2009) to produce an initial assessment of vulnerability to climate change in fisheries and aquaculture in three countries, El Salvador, Honduras and Nicaragua, which share the waters of the Gulf of Fonseca in Central America.

For exposure they considered a number of regional forecasts under both the A2 and B2 IPCC scenarios. Both (especially the former) indicated an increase in temperature and a decrease in precipitation, although the latter was less clear. Hurricanes, big storms, flooding and drought were considered as the main direct threats in this study. The overlap of climatic variability, such as El Niño-Southern Oscillation (ENSO), and climatic trends was seen as a very relevant threat. For example, El Niño causes significant temperature increases that have damaged farmed tilapia production as a result of extreme heat and hypoxia. Increases in temperature were projected to be less damaging to shrimp farming (*Penaeus vannamei*). However, La Niña events might have greater impacts because of lower temperatures and salinities. Therefore, climate change could affect species and production systems differently. Indeed, the increase in precipitation is seen as a potentially more damaging factor, especially for shrimp farming, which would also have negative social consequences. Sensitivity was estimated as direct and indirect employment by fisheries and aquaculture and its contribution to the national GDP. For adaptation capacity, counties were considered as the ground level adaptation units and the authors used a combined indicator of the HDI and an index of "decentralization", which attempted to evaluate the capacity of local counties to take action on their own. The lack of national and regional coordination was seen as a constraint to reducing vulnerability of fisheries and aquaculture to climate change. The authors also emphasized the lack of information that prevented a more precise forecast of impacts on different farming systems at local scales.

21.3.3 Local assessments

a. Salmon aquaculture in Chile

Chile is the second largest producer of farmed salmon globally, with an annual production of over 700 thousand tonnes and an export value around USD 4 billion, making it the country's second largest export product after copper. Salmon farming has created a whole economy through direct and indirect employment in the south, where cities and some coastal communities are strongly dependent on the sector. Catastrophic red tides in 2015 and 2016 had a very strong impact on the industry, also affecting mussel farming and coastal fisheries (FAO, 2017a). Losses in production, employment and local livelihoods revealed the vulnerability of the industry to climatic variability and change. To address this, Soto *et al.* (forthcoming)[2] elaborated a climate change vulnerability matrix for the salmon farming sector. It is a participatory, simple,

[2] *Programa Mesoregional Salmon Sustentable Report,* CORFO, Chile.

flexible and dynamic tool open to all users, facilitating the identification of key points to reduce vulnerability.

VAs were performed for the most representative salmon farming counties, the smallest political and governance decision-making units in the country, so the risks can be linked to the local decision-making process while improving stakeholder understanding and involvement. The analysis considered climate change related impacts over the next 20 years to provide a realistic framework for local stakeholders' discussions and understanding. The estimation of VA components, considering the weighting of the different factors and indicators, was done with the active participation of the major stakeholders.

Exposure was estimated through a qualitative risk assessment of the main climate change-related threats on the production volume, adapted from the methodological approach used for a VA of Australian aquaculture (Doubleday *et al*., 2013). Threats considered included sea temperature, salinity, dissolved oxygen (DO), HABs, extreme weather events, ocean acidification and climate change related diseases. The assessment also considered several farm management aspects that could influence the magnitude of impacts (e.g. fish stress, stocking densities and eutrophication). Climatic drivers were estimated with an updated version of the PRECIS model that addresses Chile's climatic variability through the twenty-first century[3]. Forecasts indicate that Northern Patagonia (41–45 °S), where salmon farming takes place, will undergo an increase in temperature, especially during the summer period, within the next 50 years but most importantly, a forecast decrease in precipitation will result in less freshwater entering fjords and channels. Temperature increases are expected to be less pronounced in the southern part of Patagonia (from 45 °S to the southern tip of Chile). As in the case of the Gulf of Fonseca, described earlier, the overlap of climatic variability, such as ENSO events, and climatic trends such as reduction of precipitation, was seen as increasing the potential impacts. As Doubleday *et al*. (2013) highlighted, a qualitative screening-level assessment is an extremely valuable approach to guide the selection and prioritization of those elements that could reduce exposure. It helps to identify important information and research gaps and informs the development of cost-effective solutions. The participation of stakeholders is especially important in determining the most relevant risks.

Sensitivity to climate change was estimated by considering direct and indirect employment in salmon farming and by the contribution of the salmon farming taxes to the national budget. Other elements that could be considered under sensitivity were deemed to be better handled under adaptive capacity, for example, alternative livelihoods.

Adaptive capacity was estimated by considering the presence and quality of a number of conditions and services including education, infrastructure, insurance, health care, environmental monitoring and early warning, application of risk-based aquaculture spatial planning and management, alternative livelihoods, institutional coordination capacity, and adoption of better practices.

The assessment showed that the final vulnerability values for the different counties were not as important as the participatory process to identify the different components. The use of simple graphic models that facilitated understanding of the relationships between the forcing factors is an especially useful approach. In addition, it was concluded that having access to open source forecast models, such as PRECIS, for the different regions in the farming areas (even if they are low resolution) and the existence of national and local scientific capacity and knowledge are great assets for adaptation capacity. The most common weak point identified was the lack of coordination of the sector at county and national levels.

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[3] http://dgf.uchile.cl/PRECIS/

The initial VA indicated that those counties that could lose freshwater inputs in the future (which will increase salinity of fjords and coastal zones, which in turn influences the growth and proliferation of parasites such as sea lice), that have higher production levels and have greater socio-economic dependency on the sector are in general more vulnerable. As to adaptation, some indicators stand out as key to increasing adaptive capacity. These include better coordination of the sector's prevention and response strategies, transparent and accessible monitoring and early warning systems (EWS), risk-based aquaculture zoning, better management including biosecurity measures, and keeping production within the carrying capacity of the ecosystem units (fjords and channels). Increasing diversification of livelihoods (beyond salmon farming) also stood out as a key element of adaptation capacity.

b. Climate vulnerability and capacity analysis of four districts located in coastal areas in South Sulawesi, Indonesia

In the past four decades floods, droughts, storms, landslides and tidal surges have caused major loss of human lives and livelihoods in Indonesia. Being an archipelago and having a coastline that is the second longest in the world, a large part of its population live near the coast. The case study described here was a component of the project "Building coastal resilience to reduce climate change impact in Thailand and Indonesia", funded by the European Commission and implemented by CARE International (Cooperative for Assistance and Relief Everywhere) that aimed to build an understanding by the local population of the impact of climate change and develop strategies for adapting to a changing environment. The Indonesian study was carried out from November 2011 to April 2012 by Rolos *et al*. (2012). The premise of this climate vulnerability and capacity analysis (CVCA) component of the two-country project was the paucity of knowledge on the impact of climate change on local livelihoods even as climate change scenarios on a global level are available. The important livelihoods in the study area were seaweed farming, coastal fisheries, pond aquaculture, farming of rice, maize and sweet potato, livestock raising, small business, masonry and driving a motorcycle taxi.

The CVCA methodology applied in this case study prioritizes local knowledge, information and data at community, household and individual levels. It incorporates climate risks and adaptation strategies and takes account of the roles of national institutions and policies in facilitating adaptation. It combines community knowledge and scientific data to improve understanding of the local impacts of climate change. In this case, because of the lack of local-scale information on climate change impacts, exacerbated by inadequate data and information on weather and climate predictions, the participatory exercises provided the opportunity to link community knowledge to scientific information on climate change. The aim of the analysis was to help local stakeholders understand the implications of climate change on livelihoods so that they could better analyse risks and plan for adaptation.

The CVCA was implemented by field facilitators recruited from villages and trained and supervised by CARE's district facilitators and the district government technical team. Data collection tools included key informant interviews of government officials from national and local government agencies, secondary data compilation from published printed and electronic sources, particularly on climate variations, local context and reported risks, and focus group discussions of which 563 were organized. Focus group discussions were used to identify the most vulnerable groups, types of livelihood resources, types and frequency of hazard occurrence in the localities, seasonal activities in the community, historical trends and seasonal changes over time, and important institutions in the community.

Quantitative data were derived from a baseline study, the main component of which was a household survey to collect demographic information of villages, socio-economic data that included descriptions of current livelihoods and potentials, climate risks, disaster preparedness measures and factors affecting resilience and adaptive behaviours. Current adaptation strategies can be a baseline for comparison with the achievements made at the end of the project.

The six participatory rural appraisal (PRA) tools used included:

- Hazard mapping to identify the important livelihood resources and the individuals and institutions that have access to and control over these, and the areas and resources at risk from climate hazards.
- Seasonal calendars to identify periods of stress, hazards, diseases, hunger, debt, vulnerability and others, which also helped identify livelihood strategies and coping mechanisms.
- Historical timelines to gain insight into past hazards, changes in their nature, intensity and behaviour. This tool made people aware of trends and changes. It also informed risk analysis, adaptation planning and investments.
- Vulnerability matrix to determine the hazards with the most severe impacts on livelihood resources and identify current coping strategies for the hazards.
- Participatory development of Venn diagrams to provide an understanding of the relative importance of the institutions in the community and indicating the engagement of different groups in local planning processes. The tool also provided an assessment of the people's access to services and the availability of local safety nets.
- Daily activity records for information on the production and family activities of men and women in a day.

The value of this study for VA practitioners is considered to be the strategic approach it employed to engage the participation of target communities. Local people participated in the process to devise an adaptation strategy and plan. The participatory methodologies and tools used served to increase awareness and understanding, based upon their own experiences and perceptions, of what makes their livelihoods vulnerable to climate change risks and why. Participants were thus made aware of the gaps between their current strategies for coping and adaptation and what is required in order to cope and adapt to future risk scenarios.

The findings showed the range of interrelated and complex threats to a community's livelihoods. The most vulnerable groups were found to be farmers and fishers who are likely to be more affected by climate variability than others, as their livelihoods are strongly related to weather conditions. Increased weather unpredictability disrupts cropping schedules of farmers while increased storminess prevents fishers from going out to fish. The major climatic hazards and impacts on the communities were identified as:

- Flooding, which has become more frequent in recent years. The impacts of this are salinity change on seaweed growing sites when pond dykes burst and discharge freshwater to the coast; loss of stock when ponds overflow or their dykes collapse; and flooded rice and corn fields, which destroy crops. Bringing a product to market becomes either impossible or costly when roads are damaged and under water.
- Tidal surges, which increase the salinity of coastal brackish water ponds because of the influx of seawater, and damage seaweed plots.
- Drought, which severely reduces freshwater supplies to Gracilaria seaweed ponds, increasing salinity and damaging or killing the seaweed. Fish in highly saline ponds become stunted. If drought occurs during the growing period of rice and corn, the crops wither or yields are reduced.
- Heavy, prolonged rainfall which adversely affects Gracilaria seaweed because the salinity of pond water is reduced and the species needs stable salinity to grow well;
- Strong winds make it difficult to go out to sea to fish, damage poorly built houses and contribute to soil erosion.

- Soil erosion from floods exacerbated by drought is another hazard. Pond dykes weakened by drought easily erode when floods occur. This is expensive and it disrupts production schedules to undertake dyke and pond bottom repair and rehabilitation. Soil erosion washes away topsoil, rendering croplands infertile.

Recommendations arising from the analysis included the need for:

- A strategy to assist communities to develop resilient livelihoods as a starting point for adaptation to climate change.
- A strategy for disaster risk reduction that emphasizes preventive activities such as coastal zone management, EWS and reliable weather forecasts based on a good national data infrastructure, and training of EWS providers and others on how to respond to warnings.
- Capacity development for government officers and local people, which is also addressed by their involvement in VAs (sharing of best practices at the local level, facilitated by a community learning centre is proposed).
- Measures to address underlying causes of vulnerability, which emphasize the crucial role of women in dealing with impacts of climate change and propose among other things that they be actively involved in the VAprocesses.
- Enabling access to basic services when a disaster occurs and while recovery is going on.
- Training and provision of opportunities in alternative occupations.

21.3.4 Watershed level assessment

The VA of capture fisheries and aquaculture (ICEM, 2013) in the Mekong river watershed was a systematic appraisal of the threats and impacts on species (in the context of fisheries) and aquaculture production systems in selected eco-regions of the lower river basin, based on projections to 2050 of weather patterns and climate conditions. Important fish species were selected as indicators of the sensitivity of hotspots for fisheries to changes in climate. For aquaculture, the focus was on species and production systems. The mainly qualitative assessment highlighted the difficulty of isolating climate change signals from other causes of vulnerability and the pitfall of trying to consider threats in isolation, or in a single farming system context.

To illustrate the climate-related hazards that influence the vulnerability of aquaculture production systems and species, the results rather than the methodology are emphasized here:

In terms of exposure, for both fisheries and aquaculture, the threats were identified as being increased temperatures, decreased water availability, decreased and increased rainfall, drought, flooding, storms and flash floods. Rising sea levels and salinity changes, which are common threats to coastal aquaculture, are not applicable to these inland study areas.

The factors that were considered to affect sensitivity were:

- The wide range of indigenous and exotic species being cultured or available for culture, which reflects the importance of biodiversity and aquaculture diversification.
- The production systems, which include extensive, semi-intensive and intensive, are still dependent on wild caught juveniles for seed and low value fish for feed. A climate change-induced scarcity of wild fish would disrupt the operation of most of the farms and thus the livelihoods of the farmers and farm workers.
- At the time of the study, production was 2 million tonnes per year and the growth in production had been exponential, dominated by Pangasius in Viet Nam's Mekong Delta. The adverse impact of climate change risks were likely to

be magnified by the large number of households dependent on aquaculture and ancillary industries for livelihoods.

- Cultured fish is important for food security in urban areas and to small-scale farmers. The Lower Mekong Basin has a population of 60 million, most of whom are small-scale farmers, and the effect of major climate change induced disruptions in fish supplies can thus be expected to have serious impacts on food security and livelihoods.

While intensive and some semi-intensive production systems have a greater risk of failure (e.g. densely packed fish are often more stressed, diseases and parasites can spread easily and if something goes wrong in one pond or farm more fish are lost) they often have greater adaptive capacity (greater capacity to invest, rebuild, relocate, secure credit, insurance, etc.) Extensive systems tend to have a lower risk of failure but also lower adaptive capacity. All three systems are vulnerable to climate change, yet intensive and semi-intensive systems are more vulnerable, as indicated in the qualitative VA described in Table 21.2, meaning that exposure can override adaptive capacity.

TABLE 21.2
Vulnerability of different farming systems

	Storms	Flash-floods	Temperature increase	Rainfall increase	Rainfall decrease	Decreased water availability	Drought	Flooding
Intensive catfish farming	H	H	H	L	M	VH	VH	VH
Semi-intensive pond polyculture of tilapia, silver barb and carps	H	H	H	M	VH	M	H	VH
Extensive pond polyculture of carps and tilapia	M	M	M	L	M	H	H	H

Vulnerability indications: VH – very high; H – high; M – medium; L – low.

21.3.5 Conclusions

The focus of the case studies presented here was assessments, based on the IPCC and derived models, of the components of vulnerability, i.e. the exposure of the subject, its sensitivity to the expected risks, and its capacity to adapt and prevent and mitigate likely impacts. Assessing each vulnerability component is as important, or even more important, than deriving a simple vulnerability value because reducing vulnerability (increasing resilience) is in fact the outcome of reducing exposure, lowering sensitivity and increasing adaptive capacity.

An assessment of vulnerability is one approach to evaluating the threats to a social ecological system and its ability to cope with those threats and there are also other frameworks for doing this. An "IPCC+ Framework" has been recommended, which acknowledges the existence and relevance of the other frameworks and builds complementary perspectives around IPCC vulnerability components (Brugere and De Young, 2015). The various models of VA could comprise the steps indicated in Table 25.4 in Chapter 25: Methods and tools for adaptation. However, in practice, most case assessments have covered only portions of the recommended steps.

Stakeholder engagement underpins the value of an assessment to beneficiaries. Handyside. Telfer and Ross (2017) suggested investigations at a more localized level, involving specific aquaculture practices and environmental conditions, could be considered. The VA cases reviewed here yield the following lessons on what this would imply for stakeholder engagement:

- It is at national and especially local levels where, in addition to being able to obtain more specific information on aquaculture practices and work on more detailed agro-ecological conditions, the social and economic circumstances and livelihood strategies of people, as well as opportunities and constraints, can be described and measured in finer detail. Data and information on sensitivity and adaptive capacity become more precise and the information more reliable and locally relevant.
- The subjects, i.e. the people in the target areas and those working at institutions providing services to them, can actively participate in the assessment process.
- The application of participatory methodologies and tools for social analysis, such as PRA, focus group discussion and risk analysis, are especially practicable.
- An inclusive bottom-up approach involving the beneficiaries of the assessment, such as recording perceptions of climate change and risks, can provide a better understanding of the climatic impacts and people's responses. Historical responses to different types of risk can be elicited to better inform the considerations of possible responses to future risk scenarios and management regimes.
- At the application stage, consultations can be carried out among primary stakeholders (policy and regulatory agencies, development agencies, civil society organizations, public-private service providers, science and technology institutions and the beneficiaries) to develop policies, strategies and action plans to increase adaptive capacities and resilience. The consultations should include determination of agency and institutional roles, capacity building and reforms.

Of the three components of a VA, exposure is the most difficult to establish, especially at the local level, because of the lack of high resolution models to understand local risks to aquaculture or aquaculture-based livelihoods. It is thus imperative to use proxies such as knowledge of past extreme events as well as methods and tools that incorporate local people's knowledge and involve their close participation. This enables a better understanding and a credible analysis of the risks that aquaculture systems and people face and to which resources and systems are exposed.

Finally, VA is not a once-off activity. Identification of groups and areas vulnerable to climate change, and updating to take account of change, must be a regular and continuous process for setting priorities and allocating resources.

21.4 ADAPTATION OPTIONS AND NEW OPPORTUNITIES

As highlighted elsewhere in this volume, climate change presents both challenges and opportunities for the sustained production of farmed aquatic food and those engaged throughout the value chain.

21.4.1 Risk-based zoning and siting

Most zoning and aquaculture site selection around the world has been undertaken on an ad hoc basis for a single farm or collection of farms without integrated or broader strategic planning. The spatial distribution of aquaculture has happened with limited attention to the impacts of climate change. However, a growing number of national and regional authorities are beginning to engage in aquaculture spatial planning processes (Aguilar-Manjarrez, Soto and Brummett, 2017; FAO, 2017a).

Adequate zoning and site selection for aquaculture through risk analysis can be an important adaptation measure to climate change. When selecting aquaculture sites, it is very important to identify the likely threats through risk assessment analysis (Cattermoul, Brown and Poulain, eds., 2014). For example, the location of marine fish cages must consider exposure to weather events, changes in currents, or to a sudden influx of freshwater, in addition to longer-term trends such as rising temperature and salinity and decreasing DO levels in order to define zones for aquaculture and decide on the location of individual farm sites. In general, moving floating fish cages farther offshore can help mitigate environmental and food safety concerns and in a few offshore sites submersible cages are being used to withstand adverse weather events. However, there are tradeoffs: moving fish farms into more exposed areas also leads to increased technological and economic challenges.

The allocation of space for inland and coastal ponds in many places around the world has been governed more by land and water access opportunities than shelter from climate change and other risks. Important climate-related risks for earthen fishponds include extreme temperatures, excessive rainfall, prolonged cloud cover, flood and drought (Pimolrat *et al*., 2013). The consideration of climate change and other risks in zoning and site selection is needed in areas both where aquaculture is beginning to develop and where aquaculture has developed and it is difficult to relocate fixed structures. Area management approaches in cases where several farms share a common water body or water source, become essential in addressing potential risks. Advances in remote sensing technology, risk communication, weather information systems and integrated monitoring systems create new opportunities to increase the effectiveness of zoning and siting strategies for aquaculture.

21.4.2 Environmental monitoring systems

Although fisheries and aquaculture are sensitive to sudden climate changes and climatic variability (as well as to long-term trends and changes) there are very few examples worldwide of integrated monitoring systems providing information and interpretation of the information that small-scale fishers and fish farmers can trust and use to make decisions. Even though information on meteorological conditions can reach fishers and fish farmers and they may have some experience interpreting this information and the potential consequences for the farm or fishing operation, simple information collected systematically over the long-term can provide a highly relevant tool for decision-making, especially when changes can produce dramatic consequences. For example, temperature changes can trigger disease in farmed aquatic products and sudden water movements or internal circulation can bring anoxic water to the surface or trigger toxic algal blooms. Changes in pH or salinity can also affect farmed fish survival, growth and production, while changes in monsoon and rain patterns can influence freshwater delivery, with sudden floods or droughts. Aquaculture farmers need to be prepared.

Early detection of HABs allows fish farmers and fishers to make timely decisions in order to minimise the damage to aquaculture and coastal fisheries. Phytoplankton monitoring networks are more common for salmon farming and for harvested or culture-based fisheries of filter feeders such as mussels and clams. Anderson (2009) reported that monitoring programmes for toxins in shellfish were being conducted in more than 50 countries. The detection of dangerous levels of HAB toxins in shellfish leads to harvesting restrictions to prevent contaminated products from entering the market. Monitoring of other variables relevant to aquaculture is much less common. Some programmes are implemented for salmon,[4] in which densities of spiny algal cells that can damage fish gills and may generate massive fish kills, rather than HAB toxins, are of interest. Adequate monitoring and early warning can facilitate mitigation strategies, such as early harvesting or relocation of fish net pens from sites of intense HABs. Even the use of simple methodologies and Secchi disk readings can facilitate early identification of a HAB and raise alarm. Other events that could be prevented or mitigated include extensive anoxic events affecting fish farming in lakes. Such events can be caused by certain winds and changes in temperature that facilitate upwelling of anoxic hypolimnetic waters. Monitoring of DO and temperature, especially the

[4] Open platform to follow phytoplankton conditions and HAB risks in salmon farming areas in Southern Chile http://mapas.intesal.cl/publico/

latter, can facilitate the identification of colder and deeper water masses that can generate such events. Another common threat is the sudden rise in water levels during extreme monsoons or heavy rain events that can damage fish and shrimp ponds. Monitoring lake and reservoir water levels may provide a simple estimate of water level rises and communication of readings through local networks can assist rapid action and prevention. The monitoring of environmental variables such as DO and water transparency can also indicate excessive nutrient output from farms that could exacerbate the effects of climate variability on farmed fish.

Integrated monitoring systems

Integrated monitoring systems involve continuous measuring and reporting of variables in strategic locations within a connected ecosystem so that the collected information can be integrated into a GIS or simple database. Information is periodically assessed and evaluated by a technical team that can identify early warning signals and provide feedback to users for their consideration in management decisions even at the lowest level; e.g. whether fishers will stay home or go fishing or whether a fish farmer feeds or avoids feeding fish. Decisions by fishers and fish farmers involve the knowledge and trust of risk-related information provided by those analysing the information.

Measuring variables in the field is ideally done both by technicians and experts collecting more sophisticated information and by farmers and fishers collecting simple information so that the latter are part of the monitoring system, are more aware, and can also trust the information and feedback because there is ownership of the monitoring and EWS. Obviously, because fish farmers and fishers are in the field every day, they can make observations and collect information at higher frequencies and with lower cost. Monitoring and reporting on any variable requires standardization of methodologies, indicators, etc. and training, considering the different background and knowledge of trainees, is required. Training also contributes to better understanding of threats and risks and therefore improves resilience and adaptation to climate change.

A basin-wide assessment of integrated monitoring and EWS for fisheries and aquaculture in the lower Mekong, (including Thailand, Viet Nam and Cambodia; FAO, 2017a) provides relevant information on the available systems and improvement needs, including the following key aspects:

- Environmental monitoring systems follow a risk-based approach recognising that increased risk requires increased monitoring.
- The involvement and the value of locally collected information by farmers and fishers enables them to better understand the biophysical processes and become part of the solution, e.g. rapid adaptation measures and early warning, long-term behavioural and investment changes.
- Early warning can range from large-scale life or property threatening events such as floods and storms to issues that are particularly pertinent to fisheries, fish farmers, crops and livelihoods, seasonally or over the long-term.

EWS need to be robust, reliable, timely and operate automatically where appropriate in order to avoid unnecessary delays caused by waiting for human intervention. The type of warnings such systems should provide need to be carefully considered, in addition to the time frame within which the warnings need to be communicated. Cellphones that are currently available globally are increasingly being seen as useful tools, including instant messaging, and could be a useful way to communicate with end users, although sudden public emergencies could overload mobile phone networks, so the length of the warning period is important. Warning systems need to have multiple levels of redundancy to ensure 100 percent uptime (FAO, 2017a). In addition, there are a number of global environmental monitoring systems that are increasingly being networked to provide early warnings of, for example, HABs[5].

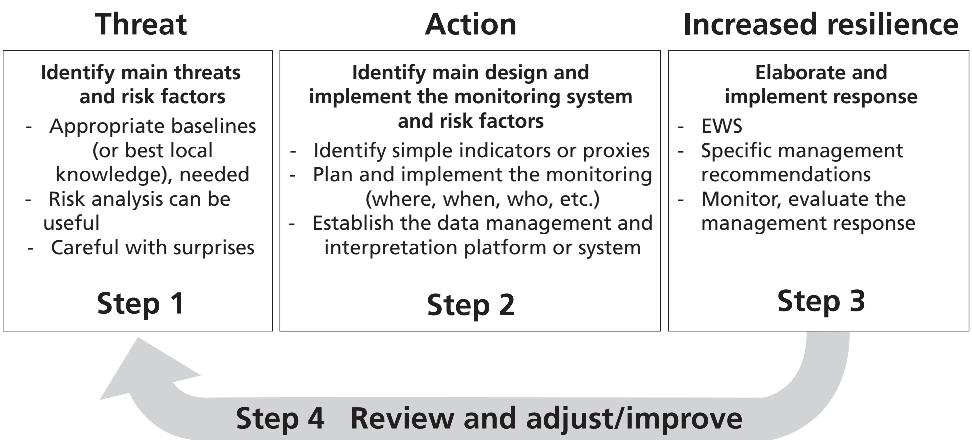
The main principles guiding the development of environmental monitoring and EWS can be summarized as follows:

- useful to farmers
- involve farmers
- cost-effective (simple, doable and useful to fish-farmers for management decisions)
- timely
- lead to and promote sustainable use of resources
- long-term
- reviewed and maintained regularly.

Key activities include training of local stakeholders on the value of the information and the monitoring and use of the feedback for decision-making. Any integrated monitoring system must also provide and enable implementation of a simple network or platform that receives and analyses information, coordinates connection with broader forecasts and monitoring systems and provides timely feedback useful to local stakeholders. This can be implemented through public-private partnerships and involving relevant research and technical institutions. A step-wise process is recommended, as shown in Figure 21.3.

Clearly, at a global level there is an increasing wealth of information being generated, but there is an urgent need to coordinate and integrate its use to benefit fishers and fish farmers and ensure the sustainability of the resources they are exploiting.

FIGURE 21.3
Schematic representation of the process and steps to implement local monitoring and early warning systems



21.4.3 Access to financial services

Credit

An issue that hangs over aquaculture is the general perception that it is a high-risk economic activity, now exacerbated by the uncertainties brought about by climate variability. The result is commonly for financial service providers to either shy away

[5] http://www.pml.ac.uk/Research/Projects/S_3_EUROHAB_Sentinel_products_for_detecting_EUtR; http://www.waterinsight.nl/info/wisp-3. Both accessed 20 February 2018.

from providing loans or insuring crops and farm assets or charge a high interest rate or premium that farmers, especially the small-scale, can ill afford.

Credit will invariably be needed to implement measures to prevent, reduce or cope with the impacts of climate change-induced risks. Capital investment is needed for relocation, infrastructure and equipment upgrade, repair or replacement required to prevent or reduce impacts of extreme weather, such as strong winds, heavy rains or floods as well as tidal surge. Adaptation increases operating costs: for example under extreme weather conditions, aeration may be needed to maintain water quality; and vitamin C, probiotics and other feed additives may be used to increase stress resilience in farmed fish. Although cost-effective, such actions may not be adopted because of poor access to affordable funds. In fed aquaculture, credit is frequently crucial to re-start operations, feed being a major portion of operational costs, and farmers who have lost their crop typically have little or no savings set aside for feed or seed. In some countries, feed dealers who supply feed on credit extend the credit line of farmers to tide them over to the next crop. There are, however, conditions attached to the harvest that are not always favourable to the farmers.

Access to affordable credit is thus crucial for effective and efficient climate change adaptation and for recovery from climate-change induced damage (Karim *et al*., 2014). This could be effected through development of appropriate policy and through mechanisms such as micro-finance schemes and loan guarantee funds.

Insurance

Recent catastrophic natural disasters and the increasing frequency, prevalence and severity of risks driven by climate change should prompt governments to explore adaptation options in addition to disaster-relief and damage compensation. Pilot aquaculture insurance programmes provide promising examples of policy and practice to enhance national adaptation. Insuring small-scale farms, which are particularly vulnerable (and a major contributor to food security), has proved a sound investment; insurance can be included in social security policies to help farmers recover quickly from disasters and relieve the strain on government budgets. Pilot programmes in China and Viet Nam yield valuable guidance: 1) models of insurance business and innovative insurance schemes can be tailored to farmers' circumstances; 2) farmers can improve their perception of risks, leading to faster adoption of climate-smart management practices that reduce risks and make them more insurance- and credit-worthy; 3) with government support insurers have devised mutually beneficial schemes with farmer organizations that make aquaculture insurance a viable and sustainable business; and 4) government has backed political decisions with policy, institutional and financial support (FAO 2016a, 2017b).

The business viability of aquaculture insurance depends on aquaculture becoming more efficient and lower-risk. The insurance-pooled model applied to small farms can help raise production efficiencies and reduce production and market risks, leading to the following outcomes: 1) farmer adoption of good practices; 2) development of farm certification schemes; 3) strengthened producer organisations with members improving their capacity to participate in value chains; and 4) provision of credit bundled with financial products (e.g. insurance with feed credit). These can make insurance affordable to small farmers without the need for expensive subsidies. Insurance thus becomes an institutionalized risk management strategy and a cost-effective complement, if not alternative, to post-disaster relief and compensation.

21.4.4 Better management practices

Better management practices (BMPs) have been increasingly promoted to improve the environmental performance, productivity and profitability of farms. They are designed to reduce production and marketing risks and invariably enhance consumer confidence in products that are responsibly farmed and safe. BMPs have gradually incorporated provisions for food safety and social responsibility, especially in relation to farm workers and the community. Many of the practices being promoted have positive effects on mitigation and adaptation, even if climate change is not yet explicitly considered in BMPs. Climate change hazards should be incorporated into aquaculture BMPs, especially with regard to the resilience of farmed aquatic plants and animals, safety at work and farming systems.

The link between BMPs as well as technological innovations (which are often the cutting edge of BMPs) and the financial services, credit and insurance, is that BMPs, by reducing risks and increasing the adaptive capacity of farmers, make aquaculture more credit- and insurance-worthy. This also tends to improve productivity and profitability, which then enables farmers to invest in capital, adopt innovations and adhere to better practices that strengthen their resilience.

21.4.5 Technological innovations

The term "technological innovations" is applied here to alternative species and climate-adapted strains and aquaculture systems that reduce susceptibility to climate change, as well as to technologies that can inform risks and adaptation.

Given the pace of innovation and growth in computational power, spatial technologies have an increasingly important role to play in climate change adaptation strategies in the aquaculture sector. Recent advances in remote sensing platforms (e.g. drones and satellite constellations) are now being integrated with information and communication technologies; examples include early warning information systems (e.g. weather forecasts and early detection of HABs) and communication of risks using mobile communication devices (e.g. smartphones and tablets), cloud-based data systems and virtual reality and simulations (see also Section 21.5.3).

Stronger materials and better system designs (including mooring), coupled with the development and implementation of rigorous technical guidelines, play a role in reducing vulnerability to climate change in the marine aquaculture sub-sector of countries such as Canada, Chile, Norway and the United Kingdom. Such technologies, however, can be costly. Moving water-based aquaculture (especially cages and pens for finfish) onto land and employing recirculating aquaculture system (RAS) technologies are also being proposed as a means of reducing exposure to climatic extremes. In such systems, water quality, including temperature, DO, salinity and pH, can be controlled to meet species' needs. RAS, however, remain comparatively expensive in terms of both capital and operational costs and require high levels of technical expertise (Murray, Bostock and Fletcher, 2014). While there has been steady progress, the long-term reliability of RAS still needs to be demonstrated. Aquaponics, the production of fish and plants in an integrated system, is proposed as a means of producing food in areas where freshwater is limited (Somerville *et al*., 2014). Aquaponics can be considered as a particular type of RAS and thus shares many of the same attributes. It is also worth pointing out that neither system is likely to be immune from extreme climate events in small island developing states or coastal areas vulnerable to such events without further development.

At the farm level, well-designed and well-built ponds or rice–fish fields can help mitigate against some of the adverse effects of climate change. Deeper ponds, for example, provide a thermal refuge and greater DO reserves for fish, while raised pond embankments can help prevent fish escapes and dyke destruction during floods and serve as water storage during droughts. A well-conceived facility can sustain multiple purposes beside aquaculture. Converting flow-through ponds and raceways into more water-efficient technologies is also desirable, as is reducing seepage through the use of pond liners.

Use of non-native aquatic germplasm, including exotic species (e.g. use of euryhaline, estuarine species or species tolerant of warmer water), has been proposed as a means of adaptation to climate change (Harvey *et al*., 2017), albeit that there are strong associated risks, as discussed in Chapter 19. While the development of strains of farmed aquatic organisms with improved salinity tolerance has long been practiced (Abu Hena, Kamal and Mair, 2005) the development of strains tolerant of higher or lower temperatures, or indeed other environmental variables impacted by climate change, is in its infancy and largely unproven, but will likely prove difficult, time consuming and costly. Transgenics are already being co-opted to deal with temperature changes[6] and CRISPR-CAS9 gene editing tools will open many important prospects. The ecological, economic and market origin pitfalls associated with diversification can be responsibly addressed by the application of the principles in Table 21.3.

TABLE 21.3.
Principles for aquaculture diversification (Harvey *et al*., 2017)

	Principle
1	Diversification demands information. Identify knowledge gaps and seek expert advice.
2	Diversification should anticipate, adapt to and mitigate the effects of climate change.
3	Diversification should be compatible with local ecosystems and not reduce aquatic biodiversity.
4	Diversification should be compatible with other responsible food producing sectors.
5	Diversification should comply with national and international laws, codes of conduct and conventions.
6	Diversification should be planned in consultation with all stakeholders and be attractive to farmers.
7	Diversification should minimize risks from pathogens and predators.
8	Diversification should be profitable in domestic and/or export markets, taking account of the risks of market shifts.

21.5 AQUACULTURE AS AN ADAPTATION OPTION

Climate change may create new opportunities to promote diversified and more resilient aquaculture-based livelihoods.

Most Pacific island countries and territories are exploring the potential of freshwater aquaculture to improve food security in the context of climate change (see for example Chapter 12). In Chile, aquaculture has long been considered an alternative for fishers and as a means to strengthen small-scale enterprises and diversify the livelihoods of fisheries-dependent coastal communities (FAO, 2017a). Aquaculture is also increasingly proposed as a solution to reduce fishing pressure on coral reefs affected by trade in live reef organisms (Pomeroy, Parks and Balboa, 2006).

Bangladesh provides several examples of the use of aquaculture as a climate change adaptation option (Karim *et al*., 2014). For instance, in the coastal region of Southwest Bangladesh, waterlogged croplands are being transformed into crop–aquaculture systems, while in a disaster-prone region of the country, aquaculture ponds were found to be important for supplying food and income during post-disaster periods. Similarly, in the northeast of Bangladesh, where rainfall can be erratic and the flooding of wetlands has affected fisheries, cage culture is being proposed as a means of producing fish during the dry season.

[6] AquaBounty has developed and is marketing a faster growing strain of Atlantic salmon, based on transgenic technologies https://www.scientificamerican.com/article/first-genetically-engineered-salmon-sold-in-canada/, accessed 20 February 2018.

In Viet Nam salt-tolerant varieties of rice and rice–fish cultivation can reduce vulnerability to sea level rise and storm surge damage (Shelton, 2014). In drought prone areas of the Near East and North Africa regions, integrated agri-aquaculture production systems are being used to promote water saving activities (Crespi and Lovatelli, 2011) while in Brazil, the introduction of cage cultured tilapia to reservoirs has provided viable alternative livelihoods and employment opportunities in areas that are vulnerable to drought and erratic rainfall (FAO, 2017a).

Climate-smart agriculture aims to sustainably increase agricultural productivity and incomes, while building resilience through adaptation to and mitigation of the impacts of climate change. It guides actions needed to transform and reorient agriculture systems to increase productivity, enhance resilience (adaptation), reduce or remove greenhouse gases (mitigation) where possible, and enhance the achievement of national food security and sustainable development goals (FAO, 2013, forthcoming). CSA differs from other approaches such as sustainable intensification of aquaculture in its explicit focus on addressing climate change and the search for maximizing synergies and trade-offs between productivity, adaptation and mitigation while ensuring accessible and nutritious food for all. This challenge has led some researchers and fish farmers to consider CSA as an alternative and innovative adaptation practice that allows increased aquaculture production while ensuring societal and environmental sustainability. For example, integrated multi-trophic aquaculture uses the farming of a combination of fish, shellfish and aquatic plants to remove particulate and dissolved wastes from fish farming and provide a self-sustaining source of food (FAO, forthcoming).

CSA principles have been applied to aquaculture to:

- improve the efficiency of natural resource use and maintain the resilience of the surrounding aquatic systems and communities that rely on them;
- the management of genetic resources to ensure that species with relevant traits for climate change adaptation and mitigation are conserved; and
- increase the uptake of RAS technologies to reduce the need for fresh, clean water while maintaining a healthy environment for fish.

To facilitate the promotion of aquaculture-based livelihoods, efforts are needed to integrate aquaculture into climate change adaptation and food security policies at national level, ensuring their incorporation into broader development planning.

21.6 CONCLUDING REMARKS

To address adaptation it is necessary to understand vulnerability and be able to identify major drivers and general exposure to climate change. It is almost always difficult to foresee what will happen in the future as a result of climate change but likely negative impacts can be reduced by reducing the sensitivity of the sector and by increasing measures to minimize exposure.

In general, aquaculture spatial planning and management following an ecosystem approach to aquaculture (FAO, 2010) could strengthen adaptation capacity, especially at local level. This requires the understanding of risks at relevant spatial and temporal scales, prioritizing those most relevant and the development and improvement of measures and management plans to address such risks through participatory approaches and using the best available information. Most important is that all measures and investments to reduce vulnerability are good for aquaculture sustainability in any future scenario. Reduction of vulnerability is unlikely to take place for aquaculture alone and the EAA can facilitate better integration of preparedness and response with other users of resources.

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Chapter 22: Climate change and aquaculture: interactions with fisheries and agriculture

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KEY MESSAGES

- Interactions of aquaculture with other sectors may either exacerbate existing climate change impacts or help to create solutions to impacts of climate change on other industries.
- With the expected increase in extreme weather events, the number of escapes from aquaculture is anticipated to rise. Minimizing impacts of escapes can be achieved by regulating the movement of non-native aquatic germplasm, certification of cage equipment, modifying pond systems, capacity development of farmers and implementation of management measures.
- Reduced availability and quality of freshwater may lead to increased competition among water users. Water consumption by aquaculture can be reduced by a series of technological or managerial innovations but ultimately, the involvement of stakeholders in the development of coherent policy, legal and regulatory frameworks is essential for effective decision-making on future food-water scenarios and water allocation decisions.
- Even though important sources of fishmeal and fish oil are vulnerable to climate change, increased use of fish processing wastes and rapid developments in novel feedstuffs is likely to mean that the issue is only of importance for aquaculture in the short- to medium-term.
- Aquaculture also offers solutions to some impacts of climate change. Culture-based fisheries, for example, can be used to address climate change aggravated issues of recruitment in wild stock, requiring minimal feed use or other types of care.

22.1 INTRODUCTION

This chapter addresses the question of how climate change influences the interactions of aquaculture with fisheries and agriculture.

Although aquaculture has been dependent in varying degrees upon fisheries as a source of seed and feed, this dependence is steadily reducing. Reliance on wild seed carries high risks from a disease perspective and in some cases has inhibited development of productive farmed strains. Few fish farming operations today rely on wild seed or broodstock. Shrimp farming is also increasingly dependent on hatchery reared stock, while fears that climate change may reduce natural spatfall - upon which much oyster and mussel farming has been dependent - has attracted greater investment in hatcheries.

Much seaweed culture is reliant upon clones, liberating it from dependence on wild material. Of greater significance in the context of climate change is the potential for culture-based fisheries to compensate for shortfalls in wild recruitment. A concern here, however, is the impact of the deliberate release of hatchery reared stock, perhaps of alien species, into the natural environment and the accidental release of farm stock from aquaculture operations as a result of flooding and extreme weather events.

Climate change is likely to change the supply of ecosystem services derived from aquatic environments qualitatively and quantitatively, forcing changes in the types and distribution of fisheries, agriculture, aquaculture and other economic activities. With increasing frequencies and intensities of storms, for example, a greater premium may be placed on sheltered coastal areas, not only for fishing but also for aquaculture sites and for marinas and tourist facilities. In areas increasingly subjected to droughts, especially where population increases are great, competition for freshwater will likely increase, promoting the use of water saving recirculating aquaculture system (RAS) technologies.

With the rapid growth of aquaculture and intensification of production practices has come an increased use of feeds for finfish and crustacean aquaculture (Tacon, Hasan and Metian, 2011). Among the feedstuffs used are fishmeal and fish oil derived from fisheries vulnerable to climate change, raising concerns about the resilience of aquaculture to climate change.

This chapter does not address issues related to greenhouse gas emissions and mitigation, which are discussed in Chapter 27.

22.2 ESCAPES AND IMPACTS ON BIODIVERSITY AND SOCIAL AND ECONOMIC CAPITAL

The expected increase in extreme weather events resulting from climate change raises the likelihood of an increase in escapees from aquaculture farms and the prospect of adverse impacts on biodiversity. Freshwater and coastal ponds account for most farmed fish production, an estimated 85 percent to 90 percent, with the rest, especially in the marine environment, being primarily produced in floating cages. Most crustaceans are farmed in coastal ponds, while mussel rafts and intertidal trestle systems account for most oyster and mussel production. Seaweeds are largely farmed using off-bottom lines in shallow water or suspended long lines in deeper water. Losses of farmed aquatic organisms occur through floods (ponds), extreme weather events (cages, long-lines and trestles) and, occasionally, marked changes in currents (off-bottom and floating long lines and cages). Earthen ponds are susceptible to stock losses, especially in areas prone to flooding. The aquaculture systems most prone to escapes, however, are net cages (Beveridge, 2004).

Much aquaculture depends on the farming of non-native aquatic germplasm (De Silva *et al*., 2009; De Silva, 2012; FAO, forthcoming). Moreover, when aquatic plants and animals are transferred from the wild into a farm environment they undergo both inadvertent and targeted domestication: the former is caused by the culture environment (e.g. unusually high stocking densities, changed water quality and exposure to pathogens) and the latter by breeding programmes selecting for such traits as faster growth and improved disease resistance (De Silva, 2012; Lorenzen, Beveridge and Mangel, 2012). Over time, the domesticated strain diverges genotypically and phenotypically from the wild fish populations from which it originated.

The genetic diversity of wild populations is essential in adapting to changing environmental conditions. While farmed organisms tend to be less fit than their wild conspecifics when released into natural environments, they nevertheless may be released in sufficient numbers and survive sufficiently well to impact on wild fish populations. Feral farmed-fish can damage ecosystems (e.g. carps in the USA), displace wild fish through ecological interactions (e.g. competition for space or food; predation), reduce fitness and genetic diversity of populations if they interbreed with wild conspecifics, and change the dynamics of infectious diseases (Beveridge, Ross and

Kelly, 1994; Naylor *et al*., 2005; Singh and Lakra, 2011). Such changes also create social and economic impacts and adversely affect public perceptions of aquaculture (Jackson *et al*., 2015). Negative interactions are most likely where wild populations are small, and/or highly adapted to local conditions, and/or declining. However, long-term outcomes of the interactions between cultured and wild fish are highly variable and difficult to predict because outcomes are influenced by complex, linked ecological and genetic processes that are highly sensitive to domestication effects in cultured fish and wild population characteristics (Lorenzen, Beveridge and Mangel, 2012).

While there has long been concern about the impacts of aquaculture on biodiversity (Beveridge, Ross and Kelly, 1994) evidence for adverse impacts of non-native aquatic germplasm on indigenous species and strains is, with a few notable exceptions, scant (Canonico *et al*., 2005; De Silva, 2012). In a review of Atlantic salmon escapes Thorstad *et al*. (2008) highlight the risks to wild populations posed by feral native aquatic species, questioning the received wisdom that farming indigenous species is preferable to that of alien species. Evidence for impacts of feral seaweed and shellfish on biodiversity is even more scant (Briggs *et al*., 2004). Moreover, few studies have examined the impacts of feral non-native aquatic germplasm on social and economic capital. Arthur *et al*. (2010) found that non-native tilapias and carps were established in many Southeast Asian aquatic ecosystems with little discernible adverse environmental impact whereas their positive impact on livelihoods and incomes was considerable.

It is nonetheless in the interest of farmers, the state and other stakeholders reliant on aquatic ecosystems to minimize the incidence of escapes into the environment. The Convention on Biological Diversity[1] seeks to regulate the movement of non-native aquatic germplasm to protect biological diversity and minimize the transfer of pathogens. Movement of non-native aquatic germplasm is addressed in various codes of conduct and technical guidelines (e.g. FAO, 2008) and is also prohibited by law in many countries.

Article 9.31. of the FAO Code of Conduct for Responsible Fisheries, which deals with aquaculture, states that countries

> *"… should conserve genetic diversity and maintain integrity of aquatic communities and ecosystems by appropriate management. In particular, efforts should be undertaken to minimize the harmful effects of introducing non-native species or genetically altered stocks used for aquaculture including culture-based fisheries into waters, especially where there is a significant potential for the spread of such non-native species or genetically altered stocks into waters under the jurisdiction of other states, as well as waters under the jurisdiction of the state of origin. States should, whenever possible, promote steps to minimize adverse genetic, disease and other effects of escaped farmed fish on wild stock." (FAO, 2008).*

In Norway, Scotland (United Kingdom) and Chile reporting of aquaculture escapes and their underlying causes is mandatory and reports are made public[2]. In a pan-European (Ireland, Scotland, Norway, Spain, Greece and Malta) survey of the extent and causes of escapes from marine fish farms over a three year period (2007 to 2009) more than 20 causes - structural, biological, operational, external and unknown - were identified (Jackson *et al*., 2015). While only 10 percent of loss incidences were directly attributed to storm damage, Jackson *et al*. (2015) concluded that adverse weather was a likely contributing factor to losses from other categories. The relationship between number of incidences and stock losses, however, is weak, with some types of incidence, including storms, accounting for a disproportionate amount of catastrophic losses. For example, Jackson *et al*. (2015) found that over 5 million fish, equivalent to 56 percent of all escapes in their study, were caused by just two incidences, neither of

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[1] http://www.cbd.int/

[2] see http://aquaculture.scotland.gov.uk/data/fish_escapes_record.aspx?escape_id=2000460, for example.

which was because of storm damage. Insurance claims provide further insights. In the European Commission funded Sixth Framework Programme Ecosystem Approach for Sustainable Aquaculture project[3] (2001 to 2006) 76 claims were made by Greek fish farmers for stock losses resulting from storm damage, accounting for 36 percent of the total value of all claims, while a further 19 percent of the total loss value was from equipment damage, also caused by storms (Jackson *et al*., 2015).

Jensen *et al*. (2010) found that differences in the numbers of fish farm escapes within Europe are in part a result of the higher equipment standards and better management practices in Northern Europe compared to the Mediterranean. A number of countries have begun to tackle the issue, primarily because of public concerns over impacts on wild fish populations. The Government of Scotland (United Kingdom), for example, is working with stakeholders to develop technical standards for fish farm equipment (Marine Scotland, 2015) and implement statutory industry training[4]. By 2020 all finfish farms in Scotland must have appropriate equipment and procedures in place to minimize escapes. Similar measures have been implemented in Chile.

No such measures have yet been taken with regard to ponds or other systems. Careful zoning and site selection to avoid flooding and modification of designs to minimize escapes during floods (e.g. Handisyde *et al*., 2014) will help reduce stock losses. While the efficacy of such measures has yet to be clearly demonstrated, evidence is mounting that they are helping drive down numbers of escapes. The methodologies being implemented in Northern Europe for cage aquaculture, involving the development and application of technical standards and implementation of good management practices, could be extended worldwide as well as to other types of aquaculture system. The combination of regulation and financial self-interest provides strong incentives. A framework for the development and management of aquatic genetic resources, which addresses many of the issues relating to use of non-native aquatic germplasm, is currently under development by FAO in consultation with *inter alia*, WorldFish and the Southern African Development Community member countries (D. Bartley, personal communication, 2018).

The optimum preventative measures to minimize escapes will vary according to the risks, costs and methods of production in different localities but implementation of suitable measures is a necessary adaptation to the consequences of climate change, particularly the expected increase in frequency and intensity of extreme events.

22.3 LAND AND WATER AND COMPETING SECTORS

According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (Jimenez Cisneros *et al*., 2014) climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions, impacting on freshwater ecosystems by changing surface and groundwater flows and water quality. This is expected to intensify competition among various types of agriculture (crop, livestock, etc.), as well as between agriculture and other demands for example, potable water supplies for urban settlements, water for industry and for energy production, potentially impacting on regional water and energy supplies as well as food security. Agriculture is one of the main users of freshwater and global adaptation to climate change must consider food production systems that are more efficient in using such resources.

Aquaculture is a relatively water-efficient way of producing animal protein (Verdegem, Bosma and Verreth, 2006). Water consumption by aquaculture can be divided into direct (i.e. net water harvesting, derived from the water content of harvested fish) and indirect use (i.e. water required to produce aquaculture feeds and to

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[3] http://www.ecasa.org.uk.

[4] see http://thecodeofgoodpractice.co.uk/chapters/.

maintain pond water levels, compensating for water losses from evaporation, seepage and intentional discharge). The former is negligible: each tonne of fish harvested results in the removal of around 760 litres of water (Beveridge and Brummett, 2016). Indirect losses may be several orders of magnitude greater. Evaporative losses increase with pond surface area and with temperature, modified by wind movement and topography, and can be as high as 6.3 mm per day (Verdegem, Bosma and Verreth, 2006), equivalent to a daily loss of 63 cubic metres per hectare. Water loss by seepage is primarily determined by soil characteristics, clay soils providing much better water retention than silt and sand soils. Although more extensive forms of pond aquaculture have limited water exchange, low stocking densities typically result in high water use per unit of production.

Water for freshwater pond fish farming may come from rainwater harvesting (i.e. the interception and storage of water before it reaches the aquifer) or from diversion or abstraction of water from rivers or canals. Groundwater resources are costly to develop and often have water quality problems (e.g. high iron, sulphur and CO_2 and low dissolved oxygen concentrations). The withdrawal of water from river channels or diversion to fish ponds can affect the flow regimes (the environmental flows) needed to sustain fish and the fisheries upon which they depend (Brummett, Beveridge and Cowx, 2013).

Cage aquaculture derives aquatic ecosystem services from the lake or reservoir in which cages are sited. The issue of water use in lakes is thus largely limited to water used to produce feeds and to disperse and assimilate wastes (see below), while in reservoirs the requirements to maintain sufficient water depths for cage aquaculture may compromise water drawdown plans for power and irrigation (Lorenzen *et al*., 2007). Dense development of cages in irrigation canals also reduces water flows, compromising supplies of water for irrigation (Beveridge, 2004).

Increased temperatures will increase respiratory demands by farmed aquatic animals and evaporative water losses from ponds, thereby increasing water use per unit of aquaculture production. Decisions on water allocation must be guided by policy and regulation and involve stakeholders (FAO, 2016a, 2016b). However, there remains a lack of key data on water use and no methodology that facilitates comparisons of freshwater use in aquaculture with other food production sectors. This inhibits analysis of synergies and trade-offs between farmed aquatic products and terrestrial foods in terms of water use and consumption, and formulation of future food-water scenarios, thereby hindering informed decision-making and policy considerations (Gephart *et al*., 2017).

Direct water consumption by aquaculture can be reduced through site selection. Hills and trees reduce solar and wind induced losses (although trees also increase evapotranspiration) and in areas with clay soils, evaporative losses per unit of fish production can be limited by deepening ponds, reducing the surface water to volume ratio. Use of concrete or butyl pond liners reduces water seepage losses, but they are expensive (Boyd and Chainark, 2009). Increasing on-farm productivity through higher stocking densities, greater reliance on external inputs and aeration can reduce on-farm water consumption. However, crop-based feedstuffs, which increasingly predominate in commercial pelleted diets, require water, increasing the water consumed per unit of farmed aquatic food production (Troell *et al*., 2014a, 2014b). If crop-based feedstuffs for aquaculture are imported as, for example, they are in water-stressed Egypt, the issue of water use can be outsourced to areas where freshwater is more plentiful, albeit at greater transport costs (and greenhouse gas emissions). Better water management too is important and can be encouraged through charging for water use or through regulation of abstraction aimed at protecting ecological flows (Brummett, Beveridge and Cowx, 2013). Similarly, reducing aquaculture wastes through use of more digestible feeds and improved feed management reduces demand on aquatic ecosystem services.

Aquaculture can also be incorporated into multiple water use basin-level initiatives, further reducing water use and consumption per unit of aquaculture production, and improving resilience to climate change (Nagabhatla *et al.*, 2012). Other aquaculture technologies that result in less direct water use include RAS and aquaponics (see Chapter 21).

While marine finfish culture is an efficient means of producing animal protein, the great majority of farmed marine finfish presently relies on feedstuffs that require freshwater (Troell *et al.*, 2014a, 2014b). In the near future, however, feeds are expected to come from alternative sources, including food processing wastes, microalgae and seaweed. Bivalves and seaweeds, of course, require no additional foods. Well implemented mariculture could thus prove to be a sound adaptation strategy to climate change induced shortages of freshwater, accompanied by initiatives to try to change consumer interest towards non-fed species (Duarte *et al.*, 2009).

22.4 CAPTURE-BASED AQUACULTURE

Capture-based aquaculture – the farming and fattening of individuals that have been captured in the wild – is still relevant in aquaculture, especially with species that are difficult to breed in captivity. These include, for example, the great majority of farmed mussels, some farmed shrimp in Asia (especially *Penaeus monodon* and, in Bangladesh, freshwater prawns), the farming of tuna worldwide and other high-value marine finfish species in Asia. Climate change, along with the disturbance of breeding grounds, may exacerbate pressure on wild populations of these species, reducing their ability to maintain viable populations. Climate change may reduce their availability and therefore affect coastal fisheries for and farming of these resources. There is thus a need to make hatchery seed more available and affordable to farmers and to identify alternatives for fishers whose livelihoods rely on the collection of seed.

22.5 CULTURE-BASED FISHERIES

Culture-based fisheries (CBF) are defined here as fisheries dependent on regular stocking of hatchery reared progeny or broodstock, either to support fisheries (discussed in Chapter 18) or as an integral part of the rehabilitation of ecosystems such as corals damaged by climate change (see De Silva and Soto, 2009). A number of issues associated with stocking open waters with fish of farm origin are covered in Section 19.2 above.

CBF are highlighted as a climate smart fish production system because, other than at the hatchery stages, they do not require feed or other care (FAO, 2013). The practice is already widespread as a response to recruitment-limited water bodies, such as man-made reservoirs (De Silva, 2016), but may have future potential in systems where natural recruitment has become constrained or no longer viable because of water scarcity, seasonal temperature fluctuations and other impacts. On the other hand, fishers engaged in CBF in non-perennial water bodies subject to changes in rainfall pattern may have to change their stocking and harvesting calendar to better fit with the altered pattern of monsoonal rains (Wijenayake *et al.*, 2010).

CBF in reservoirs and in some lakes in Central America provide an important protein source for coastal communities, especially when their usual food sources are affected by external forcing factors such as climate change.

The provision of hatchery-produced seed may help address climate change impacts on coastal CBF, for example, when benthic populations that support fisheries (e.g. clams, oysters) have been damaged by storms. Additionally, hatchery produced seed may be more resistant to lower pH or higher temperatures. Fisheries of benthic organisms in many places around the world depend on the availability of seeds and their settlement in natural beds (e.g. clams and sea urchin fisheries in Southern Chile, scallop fisheries in Peru). Settlement may be vulnerable to climatic variability and climate change, on top of heavy overfishing. Indeed, the future of many coastal fisheries will probably depend on hatchery-produced seed that are adapted to climate change. It is important to ensure that CBF do not have undesirable impacts on the genetic diversity of wild populations, as discussed in Section 19.2.

22.6 AQUACULTURE DEPENDENCE ON FISHMEAL AND FISH OIL

The proportion of finfish and crustacean aquaculture production reliant on feeds, often including fishery derived fishmeal (FM) and fish oil (FO), is high and increasing (Tacon, Hasan and Metian, 2011). However, this trend must be seen against a background of improved feeds and feeding practices (as indicated by improved food conversion ratios), reductions in fishmeal and fish oil dietary inclusion rates and the increasing use of alternative FM and FO sources (Little, Newton and Beveridge, 2016; Ye *et al*., 2017). The proportion of fish from capture fisheries that is being reduced to FM and FO has been declining (Ye *et al*., 2017) and high prices are forcing feed manufacturers to reduce FM and FO inclusion rates in favour of oilseeds such as soy and to seek cheaper, alternative sources, such as fish processing wastes (Little, Newton and Beveridge, 2016). FAO estimates that FM produced from fish processing wastes will represent 38 percent of world FM production by 2025, compared to 29 percent for 2013 to 2015 (Ye *et al*., 2017). Moreover, such estimates do not take account of the rapid development and commercialization of alternative protein and lipid sources. Many commercial feed manufacturers[5] have embarked on the development of commercially viable FM- and FO-free diets, substituting those products with novel feedstuffs, such as insect protein meal and microalgae. Thus, while the single largest fishmeal and fish oil reduction fishery, located in Peru, is vulnerable to adverse effects of climate change (Chapter 15), the implications of this for aquaculture diets is assessed as being of only minor concern in the medium to long term.

22.7 DISCUSSION

Climate change will likely increase interactions between aquaculture, fisheries and agriculture in a range of ways and as climate change progresses, aquaculture will have to set out its comparative advantages in meeting countries' economic, environmental and social objectives *vis-à-vis* these other sectors. Competition between aquaculture and other users for freshwater will intensify as resources become scarcer. Increasing use of surface and groundwater for irrigated agriculture to compensate for dwindling or unreliable precipitation, for example, may affect the availability of freshwater for aquaculture. Water allocation decisions will require consideration of the role that countries wish aquaculture to play in meeting their economic, social and environmental goals. An equitable allocation of water resources among users will require the involvement of stakeholders in the development of coherent policy, legal and regulatory frameworks. In turn, this will need an appropriate water use and consumption framework and reliable data, which ideally should be generated through initiatives that involve the cooperation of otherwise competing economic sectors.

Much can also be done to reduce the vulnerability of aquaculture to climate change. With the expected increase in extreme weather events, the numbers of escapes from aquaculture is also anticipated to rise, but this can be minimized by certification of equipment fit for purpose (i.e. able to withstand likely extreme weather events where it is being used), regulating the movement of non-native aquatic germplasm and enforcing the monitoring of escapes. Domestication, improved hatchery technology, and implementation of policies that encourage investment by farmers in seed production and distribution will further reduce use of wild aquatic resources for seed. Dependence on FM and FO can be reduced by incentivising commercialization of

[5] https://www.skretting.com/siteassets/au-temp-files/nexus-and-reports-and-brochures/nexus_issue_22_web.pdf

alternative sources of feedstuffs, such as fish processing wastes, black soldier fly larvae, microalgae and seaweeds.

Aquaculture also has the potential to reduce the impact of climate change on other sectors. One such example is through the development of culture-based fisheries, which can contribute to sustaining food security, resilience and the livelihoods of fishing communities.

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Chapter 23: Impacts of climate-driven extreme events and disasters

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KEY MESSAGES

- An extreme event is generally defined as the occurrence of a value of a weather or climate variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable. Some weather or climate events (e.g. tropical cyclone), even if not extreme in a statistical sense, can lead to extreme conditions and socio-ecological and physical impacts or disaster (Seneviratne *et al*., 2012).
- Sectors that are markedly influenced by climate, such as fisheries and aquaculture, are facing substantial threats from extreme events and other stressors.
- It is expected that a warmer climate will be one in which the hydrological cycle will be disrupted, leading to changes in the frequency, intensity, geographic distribution and timing of extreme events.
- Not all extreme events or natural hazards will lead to a disaster. The severity of the impacts on humans will vary depending on the exposure and vulnerability of the fishing and fish farming communities and industry, the intensity of the hazard in relation to the location, the type of livelihoods and existing national and local coping and adaptive capacities.
- United Nations Office for Disaster Risk Reduction (UNISDR, 2015) reports that climate-related disasters now account for over 80 percent of all disaster events. They contribute enormously to economic losses and short- and long-term population displacements.
- FAO (2018) reports that fisheries account for at least three percent of the total impact of natural disasters, including climate extremes, on the agriculture sector at large, while the share of aquaculture remains systematically overlooked and fisheries is typically under-reported.
- There is a need to improve post-disaster damage and loss assessments for the fisheries and aquaculture sector, in line with the Sendai Framework for Disaster Risk Reduction, and to try to link those assessments to loss and damage evaluations of the Warsaw International Mechanism, of the United Nations Framework Convention on Climate Change.
- It is urgent to ensure proactive management of climate risk rather than reactive management of disasters. This is done through investing in disaster risk reduction and adaptation measures for climate resilience to anticipate, prevent, prepare for, reduce the impact of and respond to extreme events and/or disasters affecting the fisheries and aquaculture sector.

23.1 SIGNIFICANT EXTREME EVENTS AND DISASTERS DURING 2016 TO 2017

The North Atlantic basin was extremely active in September 2017, with three major hurricanes (NHC, 2017). Of these, hurricane Irma reached category five for three consecutive days; no other hurricanes have matched that strength so far east in the Atlantic (Aish, Pearce and Yourish, 2017). Irma's winds reached 185 miles per hour for 37 hours, the longest time on record that any cyclone around the globe has maintained such intensity (Aish, Pearce and Yourish, 2017). The previous record was Haiyan which caused devastation in the Philippines for 24 hours in November 2013[1]. Overall, September 2017 was about three and a half times more active than an average September from 1981 to 2010. Overall, activity in the Atlantic basin in 2017 was well above average[2].

At the global level, 2016 broke multiple records according to the World Meteorological Organization (WMO, 2017) and NOAA National Centers for Environmental Information (NOAA, 2018). The WMO and NOAA reports stated that most indicators of climate change continued to follow trends of a warming world, and several, including land and ocean temperatures, sea level and greenhouse gas concentrations in the atmosphere broke records set just one year prior. The powerful 2015/2016 El Niño played an important role in influencing the global climate and demonstrated that, when natural variability interacts with anthropogenic climate change, the impacts on human societies and the natural environment can be severe (WMO, 2017).

Globally sea level has risen by an average of 20 cm since the start of the twentieth century, mostly because of thermal expansion of the oceans and melting of glaciers and ice caps (WMO, 2017). The tropical western Pacific observed some of the highest rates of sea level rise over the period 1993 to 2015, which was a significant factor in the enormous devastation in parts of the Philippines when Typhoon Haiyan caused a massive storm surge in November 2013 (WMO, 2017). Figure 23.1 below shows the significant weather and climate events and disasters during 2017.

BOX 23.1

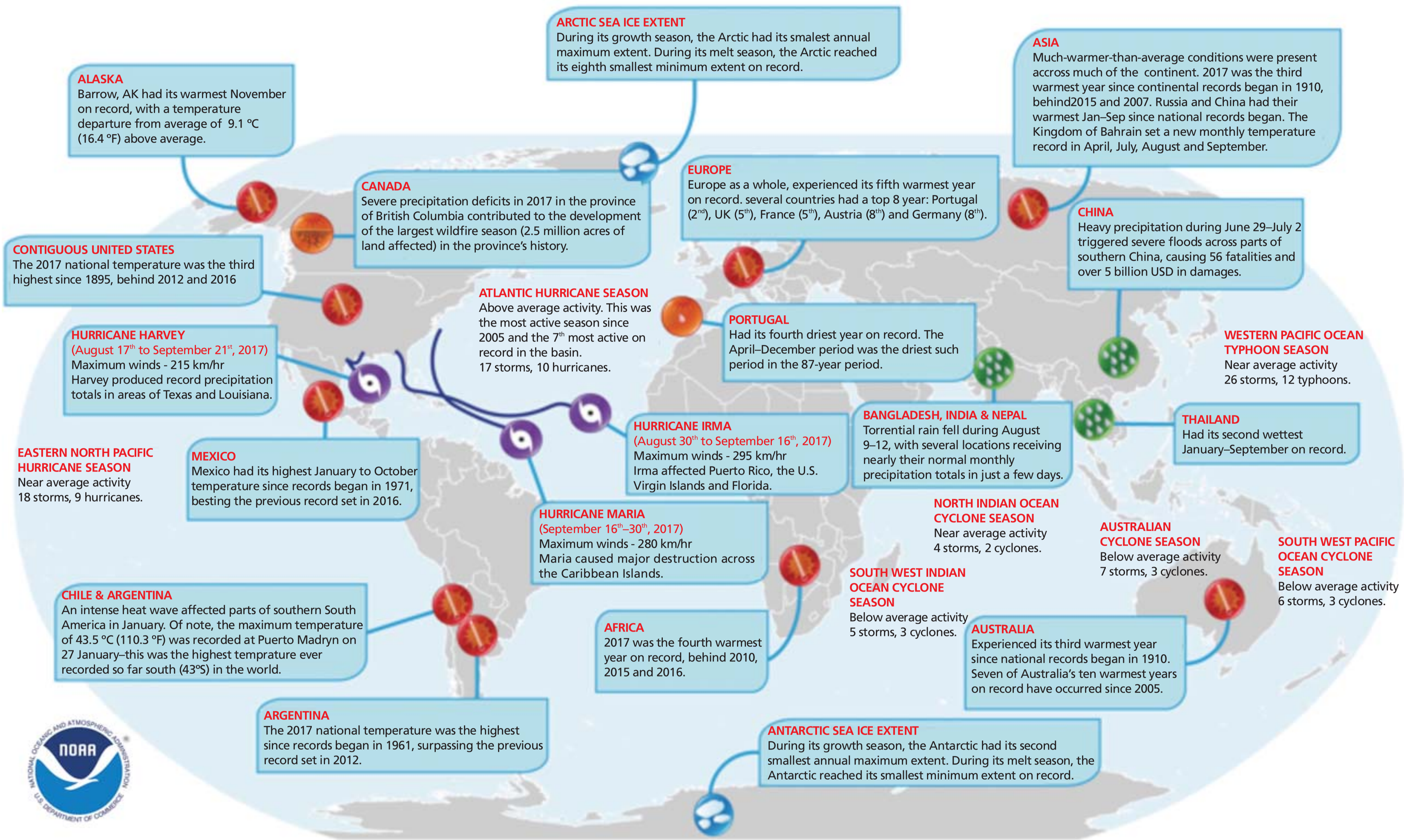
Phenomena such as El Niño–Southern Oscillation (ENSO) can have negative impacts on fisheries and aquaculture. For example, coral reefs in the central equatorial Pacific were disrupted by record-setting sea surface temperatures, linked to an anthropogenically forced trend, during the 2015/16 El Niño (Brainard *et al.*, 2018). All ENSO events differ and different types of El Niño with different impacts occur (described as e.g. extraordinary, canonical, Modoki). When an El Niño Modoki or "Central Pacific" happens, conditions off Peru are neutral or slightly cooler than average (Dewitte *et al.*, 2012). ENSO, in particular extraordinary ENSO phenomena (1982/83, 1997/98), can have negative (e.g. Peruvian anchovy) and positive effects on fisheries and aquaculture. Evidence from the early Pliocene, 4 to 5 Myr ago, when temperatures were higher than today, suggests relatively calm conditions in the Pacific, with characteristic permanent El Niño conditions (Fedorov *et al.*, 2015). Although there is no consensus concerning future changes in frequency or amplitude in El Niño events (e.g. Rädel *et al.*, 2016), extreme El Niño and La Niña events are expected to become more frequent in a warming climate (Cai *et al.*, 2015).

[1] Retrieved on 14 October 2017 from: https://webcms.colostate.edu/tropical/media/sites/111/2017/09/Hurricane-Irma-Records.pdf

[2] Retrieved on 15 March 2018 from https://www.nhc.noaa.gov/text/MIATWSAT.shtml

FIGURE 23.1

Selected significant climate anomalies and events in 2017



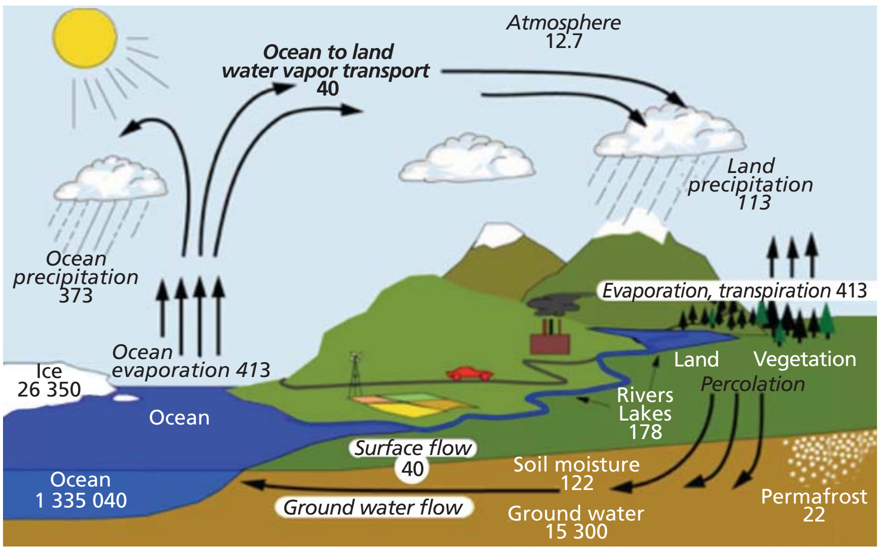
Source: NOAA National Centers for Environmental Information, 2018.

Over the course of the past decade, environment-related risks, notably extreme weather events, the failure of efforts in climate change mitigation and adaptation, as well as water crises, have emerged as a consistently central feature of the Global Risks Perception Survey (GRPS)[3]. This survey is published by the World Economic Forum (WEF) and reports on the opinions of nearly 750 experts who assessed the likelihood and impact of 30 global risks as well as 13 underlying trends that could amplify them or alter the interconnections between them. According to the same publication, in 2017, extreme weather events emerged as the single most prominent global risk, and are strongly interconnected with other risks, particularly with conflict and migration[4].

23.2 BASIC ELEMENTS ON THE GLOBAL HYDROLOGICAL CYCLE

As global warming continues, of particular concern are changes in extremes as they relate to the hydrological cycle. The hydrological cycle (Figure 23.2) describes the exchange of water from the land and the oceans to the atmosphere and back again. This system is powered by the heat of the sun, which activates the internal mechanism within the different components of the climate system and in particular the production of the water vapour arising from the strong air-sea interaction and other mechanisms involving the soil and evapotranspiration phenomena. It is to be expected that a warmer climate will be one in which the hydrological cycle will be more disrupted, leading to changes in the frequency, intensity, geographic distribution and timing of extreme weather events. A warmer atmosphere holds more water vapour, bringing more intense precipitation, which leads to more frequent and intense floods (IPCC, 2014a). In a warmer climate, the surface and sub-surface ocean layers store more heat, which intensify the air-sea interaction leading to more intense storms. As global warming will not occur evenly, continents, countries and regions will be affected differently.

FIGURE 23.2
The hydrological cycle



Units: Thousand cubic km for storage and *thousand cubic km/yr* for exchanges

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[3] World Economic Forum 20017–2017, Global Risks Reports is available at http://www3.weforum.org/docs/GRR17_Report_web.pdf

[4] World Economic Forum 20017–2017, Global Risks Reports is available at http://www3.weforum.org/docs/GRR17_Report_web.pdf

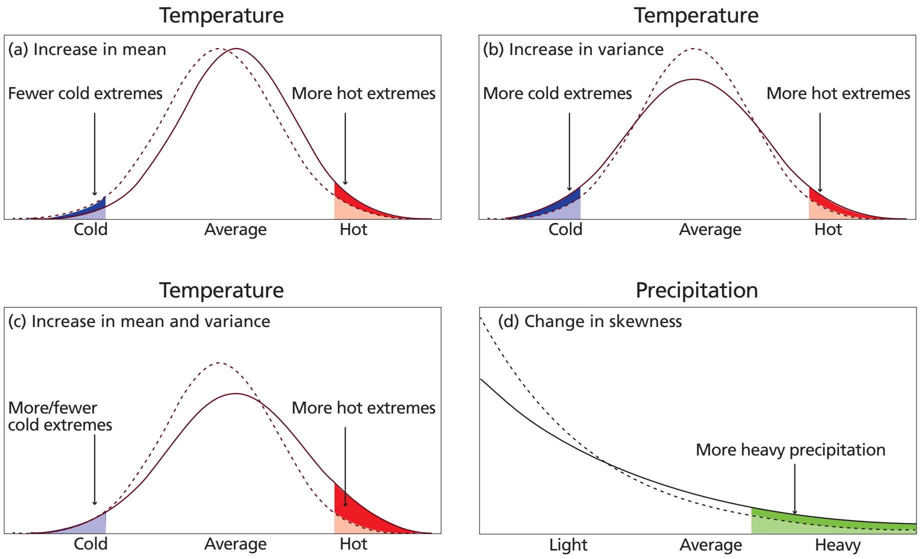
[5] From http://www.metlink.org/climate/ipcc-updates-for-a-level-geography/the-changing-water-cycle/

23.3 EXTREME EVENTS

In a statistical sense, a climate extreme weather event (e.g. hurricanes, floods) is an event that is rare at a particular place and/or time of the year[6]. When the event persists for some time, such as a season, it may be classed as an extreme climate event (e.g. drought or heavy rainfall over a season; Cubasch *et al.*, 2013). Extreme events can result from external forcing of the climate system, such as from increasing greenhouse gases, from natural variability, including phenomena like El Niño, from decadal or multi-decadal climate variability and/or most likely from a combination of the three. The word extreme can also be used to describe the impact of the event (Seneviratne *et al.*, 2012). Thus, some weather or climate events (e.g. tropical cyclones), even if not extreme in a statistical sense, can lead to extreme conditions and socio-ecological and physical impacts. When an extreme event occurs in an inhabited area, causing widespread human suffering and material, economic or environmental damages and losses that require immediate emergency responses, it is a disaster[7].

Changes in the frequency and/or severity of extreme events can result from a relatively small shift or change in the mean and/or variability of climate. Figure 23.3 shows a schematic of a probability density function (PDF) and illustrates the effect of a small shift in the mean of a variable on the frequency of extremes at either end of the distribution. An increase in the frequency of one extreme (e.g. the number of hot days) can be accompanied by a decline in the opposite extreme (in this case the number of cold days such as frost days). Changes in the variability, skewness or the shape of the distribution can complicate this simple picture (Figure 23.3b, c, d).

FIGURE 23.3
Schematic representations of the PDF of daily temperature and daily precipitation, which has a skewed distribution



Dashed lines represent a previous distribution and solid lines a changed distribution. The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. *Source:* Figure 1.8, Cubasch *et al.*, 2013.

[6] An extreme event *"is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations"* in Cubasch *et al.* (2013).

[7] Disasters: Severe alterations in the normal functioning of a community or a society as a result of hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery (IPCC, 2014b).

23.4 EXAMPLES OF IMPACTS (DAMAGES AND LOSSES) ON FISHERIES AND AQUACULTURE

As a result of their location near coastal, estuarine, riparian and lacustrine water bodies, extreme events and related disasters with the greatest impacts on fisheries and aquaculture are: cyclones, storm surges/coastal flooding, general flooding, extreme sea level rise and drought. Extreme temperatures in the ocean are also increasingly seen as another important influence on fisheries with profound ecological impacts much beyond coral bleaching and also extending for example to change in abundance, mortality, growth and phenology of fish species (Hobday *et al.*, 2016; Mills *et al.*, 2013). For example a warm event in 1999 contributed to a massive die-off of lobsters in Long Island Sound, north-west Atlantic, and to the spread of lobster shell disease which has decimated populations south of Cape Cod. On the other hand the record landings of lobsters as a result of the 2012 heat wave in the Gulf of Maine outstripped the processing capacity and market demand for the product which contributed to a price collapse (Mills *et al.*, 2013).

The severity of the impacts on humans will vary depending on the exposure and vulnerability of the fishing and fish farming communities and industry, the intensity of the hazard in relation to the location, the type of livelihoods and existing national and local coping and adaptive capacities. Thus, it has been estimated, according to frequency and mortality exposure indicators, fishery-dependence, and capacity to adapt, that the fishery sectors of many African and south-east Asian countries are very vulnerable to disasters (Badjeck *et al.*, 2013). Exposure and vulnerability to disaster are not static and can be influenced by socio-economic factors such as income, education, age and governance. Further, exposure and vulnerability are dependent on the season or co-occurrence of other extreme events (Banholzer, Kossin and Donner, 2014). The table below provides some examples of damages and losses from climate extreme events and related disasters to fishery and aquaculture systems.

TABLE 23.1
Example of damage and losses (adapted from FAO, 2018)

Disaster type	Damages to livelihoods and productive assets	Primary and secondary impacts on aquatic ecosystems
Cyclone and storm surge	• Damage and destruction of coastal and inland fishing and fish transport boats, engines and fishing gears. • Damage to aquaculture structures, such as ponds, cages and shellfish and seaweed growing systems. • Damage to and destruction of harbours and jetties, sea defences, onshore processing plants, drying racks and smoking houses, ice factories, fisheries administration buildings, boat sheds, mechanical workshops, electrical supply, fishery supply stores, fuel storage and pumping, cold storages, refrigeration equipment and fish transport vehicles.	• Ghost fishing caused by loss of fishing gear, which cannot be recovered yet they continue to fish after the disaster has finished. In Hurricane Felix in Nicaragua, 17 000 lobster traps were reported lost. • Loss of farmed aquatic plants and animals. • Damage to beaches and nesting areas, sand dunes, coastal shrubs and trees.
Coastal flood and inland flood	• Damage and destruction of coastal and inland fishing and fish transport boats, engines and fishing gears. • Washing away of coastal and inland aquaculture ponds, cages and associated equipment such as aerators, generators, laboratories and lab equipment. • Damage and destruction of hatcheries and feed stores. • Loss of fish that are in the ponds and cages. • Damage and destruction of onshore processing plants, ice factories, fisheries administration buildings, boat sheds, drying racks and smoking houses, mechanical workshops, electrical generation and distribution networks, fishery supply stores, cold stores, refrigeration equipment and fish transport vehicles and fish and food markets.	• Increased amount of water provides more volume and areas for hiding, foraging and growth of aquatic species during floods. • Coming into contact with obstacles in fast moving floodwaters may damage fish. • Floods bring land-based pollutants (plastics, garbage, pesticides, chemicals, debris, fishing gears, etc.) onto coral reefs, coastal waters and inland lakes, rivers and reservoirs causing damage and possible ghost fishing.
Drought	• Reduced water quantity and quality leading to reduced production in aquaculture and inland fisheries.	• Organic nutrients important for ecosystem health which are transported by rivers are reduced because of reduced water flow causing low primary productivity in coastal areas where these rivers used to flow. • Reduced water in rivers, lakes and reservoirs concentrate fish in smaller volumes of water making them easier to catch and reducing the amount of space to hide and available food for growth.
Harmful algal blooms	• Kill off of important fish and shellfish species targeted by fisheries, and of farmed shellfish and fish. Food safety can be jeopardized.	• The effects of the algal bloom depend on the algal species (especially, whether it produces toxins), the geographical extent and duration of the bloom, and the strength and direction of the prevailing currents at the time.

Whereas most impact assessments have tended to focus on specific time frames, such as forecasting conditions by the middle or end of the twenty-first century, a 2018 study explored the impacts of weather extremes for different degrees of warming, in particular for increases of 1.5 °C and 2 °C above pre-industrial levels, in line with global average temperature targets arising from the 2015 Paris Agreement. The research study forecast changes in weather extremes and their impacts on freshwater availability and food insecurity. It concluded that vulnerability to food insecurity would increase more at 2 °C global warming than 1.5 °C in approximately three-quarters of the 122 countries assessed. The vulnerability increase can arise from increases in either flooding or drought. At 2 °C, four countries are projected to reach unprecedented levels of vulnerability to food insecurity. These are Oman, Bangladesh, Mauritania and Yemen. They were joined by Myanmar, India and Cambodia as having "unprecedented" values at 1.5 °C (Betts *et al.*, 2018).

23.5 ESTIMATING DAMAGES AND LOSSES

Over the past 30 years the number of annual weather related disasters has nearly tripled and economic losses have quintupled[8]. Although climate change is a global issue, the impacts will not be felt equally around the planet. The International Monetary Fund (IMF) has found that small developing states are disproportionally affected by natural disasters with the annual cost being much greater than in larger countries (Cabezon *et al.*, 2015). The Post-Disaster Needs Assessment (PDNA), requested by the Government of Dominica to assess the impact of Hurricane Maria, a category five hurricane which hit Dominica on 18 September 2017, concluded that the disaster resulted in total damages of Eastern Caribbean dollars, XCD 2.51 billion (USD 931 million) and losses of XCD 1.03 billion (USD 382 million). These figures amount to 226 percent of Dominica's 2016 gross domestic product (GDP). In addition to this, the identified recovery needs for reconstruction and resilience interventions, incorporating the principle of "building back better" (BBB) where possible, amount to XCD 3.69 billion (USD 1.37 billion; Government of Dominica, 2018).

In particular, the total costs for repair and replacement of fishing vessels and engines was estimated as XCD 4.52 million (USD 1.68 million). Other losses, including fishing gear and vendor equipment, were estimated at XCD 0.87 million (USD 0.32 million). Infrastructural damages to the sector (both the government fisheries buildings as well as the fisheries cooperatives) were estimated to be XCD 1.14 million (USD 0.42 million). This included damage to roofs, fuel pumps, ice-machine rooms, freezer storages and other supporting infrastructure. Market vendors are mostly women and many lost their basic tools such as cutting boards, coolers, knives, etc. Approximately 2 200 fishers and others dependent on the sector were affected. The fishery sector, largely artisanal, was still recovering from significant damage and losses experienced in 2015 with the passage of Tropical Storm Erika (Government of Dominica, 2018).

A review of 74 PDNAs conducted in 53 developing countries between 2006 to 2016 shows that agriculture (crops, livestock, fisheries, aquaculture, and forestry) absorbed 23 percent of all damage and loss caused by medium- to large-scale natural disasters (FAO, 2018). The share of fisheries is three percent of the total impact on agriculture, while the share of aquaculture remains systematically overlooked. Furthermore, over one-quarter of the disasters assessed occurred in small island developing states (SIDS), where damage and loss in fisheries, albeit low in absolute terms, represents a significant share of agricultural value added. Overall, it has to be noted that the impact of disasters on sectors such as fisheries and aquaculture is typically under-reported in PDNAs. There are many reasons for this including the lack of or out of date fisheries statistical data, such as the number of fishers, catches, number and types of boats and gears, environment, economic and social, cultural and gender information. There is a need to link those post-disaster damage and loss assessments, in line with the Sendai Framework for Disaster Risk Reduction, to loss and damage evaluations of the Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts, as per Article 8 of the Paris Agreement[9], to reinforce convergences and synergies between the disaster and the climate actors.

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[8] https://www.un.org/sg/en/content/sg/press-encounter/2017-10-04/secretary-generals-press-encounter

[9] https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

23.6 PROJECTED EFFECTS OF GLOBAL WARMING

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) highlights the importance of understanding changes in extreme climate events because of their disproportionate impact on society and ecosystems compared to changes in mean climate (IPCC, 2014c). As a result of data sparcity and because of the intrinsic difficulty in modelling the physical processes involved, extreme events have been hard to monitor and even harder to predict (Alexander, 2016; Ghil *et al.*, 2011). Since the IPCC Third Assessment Report (TAR) in 2001, improved monitoring and data for changes in extremes are available and climate models are analysed to provide projections of extremes (Cubasch *et al.*, 2013).

In AR4 and AR5 the observational basis of analyses of extremes increased substantially; on this basis climate change studies have found an increasing trend in the observations and in the projections of extremes (Cubasch *et al.*, 2013). For temperature extremes, climate studies have assessed that the global mean number of land-based warm days and nights had very likely increased, and the global mean number of cold days and nights had very likely decreased since about 1950. In North America and Europe, the frequency or intensity of heavy precipitation events has likely increased with some seasonal and/or regional variation (IPCC, 2013). It is likely that the frequency of heat waves has increased in large parts of Europe, Asia and Australia (see Figure 23.4 for details). For tropical cyclone activities there is low confidence for any long-term trend (more than 40 years) in the observed changes as a result of uncertainties in past observational capabilities (Cubasch *et al.*, 2013). According to the IPCC Special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX; IPCC, 2012) and the Fifth Assessment Report of the IPCC (AR5), a mean global increase in extreme sea level is likely for observed trends, and very likely for the climate projections reported in the SREX and AR5 (IPCC, 2013). The figure below summarizes the state of knowledge regarding the observed trends, human contribution to the changes and the likely incidence of extreme events.

FIGURE 23.4

Extreme weather and climate events: Global-scale assessment of recent observed changes, human contribution to the changes, and projected further changes for the early (2016 to 2035) and late (2081 to 2100) twenty-first century

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes: Early 21st century	Likelihood of further changes: Late 21st century
Warmer and/or fewer cold days and nights over most land areas	*Very likely* (2.6)	***Very likely*** (10.6)	*Likely* (11.3)	*Virtually certain* (12.4)
	Very likely	*Likely*		*Virtually certain*
	Very likely	*Likely*		*Virtually certain*
Warmer and/or more frequent hot days and nights over most land areas	*Very likely* (2.6)	***Very likely*** (10.6)	*Likely* (11.3)	*Virtually certain* (12.4)
	Very likely	*Likely*		*Virtually certain*
	Very likely	*Likely* (nights only)		*Virtually certain*
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale *Likely* in large parts of Europe, Asia and Australia (2.6)	***Likely***[a] (10.6)	Not formally assessed[b] (11.3)	*Very likely* (12.4)
	Medium confidence in many (but not all) regions	Not formally assessed		*Very likely*
	Likely			*Very likely*
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	*Likely* more land areas with increases than decreases[c] (2.6)	***Medium confidence*** (7.6, 10.6)	*Likely* over many land areas (11.3)	***Very likely*** over the mid-latitude land masses and over wet tropical regions (12.4)
	Likely more land areas with increases than decreases	*Medium confidence*		*Likely* over many areas
	Likely over many land areas	*More likely than not*		*Very likely over most land areas*
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale *Likely changes in some regions*[d] (2.6)	***Low confidence*** (10.6)	*Low confidence*[g] (11.3)	***Likely*** *(medium confidence)* on a regional to global scale[h] (12.4)
	Medium confidence in some regions	*Medium confidence*[i]		*Medium confidence* in some regions
	Likely in many regions, since 1970[e]	*More likely than not*		*Likely*[e]
Increases in intense tropical cyclone activity	*Low confidence* in long term (centenial) changes *Virtually certain* in North Atlantic since 1970 (2.6)	***Low confidence***[j] (10.6)	*Low confidence* (11.3)	***More likely than not*** in the Western North Pacific and North Atlantic[l] (14.6)
	Low confidence	*Low confidence*		*More likely than not* in some basins
	Likely in some regions, since 1970	*More likely than not*		*Likely*
Increased incidence and/or magnitude of extreme high sea level	*Likely* (since 1970) (3.7)	***Likely***[k] (3.7)	*Likely*[l] (13.7)	***Very likely***[l] (13.7)
	Likely (late 20th century)	*Likely*[k]		*Very likely*[m]
	Likely	*More likely than not*[k]		*Likely*

Numbers in parentheses in the table refer to the relevant chapters of AR5 IPCC, 2013. Bold indicates where the AR5 (black) provides a revised* global-scale assessment from the SREX (blue) or AR4 (red). Projections for early twenty-first century were not provided in previous assessment reports. Projections in the AR5 are relative to the reference period of 1986 to 2005, and use the new representative concentration pathway (RCP) scenarios (see Box SPM.1 in IPCC, 2013) unless otherwise specified. See following box for further explanation.

Explanatory notes for Figure 23.4

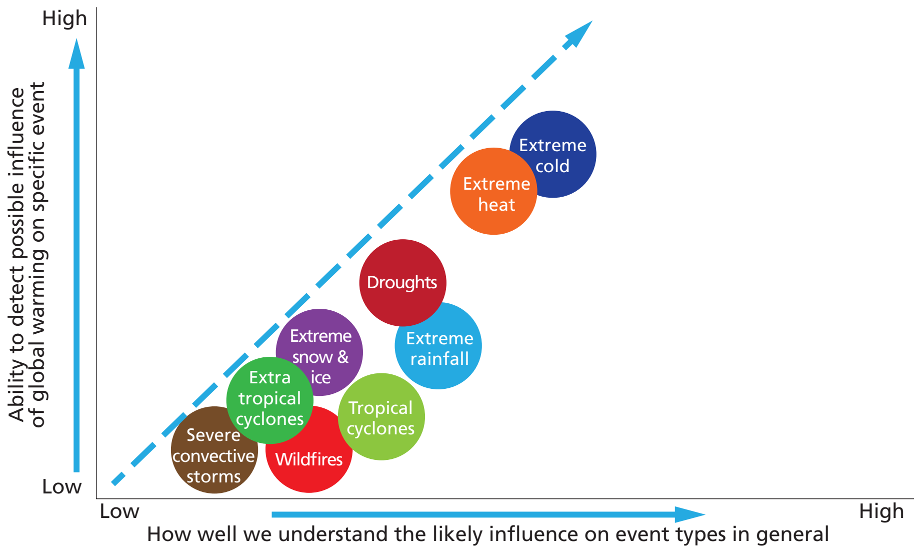
* The direct comparison of assessment findings between reports is difficult. For some climate variables, different aspects have been assessed, and the revised guidance note on uncertainties has been used for the SREX and AR5. The availability of new information, improved scientific understanding, continued analyses of data and models, and specific differences in methodologies applied in the assessed studies, all contribute to revised assessment findings.

Notes:
a) Attribution is based on available case studies. It is *likely* that human influence has more than doubled the probability of occurrence of some observed heat waves in some locations.
b) Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells.
c) In most continents, *confidence* in trends is not higher than *medium* except in North America and Europe where there have been *likely* increases in either the frequency or intensity of heavy precipitation with some seasonal and/or regional variation. It is *very likely* that there have been increases in central North America.
d) The frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa, and *likely* decreased in central North America and north-west Australia.
e) AR4 assessed the area affected by drought.
f) SREX assessed *medium confidence* that anthropogenic influence had contributed to some changes in the drought patterns observed in the second half of the twentieth century, based on its attributed impact on precipitation and temperature changes. SREX assessed *low confidence* in the attribution of changes in droughts at the level of single regions.
g) There is *low confidence* in projected changes in soil moisture.
h) Regional to global-scale projected decreases in soil moisture and increased agricultural drought are *likely (medium confidence)* in presently dry regions by the end of this century under the RCP8.5 scenario. Soil moisture drying in the Mediterranean, south-west United States of America and southern African regions is consistent with projected changes in Hadley circulation and increased surface temperatures, so there is *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario.
i) There is *medium confidence* that a reduction in aerosol forcing over the North Atlantic has contributed at least in part to the observed increase in tropical cyclone activity since the 1970s in this region.
j) Based on expert judgment and assessment of projections which use an SRES A1B (or similar) scenario.
k) Attribution is based on the close relationship between observed changes in extreme and mean sea level.
l) There is *high confidence* that this increase in extreme high sea level will primarily be the result of an increase in mean sea level. There is low confidence in region-specific projections of storminess and associated storm surges.
m) SREX assessed it to be *very likely* that mean sea level rise will contribute to future upward trends in extreme coastal high water levels.

23.7 EXTREME EVENT ATTRIBUTION

Once a signal of change in an extreme is found, the question becomes if and how the change is related to human-induced climate change. Scientists are increasingly confident that the increased number of extreme weather events, such as fewer cold days, more hot days, extreme high sea levels and heavy precipitation events in a number of regions is linked to human-induced climate change (IPCC, 2014a). This influence is increasingly being demonstrated by attribution studies (WMO, 2017). In general, scientists have the highest confidence for heat events because: observational records are long and of high quality, models effectively simulate heat events, and the mechanism of how climate change will impact heat events is well understood (NAS, 2016; Herring *et al.*, 2016). The figure below summarizes the relative confidence in attribution of different extreme events.

FIGURE 23.5
Relative confidence in attribution of different extreme events



Source: NOAAClimate.gov, adapted from NAS, 2016.

23.8 ADAPTATION, DISASTER RISK REDUCTION AND DISASTER MANAGEMENT APPROACHES

While there are clear indications that climate induced disasters have impacts on the fisheries and aquaculture sector, it tends to be under-reported in post-disaster needs assessments. Further efforts are needed to quantify and report damage and losses to the sector in order to understand and address the main challenges (FAO, 2016) as well as to encourage investment at scale in prevention and impact mitigation in advance of climate extremes and variability. It is extremely important to proactively manage risk rather than reactively manage disasters.

Fisheries and aquaculture contribute significantly to food security, livelihoods and to national economies. Given the specific characteristics and complexity of the sector, it is important that appropriate guidance and relevant technical expertise be employed for prevention and risk reduction when responding to natural disaster situations affecting it. Deployment of the right expertise in fishery or aquaculture can bring significant dividends in terms of advising on risk reduction, emergency response, recovery, re-establishment of food security and livelihoods as well as facilitating generation of significant economic spin-offs in a sector that often employs substantial numbers of people.

Key measures and solutions for climate resilience in the sector comprise the following:

- *Climate risk informed fisheries and aquaculture policies, strategies, management plans and regulatory frameworks:* policies and measures to strengthen the climate resilience of marine capture fisheries, for example, would need to consider possible intensification of storms and extreme sea level rise as well as heat waves; whereas for inland fisheries and aquaculture, it is necessary to consider, as examples, the risk and impacts of inland and coastal floods and droughts.
- *Understanding risks, monitoring and early warning systems:* fishers and fish farmers need to understand more fully the different threats and associated risks posed by climatic variability including climate extremes, and other gradual climate change as well as other external threats that are likely to have disastrous effects on

their livelihoods and related sectors (FAO, 2016). They must be empowered to assess the changes to local conditions, through, for example, simple environmental indicators (such as water temperature, salinity, water level, water transparency, and fish health indicators) and to respond accordingly (FAO, 2016). In particular for climate extremes, early warning systems are essential to protect people and their assets. Local, district, national and regional knowledge networks are needed to analyse and share the information collected and provided, and to assess the risk level and agree on early warning triggers for early action and emergency responses.

- *Investing in vulnerability reduction and adaptations measures:* in order to prevent, prepare for and reduce the impact of extreme events and disasters on the fisheries and aquaculture sector, it is a matter of urgency to invest at scale in disaster risk reduction and adaptation measures for climate resilience (such as safety at sea, climate resilient infrastructure, see Chapter 25 for other examples). In fisheries and aquaculture, due consideration to the health of the aquatic ecosystem, including wetlands, coral reefs, mangroves, threatened species and the biodiversity of marine and inland fish stocks, plays an essential role in climate change adaptation and disaster risk reduction. Overfished and poorly managed ecosystems pose a significant underlying risk in disaster risk reduction as highlighted in the Sendai Framework for Disaster Risk Reduction[10]. Other vulnerability reduction measures such as insurance and social protection schemes, are also very important for climate vulnerability reduction of the most vulnerable groups.
- *Preparing and responding to climate related disasters affecting fish dependent livelihoods:* even with proactive management of risks, disasters cannot be fully prevented and emergency preparedness and response are essential for the climate resilience of the sector.

The process of disaster emergency response, rehabilitation and reconstruction in fisheries and aquaculture can create significant opportunities for building back better and for addressing some of the risks, weaknesses and issues in the sector, particularly in terms of overexploitation of resources and damage to fisheries ecosystems (Cattermoul, Brown and Poulain, eds., 2014). Using the principles of "building back better" in fisheries and aquaculture rehabilitation and reconstruction for anticipating future climate risks will significantly contribute to medium- and long-term national economic sustainability.

23.9 CONCLUSION

A changing climate leads to alterations in the frequency, intensity, spatial extent, duration and timing of extreme climate events. These can result in unprecedented disasters induced by extreme weather and climate events. While uncertainties exist, some categories of extreme events are projected to increase in frequency and/or severity during the twenty-first century, particularly those related to global warming. A review of 74 PDNAs conducted in 53 developing countries between 2006 to 2016 concludes that agriculture (crops, livestock, fisheries, aquaculture, and forestry) absorb 23 percent of all damage and loss caused by medium- to large-scale natural disasters, which includes about 80 percent of climate related disasters (FAO, 2018). According to this review, the share of fisheries accounts for three percent of the total impact on agriculture, while the share of aquaculture remains systematically overlooked. However, in spite of this, agricultural sub-sectors like fisheries and aquaculture alike often tend to be under-estimated in PDNAs. The character and severity of impacts on the fishery and aquaculture sector from extreme climate events and weather variability will most likely increase, affecting the most exposed and vulnerable countries and

[10] https://www.unisdr.org/we/coordinate/sendai-framework

communities that depend on the sector for their livelihoods. It is expected that the fishery and aquaculture sector in African, southeast Asian countries and in SIDS will more likely be more impacted than in other regions. It is therefore important that coherent and convergent disaster risk reduction and adaptation measures including preparedness for climate disaster response and recovery be mainstreamed in the fisheries and aquaculture sector as a matter of urgency and at an appropriate scale, particularly in the above mentioned regions.

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Chapter 24: Climate change-driven hazards on food safety and aquatic animal health

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KEY MESSAGES

- Food safety can be affected by a number of parameters that are gradually changing, such as the temperature, pH and salinity of water, as well as by extreme weather events, such as hurricanes and intense rainfalls.
- Climate change is leading to the need for new food safety risk assessments to consider specific and emerging food safety hazards, which will inform risk management, including policymaking and decision-making.
- Enhanced early warning systems are essential to reduce the food safety risk posed by climate change-related natural disasters and emergencies. This requires good collaboration and communication between sectors (e.g. aquatic animal health, marine environment, food safety and public health) at national and international levels.
- Climate change will impact aquatic animal health directly in several ways through production intensification, species and genetic diversification and expansion outside natural species' geographic ranges.
- Climate change impacts on the production environment including on pathogen prevalence and/or virulence, host susceptibility, transmission, and the risk of escapes from storm-damaged holding facilities (land-based or coastal).
- To minimize these impacts it is essential to have a good biosecurity plan (know the species, know the pathogen, know the system), incorporate all the essential elements of a national biosecurity strategy (e.g. risk analysis, emergency preparedness, communication), with a focus on prevention, responsible and effective aquaculture biosecurity and health management practices, and sharing of risk reduction responsibilities. Active engagement and long-term commitment of all relevant stakeholders will be essential.
- Improving implementation of international standards and other regional and national instruments will encourage adoption of best practices, assist in reducing the risk of disease transfer and other adverse impacts on wild and cultured stocks and promote responsible movement of live aquatic animals.

24.1 INTRODUCTION

Consumption of fishery and aquaculture products contributes significantly to food security and nutrition and plays a key role in feeding a growing global population, which is expected to reach 9.7 billion by 2050. Fish is one of the important sources of animal protein in the human diet, accounting for about 17 percent of protein consumption at the global level, and is an excellent source of micronutrients needed for a healthy diet (FAO, 2016). Addressing climate change implications in the context of food security in its four dimensions (availability, access, utilization and stability) will be crucial to ensure the sustained supply of fish and fish products to consumers for the future. This requires giving attention to the climate change implications for both consumption issues – centred on food safety – and for production issues, centred on animal health. The following two sections detail the climate change impacts on both of these topics.

24.2 FOOD SAFETY FOR FISHERY AND AQUACULTURE PRODUCTS IN THE CONTEXT OF CLIMATE CHANGE

24.2.1 Impact on food safety through gradual changes in the marine environment

Food safety can be affected by a number of parameters that are gradually changing, such as the temperature, pH and salinity of water. Indeed, a strong relationship is observed between specific bacterial growth rates and temperature (White *et al.*, 1991). The growth rate of pathogenic bacteria that occur naturally in the marine environment, such as *Vibrio cholerae, V. parahaemolyticus, V. vulnificus, Listeria monocytogenes, Clostridium botulinum* and *Aeromonas hydrophila,* and those that are present from faecal contamination of waters, such as *Salmonella* spp., *Escherichia coli, Shigella* spp., *Campylobacter* spp., and *Yersinia enterocolitica* (Feldhusen, 2000), have been observed to increase at higher water temperatures. Furthermore, there are several examples of food-borne disease outbreaks in geographical areas that previously were not considered as risky. For example, in Alaska in 2004, the outbreak of *V. parahaemolyticus* extended the previous geographical range of outbreaks by about 1 000 km (McLaughlin *et al.*, 2005).

In addition, seasonality and gradual changes in temperature and other environmental conditions influence the prevalence of parasites and certain food-borne viruses, such as norovirus, in edible aquatic species. These gradual changes also modify the population dynamics of aquatic species as intermediate and definitive hosts of food-borne parasites (Broglia, 2011).

The spatial distribution of fish is changing through their migration in search of suitable conditions. Warm-water species are being displaced towards the poles (Cochrane *et al.*, eds., 2009) and warm-water top predators, such as barracudas (*Sphyraena* spp.) and dolphinfish (*Coryphaena hippurus*), are now frequently caught and sold in Northwest Mediterranean markets (Lejeusne, 2010). The movement of fish introduces new profiles from different species and changes food safety hazards.

Another important concern is the frequency, intensity and duration of algal blooms. There are around 75 species of microalgae with the capacity to produce potent toxins that can be present in molluscs, crustaceans and fish. Studies suggest that blooms may take place above certain temperatures depending on the species. Optimal growth of *Gambierdiscus* spp. in the Caribbean Sea and the Western Indian Ocean has been reported at temperatures above 29 °C, noting that the number of days each year with sea surface temperatures above 29 °C has nearly doubled, from 44 to 86, over the last 30 years in some areas such as the Gulf of Mexico (Tester, 2010). Toxins, such as ciguatoxins, produced by *Gambierdiscus* spp. and associated with coral reefs, are biomagnified and biotransformed during their transfer up the food chain, from toxic epiphytic dinoflagellates ingested by herbivores, to predatory fish that feed on the ciguatoxic herbivores, and finally to humans consuming ciguatoxic predatory fish. Ciguatera fish poisoning, which was previously considered to be mainly of tropical and subtropical origin, is now also occurring in Europe with the Canary Islands and Madeira reporting outbreaks since 2008 and Germany since 2012 (Bravo *et al.*, 2015).

Proliferation and spatial distribution of toxic algae, affected by gradual changes in seawater temperatures, influence the toxicity of certain molluscs, crustaceans and fish present in these production areas.

Higher sea-surface temperatures also have an impact on the availability and toxicity of certain contaminants, such as mercury. Methylation of mercury to form methylmercury (MeHg), which is readily absorbed by the gastrointestinal tract, has been found to increase when temperatures rise. Higher concentrations of MeHg in fish can consequently increase human exposure to this neurotoxic contaminant (Dijkstra *et al.*, 2013). Bioaccumulation and toxicity of other heavy metals have been reported to increase with warmer seawater temperatures for several marine organisms, including crustaceans, echinoderms and molluscs. This can have an impact on consumers' health when maximum tolerable or admissible intakes are exceeded.

Salinity and pH are recognized as the key variables that control the bioavailability and the toxicity of heavy metals such as zinc, lead, cadmium and copper and it is known that some heavy metals are taken up more rapidly by molluscs and crustaceans at reduced salinities as a result of bioavailability or physiological factors (Riba, 2004).

Environmental conditions may also have an impact on the risks associated with seaweed consumption. For instance, it is known that the formation of certain toxins that can be present in seaweed is accelerated with warming of the aquatic environment. Additionally, the capacity of seaweed to accumulate metals depends on a variety of factors such as location, wave exposure, temperature, salinity, light, pH, nitrogen availability and seasonality among others and changes in these factors can have an impact on the concentration of metals, such as aluminium, cadmium and lead, in certain seaweed species (Besada, 2009).

24.2.2 Impact on food safety caused by extreme weather events

Food safety can be affected by extreme weather events, such as hurricanes and intense rainfalls; increasing run-off of fertilizers, topsoil, as well as pollutants, such as pesticides, herbicides, trace metals and persistent organic pollutants, e.g. dioxins; and bringing pathogens and nutrients to marine and inland production waters. Within certain temperature ranges, these events will create the appropriate conditions for the proliferation of microorganisms and algal blooms. Some of these algal blooms can be toxic for humans, with suspension-fed bivalve molluscs being the principal vectors for the transfer of major groups of phycotoxins, such as paralytic shellfish poisoning toxins, diarrhoeatic shellfish poisoning toxins, and domoic acid, the causative agent of amnesic shellfish poisoning (Shumway, 1998).

It is important to mention that extreme weather events may break down natural biogeographic barriers, causing problems such as the destruction or bleaching of coral reefs and contributing to the proliferation of *Gambierdiscus* spp., producing toxins such as ciguatoxin. In general, more frequent storms and hurricanes create better conditions for harmful algal blooms and make the occurrence of outbreaks of marine biotoxins less predictable.

Moreover, flooding, resulting from intense rainfalls, can cause the overflow of untreated sewage, leading to the increased likelihood of the presence of enteric viruses and other pathogens during the production of molluscan shellfish and other fishery and aquaculture products (FAO/WHO, 2008).

Events such as the El Niño have been identified as an important risk factor for viral, bacteriological and parasitic infections. For example, an increase of more than 200 percent in the incidence of gastroenteritis from viral infection was reported in Lima, Peru, when the ambient temperature increased by more than 5 °C above the usual values for the winter season during an El Niño event (Rohayem, 2009). Global spread of this pathogen has been influenced by events such as El Niño, which led to outbreaks in Chile and Peru (Martinez-Urtaza *et al.*, 2008) and transoceanic spread has led to outbreaks in Europe, caused by strains from the Pacific Northwest regions of the United States of America (Martinez-Urtaza *et al.*, 2016). Concerning parasites, it is known that anisakiasis emerged in Peru during 1997 to 1998 because of an El Niño event, when the increased temperatures led to the migration towards coastal areas of certain fish species, such as *Coryphaena hippurus*, that hosted the parasites. This led to the catch and consumption of these fish and consequently to increases in human cases of anisakiasis (Cabrera, 2004).

24.2.3 Emerging food pathogens in fishery and aquaculture products in the context of climate change

With higher water temperatures, it can be expected that the concentration of bacteria may continue to increase, which can be a problem if they are pathogenic. In addition, these conditions may generate a larger pool of microorganisms, facilitating mutations and gene transfer. As a result, new pathogens may emerge. An example of this was the emergence of a new bacterial serotype in Peru, *V. cholerae* serotype O1, which resulted in one million cases of cholera and 10 000 reported deaths in Latin American countries over a period of 18 months in early 1994 (Tauxe, Mintz and Quick, 1995).

In addition, evidence suggests that transmission rates and virulence of some common parasites may increase with higher temperature, as well as their growth and maturation and the possibility of continuous year-round transmission (Marcogliese, 2008).

On the contrary, the infection peak of norovirus, which is one of the most important agents of food-borne gastroenteritis worldwide, occurs over wintertime, but changes in rain patterns and winds, humidity and temperature cycles may have an impact on transmission, resistance and host susceptibility to infection by the virus. Moreover, it may influence the interaction of norovirus with its host (Rohayem, 2009).

Normally, an emerging pathogen is recognized only when it produces unique symptoms or affects a unique human subpopulation and when its incidence reaches some threshold levels among other infectious diseases in a population. It can be assumed that new pathogens will continue to emerge and also that many may not be recognized and then disappear (Ryder, Karunasagar and Ababouch, eds., 2014).

24.2.4 Adaptation to climate change in the context of food safety for fishery and aquaculture products

This changing environment will lead to the need for new food safety risk assessments to consider specific and emerging food safety hazards, which will inform risk management, including policymaking and decision-making. More attention should be given to the monitoring of environmental parameters, such as water and air temperature, pH and salinity, to predict food safety problems and events and determine the safety of fishery and aquaculture products, such as bivalve molluscs and specific fish species that are more likely to contain toxins and/or pathogens and contaminants.

Further efforts will be needed at national levels for the classification of production areas based on food safety criteria, taking into consideration microbiological and chemical criteria.

As fishery and aquaculture products are one of the main traded food commodities globally, importing countries should also carry out these exercises to establish the necessary measures and surveillance systems to prevent the occurrence of food safety problems of products coming from countries that may experience emerging food safety issues.

24.2.5 Good practices and emergency preparedness

Enhanced early warning systems are essential to reduce the food safety risk posed by climate change-related natural disasters and emergencies. This requires good collaboration and communication between sectors (e.g. aquatic animal health, marine environment, food safety and public health) at national and international levels. Countries should also develop food safety emergency plans to ensure adequate consideration of food safety management issues in those situations (FAO, 2008).

Methods for rapid food-borne pathogen and toxin detection would be important tools for food safety management in emergency situations, and systems such as the

FAO Emergency Prevention System for Food Safety (EMPRES Food Safety)[1] or the International Food Safety Authorities Network (INFOSAN)[2] will be key systems to assist in the prevention and management of global food safety emergencies.

Other national or regional systems, such as the Rapid Alert System for Food and Feed (RASFF)[3], the US Food and Drug Administration Import Refusal Reports[4] or the web portal for Imported Foods Inspection Services of the Ministry of Health, Labour and Welfare in Japan[5], contribute to food safety prevention and management. Moreover, the accessibility and transparency of information allows the analysis of the rejections and detentions, providing an overview of the global situation and problems, as well as the main trends.

In general, foresight exercises will be key to gathering and interpreting intelligence leading to the development of proactive strategies to identify and address emerging issues in advance of their occurrence.

24.2.6 International standards and other guidelines supporting the adaptation process

A number of Joint FAO/WHO expert bodies carry out risk assessments on chemical and microbiological hazards in fish, mainly to provide scientific advice to Codex Alimentarius. Other Joint FAO/WHO ad hoc expert committees[6] deal with emerging issues as they arise. FAO and WHO member countries can influence the prioritization of risk assessment work to be carried out at international level, including on emerging hazards. An example was the request received by the 11th session of the Codex Committee on Contaminants in Foods[7] in 2017 to evaluate known ciguatoxins, including geographic distribution, rate of illness, congeners and methods of detection. This information will allow the development of appropriate risk management options.

24.2.7 Research needs

Understanding the impact of climate change on food safety in fishery and aquaculture products is an area of increasing interest. There is still much to be done to know how certain gradual changes or extreme weather events could influence the occurrence of certain pathogens, contaminants and marine biotoxins. Analysing the current data gaps, some research needs were identified. In general, knowledge on how changes in the pH can influence the presence of common human pathogens or modify common contaminants or toxins in waters and fishery and aquaculture products would contribute to better understanding of the hazards and help to take risk management decisions. Impact of the changes of other environmental parameters is better described in the available literature for fishery and aquaculture, but further research would allow a better understanding of the effects of climate change on food safety. Furthermore, changes in environmental conditions that could influence the capacity of edible seaweed to accumulate certain metals and contaminants are still not well understood and data on occurrence and concentration of marine biotoxins in edible seaweed is lacking.

Lastly, there is a need to have better data on the impact of the changes in environmental conditions and relative toxicity of common marine biotoxins and their

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1 http://www.fao.org/food/food-safety-quality/empres-food-safety/en/
2 http://www.fao.org/food/food-safety-quality/empres-food-safety/early-warning/en/
3 https://ec.europa.eu/food/safety/rasff_en
4 https://www.accessdata.fda.gov/scripts/importrefusals/
5 http://www.mhlw.go.jp/english/topics/importedfoods/
6 http://www.fao.org/fao-who-codexalimentarius/about-codex/faq/faq-detail/en/c/454769/
7 http://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FMeetings%252FCX-735-11%252FREPORT%252FREP17_CFe.pdf

analogues, so that the total toxicity of fish and fish products, which are increasingly being contaminated by these toxins, can be estimated.

24.3 AQUATIC ANIMAL HEALTH HAZARDS IN AQUACULTURE AND FISHERIES AND CLIMATE CHANGE

24.3.1 Brief description of infectious agents as biological hazards: parasites, bacteria, fungi, viruses

In the context of risk analysis, a biological hazard includes both pathogenic agents (infectious or non-infectious) that impact survival or physiological fitness, and ecosystem competitors (introduced via human-mediated mechanisms or geographic expansion) that impact access to habitat requirements for population stability. The most common infectious pathogenic agents in aquatic ecosystems are parasites, bacteria, fungi and viruses, while the most common non-infectious agents are pollutants or toxins.

Biological impacts stem from tipping an established "steady-state" relationship between an aquatic animal (individual or population), an infectious agent and their supporting environment or habitat. This hazard relationship applies to both wild and farmed aquatic animals, but was first captured diagrammatically by Snieszko (1974) through examination of disease outbreaks in farmed fish (Figure 24.1).

FIGURE 24.1
Representation of the relationship between the host, the pathogen and the environment that may result to disease development (Bondad-Reantaso *et al.*, eds., 2001; Snieszko, 1974)

The development of disease in a particular aquaculture system involves three major factors: the farmed fish (host), the disease-causing organisms (pathogens) and the surroundings and culture conditions (environment). A complex interaction exists between these three factors as represented in the diagram. For a disease situation to exist, there should be a viable pathogen, a susceptible host, a viable transmission pathway and environmental conditions that bring about either increased virulence of the pathogen, decreased resistance of the host or conditions for the pathogen to replicate to overwhelming numbers. Stress, defined as the sum of physiological responses the fish makes to maintain or regain its normal balance after unsuitable conditions, such as handling, overcrowding, malnutrition, or poor environmental conditions, is a very important consideration. Once a pathogen or disease agent is introduced and becomes established in the natural environment, there is little or no possibility for either treatment or eradication. Bondad-Reantaso *et al.* (2005) noted that while consequences of "trickle" infections from wild to cultured populations have predictable consequences as a result of accessible hosts being held and vulnerable under cultured conditions, the consequences of culture-borne transmission to wild stocks are harder to predict. Bondad-Reantaso *et al.* (2005) noted the evidence showing infection of cultured stocks via wild stock reservoirs through examples of shrimp diseases as described by Flegel and Alday-Sanz (1997), Ruangsiri and Supamattaya (1999), Rajendran *et al.* (1999) and for marine finfish disease by Dixon (1999). Another example from Japan is *Neoheterobothrium hirame*, a monogenean parasite, the original host probably being southern flounder from the United States of America, which is believed to have been the cause of a decline in the catch of olive flounder in some parts of Japan (Anshary *et al.*, 2002).

In the context of climate change, the change to the environment or habitat of aquatic animals can be considered to be analogous to that of farm-based habitat changes. The primary change impacts feed availability and seasonal dynamics that, as a result, impact spawning (timing or success) and/or migration patterns (wild populations). Traditional fisheries that were, historically, managed based on fishing effort and an approximate natural mortality, now face serious challenges because of changing ecosystem dynamics that impact primary productivity through to prey availability for top predators. In a marine aquaculture context, shifts in seasonal temperature and salinity impact natural feed (bivalves, shrimp) as well as feed conversion and maturation for artificially-fed animals. More recently, recognition of changes in ocean pH or acidification also present an unknown factor influencing aquatic animal health via feed availability or physiological effects (e.g. crustacean moulting, egg viability).

24.3.2 Climate change related factors that contribute to disease challenges

Intensification

The current trend in aquaculture development is towards increased intensification to ensure economically sustainable productivity. However, as with terrestrial crop and animal farming sectors, the likelihood of major disease outbreaks and the difficulty of controlling them increases exponentially under intense, and especially monoculture (single species), conditions. Production intensification, even under consistent environmental conditions, poses sustainability risks and challenges that require stringent management in order to be able to respond effectively to pathogen detection and/or disease outbreaks. Climate change will increase those threats and challenges.

Large-scale production of a single species within a production environment needs: 1) a rapid response to off-feed animals, signs of morbidity and mortalities; 2) capacity to isolate affected animals from unaffected populations and farms; and 3) capacity to depopulate affected sites where treatment is not feasible.

Increasingly, intense farming is being impacted by weather extremes that stress farmed animals and impede management mechanisms, e.g. prevention of escapes (destruction of holding systems) and isolation of diseased and stressed animals from unaffected animals.

Species and genetic diversification

Over the last 30 to 40 years, aquaculture has developed using species diversification (selection of species showing best production results under farmed conditions) and genetic strains developed under experimental conditions for commercial production.

Both selection methodologies include disease tolerance (infection without expression of significant mortality) and resistance (ability to prevent infection).

Species and strain selection advantages, however, rely on consistent environmental parameters in a production system, i.e. no significant changes to production conditions. Where such conditions are subject to "extremes" (temperature, salinity, turbidity) selected species and/or strains may be more vulnerable to high losses than less-selected and more genetically diverse stocks; especially those native to the production area.

Expansion outside natural species geographic range

Native species used for aquaculture that show robust farmed production are often subject to farm expansion to the peripheries or outside their natural geographic range. The animals may be able to withstand slight seasonal temperature and/or salinity changes but are at a survival disadvantage when extreme conditions impact normal reproductive or growth production cycles.

As for intensification, and species and genetic diversification, where such environmental changes occur, resistance to opportunistic or primary pathogen infections can be reduced significantly.

24.3.3 Disease impacts on food security, livelihoods and the environment

Impacts on food security

- *Availability of food.* Aquatic animal diseases reduce quantities and/or quality of domestic or imported aquatic animal products. Quantity is reduced by mortalities or stock destruction while quality is reduced by marketing sub-optimal or a sub-size product before it is rendered unmarketable because of disease.
- *Access to food via trade markets.* Animal health standards are designed to safeguard international trade through the World Trade Organization's (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement; WTO, 2018) related to food safety for consumers, and the World Organisation for Animal Health (OIE – Office International des Epizooties) standards related to prevention of spread of aquatic animal diseases (OIE, 2017). Disease outbreaks and detection of contamination of aquatic animals are controlled by mandatory reporting to trade partners and subject to provision of evidence of responses and controls that guarantee that product trade will not compromise consumers or aquatic animals in the importing country.
- *Utilization of food.* Food utilization in relation to aquatic animal diseases chiefly concerns food safety for the consumer. This includes safety mechanisms for application of veterinary medicines before a product is marketed ("withdrawal times" post treatment) and control of therapeutants approved for legal application to aquaculture animals. Evidence of use of illegal chemicals or overuse of antibiotics (e.g. development of antibiotic resistance) can also result in market closure and prohibitions locally, nationally and internationally.
- *Stability of food production.* Production impacted by losses (quantity and quality) and market access impact consumer and market confidence in both the product and supplier (local or national). Regaining consumer confidence and market access requires significant effort and ability to deal with the disease challenges that affected them in the first place.

Impacts on livelihoods

Examples of impacts on livelihood include: losses in production, income, employment, market access or market share, investment and consumer confidence, industry failure or closure of business.

The most obvious impacts are felt through loss of productivity, either directly through mass mortalities (acute or cumulative), or through reproductive or growth failure. Mass mortalities may occur seasonally as infections proliferate and weaken host populations; e.g. Perkinsiosis in various oyster species, or be acute as a new pathogen is introduced to a vulnerable population, e.g. Bonamiosis in European flat oysters.

Additional economic losses can also result from disease impacts on product quality and marketability, even though no diseases of molluscs pose a health hazard to consumers. The protozoan *Marteiliodes chungmuensis* is a strong example of loss of marketability of Pacific oysters because of the grossly visible lesions produced in the soft tissues of the mantle.

Marketability is also impacted for aquatic animals that have been weakened to the extent that usual shelf-life (live-holding) is reduced to a point where the product cannot reach some markets before becoming moribund or dying (transportation losses). Emergency marketing risks loss of consumer and trade partner confidence if product quality cannot be sustained. In the context of marketing product, reduced quality can trigger loss of consumer confidence in not only the directly affected product but in all products from an area or country, regardless of their health status.

Some countries provide a compensation or insurance programme to offset losses attributed to disease impacts on aquatic animal productivity and marketability; however, these are relatively uncommon and rarely compensate for all economic losses. In addition, such compensation does not extend to the industries that support aquatic animal production (feed producers, net makers, boat suppliers, etc.). This underscores the importance of biosecurity, stringent surveillance and rapid response to any indication of an emerging disease.

Impact on the environment.

Arthur and Subasinghe (2002) summarized the impacts of aquatic animal diseases on wild populations and biodiversity. These impacts can be measured in terms of effects on aquatic community structure through changes in predator and prey populations; changes in host abundance (e.g. altered genetic demands, altered host behaviour, increased mortality, decreased fecundity, increased susceptibility to predation, etc.); reduction in intra-specific genetic variation; local extirpation of susceptible components of aquatic communities; establishment of reservoirs of infection, and possible extinction of species (Arthur and Subasinghe, 2002). Other impacts include use of chemicals to prevent or control disease emergence via feed, water-baths, or inoculation; and/or disinfection of holding pens or production facilities. Because of the open water nature of most aquatic animal farming, chemical based disease management poses a significant chance of exposure of non-farmed animals and equipment.

Another impact on the environment is that posed by “magnification” of pathogen concentrations as a disease proliferates in a production cage or tank situation. As with chemicals, unless the animals are isolated or quarantined from the surrounding environment, pathogens are likely to escape. Depending on their ability to survive outside the host, they may establish benign infections in “carrier” hosts, encyst in the sediment, or establish serious infections in wild populations of the same or closely related species to the farmed animal. Environments that provide conditions that differ significantly from those where a pathogen is well-established may be effective in controlling disease spread; however, once released into an open environment there are few if any examples of effective eradication of the infectious agent.

As with impacts on livelihood, these environmental impacts also underscore the need for rapid and effective intervention at the earliest sign of an emerging disease situation.

24.3.4 Climate change dimension: environmental and other risk factors impacting aquatic animal health

Aquatic animals are very vulnerable to changes in their aquatic habitat, especially where they cannot move away from changes that negatively impact their well-being; e.g. sessile animals or animals held in static farm cages, pens, etc. Climate change can impact on the production environment including pathogen prevalence and/or virulence and host susceptibility (immunosuppression) and transmission. There is also the risk of escapes as a result of storm-damage of holding facilities (land-based or coastal). Table 24.1 gives examples of disease proliferation correlated to extreme environmental changes.

TABLE 24.1
Examples of parasitic, bacterial, fungal and viral diseases affecting aquatic animals (finfish, crustacean and molluscs) that have climate change dimensions (environmental and other risk factors)

Disease	Environmental and other risk factors	Impacts	Reference
Parasite Oyster diseases	**Bonamiosis** (*Bonamia exitiosa, B. ostreae*): prevalence and intensity of infection tends to increase during the warm water season. **Marteiliosis** (*Marteilia refringens*): cold temperatures prolong survival (35 days at 15 °C). **Perkinsiosis** (*Perkinsus marinus, P. olseni*): proliferation of *Perkinsus* spp. correlates with warm water temperatures (>20 °C) and this coincides with increased clinical signs and mortalities. Effects appear cumulative with mortalities peaking at the end of the warm water season in each hemisphere; *P. marinus* shows a wide salinity tolerance range and *P. olseni* is associated with full-strength salinity environments.	El Niño occurrence was correlated with Mexican oyster pathogen outbreak and range extension of other oyster pathogens in New England.	Arzul *et al.*, 2012 Audemard, Carnegie and Burreson, 2008 Spiers *et al.*, 2014 Wesche, 1995 Cook *et al.*, 1998 Ford and Chintala, 2006 La Peyre *et al.*, 2003 Soniat *et al.*, 2009
Bacteria *Vibrio parahaemolyticus* strain causing acute hepatopancreatic necrosis disease (AHPND)	Ecology of *V. parahaemolyticus* organism is affected by temperature, salinity, turbidity, and the presence of zooplankton, crustaceans and molluscs. The pathogen can thus be present both in cultured shrimp and in the water, sediments and associated organisms of the culture ponds, as well as in the broader aquatic environment. Environmental factors believed to promote infection by *V. parahaemolyticus*: high water temperature, salinity >5 ppt and pH >7. Unconfirmed routes of disease transfer: attachment of flocs to zooplankton that are carried long distances by ocean currents and El Niño phenomena; attachment on crustaceans and in ships' ballast waters.	Currently the most important non-viral disease threat for cultured shrimp. *Vibrio* bacteria are ubiquitous in marine and brackish water environments.	FAO, 2017 Karunasagar, 2017 Bondad-Reantaso, 2016

Disease	Environmental and other risk factors	Impacts	Reference
Fungi Epizootic ulcerative syndrome (EUS): fungi	Shipping movements, ballast water, fish migrations, ocean currents, rainfall. EUS in wild estuarine populations (e.g. Australia and the Philippines) associated with acidified run-off water from acid sulphate soil areas. Heavy rainfall, flooding, low temperature between 18 °C to 22 °C and after heavy rainfall – conditions which favour fungal sporulation. EUS outbreaks have been associated with mass mortality of various species of freshwater or estuarine fish in the wild (e.g. in rice-fields, estuaries, lakes and rivers) and in farms often during periods of low temperatures (low for tropical climes, e.g. 18 °C to 22 °C), but outbreaks have been observed across a broad temperature range (10 °C to 15 °C to 33 °C). The spread from wild to cultured populations or vice versa can occur via several routes. Once an outbreak occurs in rivers/canals, the disease can spread downstream as well as upstream where susceptible fish species exist.	EUS is one of the most serious aquatic diseases affecting finfish. Indirect long-term effects may include threats to the environment and aquatic biodiversity through, for example, declining fish biomass and irreversible ecological disruption. High losses to fish farmers and fishers through mortalities, market rejection and public health concerns because of the presence of ugly lesions and reduced productivity of all susceptible fish species.	Virgona, 1992 Vishwanath, Mohan and Shankar, 1997 Bondad-Reantaso *et al.*, 1992 FAO, 2009, 2017 Lumanlan-Mayo *et al.*, 1997 Cromie *et al.*, 2012
Viral diseases of shrimp	El Niño events in 1987/1988, 1991/1992, 1994/1995 and 1997/1998 have been associated with the emergence of viral diseases such as infectious hypodermic and haematopoietic necrosis virus (IHHNV); Taura syndrome virus (TSV) and white spot syndrome virus (WSSV), respectively.	Impacts of shrimp diseases are estimated from several hundreds of millions to several billions of USD.	V. Alday, personal communication, 2018 Bondad-Reantaso *et al.*, 2005

24.3.5 Reducing and managing risks of aquatic animal diseases that impact food security

Managing the risks of aquatic animal diseases can be tackled at different levels and different ways through: 1) prevention: reducing the probability of the risk occurring; 2) mitigation: reducing the impact that a risk event will bring and when everything else has failed; and 3) coping: reducing the impact of a risk event that has occurred (Holzmann, 2001). Table 24.2 below shows some examples of generic biosecurity measures and categorizes them as prevention, mitigation and/or coping measures. These are all part of national strategies on aquatic animal health and biosecurity that provide a good entry point for capacity building for many countries, at whatever level of national economic development they may currently be. The focus should be centred on prevention, responsible and effective aquaculture biosecurity and health management practices, and ensuring and maintaining healthy aquatic production and sharing of risk reduction responsibilities (Bondad-Reantaso and Subasinghe, 2008). This will require active engagement and long-term commitment of all relevant stakeholders.

TABLE 24.2
Examples of generic biosecurity risk management measures to prevent, mitigate and cope with aquatic animal disease risks

Generic aquaculture biosecurity measures	Prevention	Mitigation	Coping
Best practices			
• Risk analysis	✔		
• Good husbandry practices (healthy stock, proper stocking density, high water quality, good nutrition, etc.).	✔	✔	✔
• Good biosecurity practices (biosecurity plan: know your species, pathogen, system; facility disinfection, facility sanitation (foot/vehicle baths, hand washing stations), facility biosecurity maintenance (critical control points, health monitoring and testing, etc.).	✔	✔	✔
• Movement tracing (live samples, fresh samples, effluents and waste products, vehicles, farm materials).	✔	✔	✔
• Record-keeping (production, water quality, stock movement, feeding, health and climatic records).	✔	✔	✔
• Prudent and responsible use of veterinary medicines or alternatives (based on accurate diagnosis, following treatment protocols and drug labels and administered by a recognized professional).	✔	✔	
• Biosecurity enhancing practices/technologies/systems (e.g. use of specific pathogen free stocks, polyculture, green water technology, biofloc, recirculation systems).	✔	✔	✔
• Risk communication	✔	✔	✔
Border controls (pre-border, border, and post-border)			
• Pathogen risk analysis	✔		
• Health certification	✔		
• Quarantine	✔		
• Surveillance and zoning	✔	✔	✔
• Control of people (unauthorized entry, visitors)	✔	✔	✔
• Risk communication	✔	✔	✔
Emergency preparedness and contingency plans			
• Early warning (advance knowledge of high-risk diseases; good awareness of current disease situation of trading partners and emerging diseases at global level; good communication linkages and access to disease databases).	✔	✔	
• Early detection (rapid recognition of signs of a suspicious or an emerging disease situation or unexplained disease mortality in aquatic animals in an aquaculture facility or wild populations; rapid communication of the event to the competent authority; rapid activation of disease investigation and disease reporting with minimum delay).	✔	✔	
• Early response (rapid and effective containment of an emergency disease outbreak to preventing it from spreading and becoming an epizootic). The three types of early response are: eradication is the highest level of response but not always possible; containment within specified zones with controls in place around infected zones to prevent further spread; and mitigation which is reduction of the impacts of the pathogen by implementing control measures at the farm or affected population levels.	✔	✔	
• Specific disease strategy manuals (part of contingency plan that contains measures such as fallowing, emergency harvest, destruction and proper disposal of infected animals, vector control (e.g. prevention of spread by birds or other wildlife, physical barrier, avoidance of live feed)).	✔	✔	✔
• Risk communication	✔	✔	

In the long term, enhanced biosecurity will lead to the following:

- improved human health
- agricultural development
- improved food safety
- maintenance of biodiversity
- environmental protection
- increased trade
- genetic improvement
- strengthened market access.

24.4 CONCLUSIONS

Planning for a future where climate change will have both predictable and unpredictable impacts on aquatic productivity (wild and farmed), as well as product safety for consumers, requires robust forward-thinking as opposed to focusing on short-term economic cost–benefit analyses. This is an immense challenge – equivalent to the 1960s thinking about information technology and the economic risks taken through that communication transformation period. It demands risk and vision for aquatic production and food safety for the future. The few examples given here are the tip of researched and published reality, in the face of such a monumental planetary shift. Adaptability, imagination and practical application of ideas are needed, if the existing aquatic resources and production are to be maintained and developed past the next two generations. With the support of immense data and historic records, good management guidelines and risk assessments, there is now a much stronger foundation than was previously available to plan progressive steps towards food safety and aquatic animal health across all the aquatic productivity sectors of countries (capture and farmed). Building on the experience of terrestrial food production systems and using international standards, where appropriate, industry stakeholders, environmental interests and government authorities at all levels are now better positioned than ever to work together on biosecurity measures that benefit all and solidify long-term sustainability. Complacency for food production was never an option and, under current production environment models and human demographic forecasts, can never afford to be.

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Chapter 25: Methods and tools for climate change adaptation in fisheries and aquaculture

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KEY MESSAGES

- When confronted with the impacts of climate change, the viability and sustainability of fishery and aquaculture socio-economic and ecological systems will be determined by their ability to adapt to those impacts. A good understanding of the ecological functions, socio-economic and institutional contexts of a given fishery or aquaculture system should be part of the building blocks required to strengthen resilience and devise the most appropriate adaptation response.
- Adaptation should be viewed as an on-going and iterative process, incorporating flexibility and feedback to learn from past experiences and avert new risks.
- Climate change adaptation should start with an accurate assessment of current climate variability and consider future climate change, as pre-requisites for determining early low- or no-regret options and longer-term adaptation interventions respectively. Decisions need to be made despite and taking into account uncertainties.
- It is important to consider transboundary issues, where appropriate, when developing an adaptation strategy, as all regions are likely to have to deal to some extent with changing stock distributions as a result of climate change.
- A toolbox of existing and recommended fisheries and aquaculture adaptation and disaster responses that would enhance the resilience of the sectors to climate change can help guide communities, countries and other key stakeholders in their adaptation efforts.
- Evaluations of success are often missing from adaptation studies. More research is needed to assess the effectiveness of adaptation tools in fisheries and aquaculture.

25.1 INTRODUCTION

Climate change is challenging the effectiveness of contemporary fisheries and aquaculture management in many parts of the world and gives rise to significant additional ecological and socio-economic uncertainties (e.g. shifting species distributions, change in species compositions and overall productivity) and risks to fishers, fish farmers and fish-dependent communities (e.g. increased storm frequency and/or intensity). The effective management and development of fisheries and aquaculture in the future will have to take into account the greater possibility of unforeseen climate-related events that may impact fisheries and aquaculture socio-economic and ecological systems. Moving forward, countries and communities will have to address climate change uncertainty, complexity and risks in fisheries and aquaculture management, markets and livelihoods, as well as mainstreaming fisheries and aquaculture in their own climate change related commitments. The potential for significant risks, uncertainty and irreversibility (e.g. sea level rise) of climate change impacts on fisheries and aquaculture have moved the focus of adaptation from being primarily spontaneous and reactive to becoming a planned and proactive endeavour.

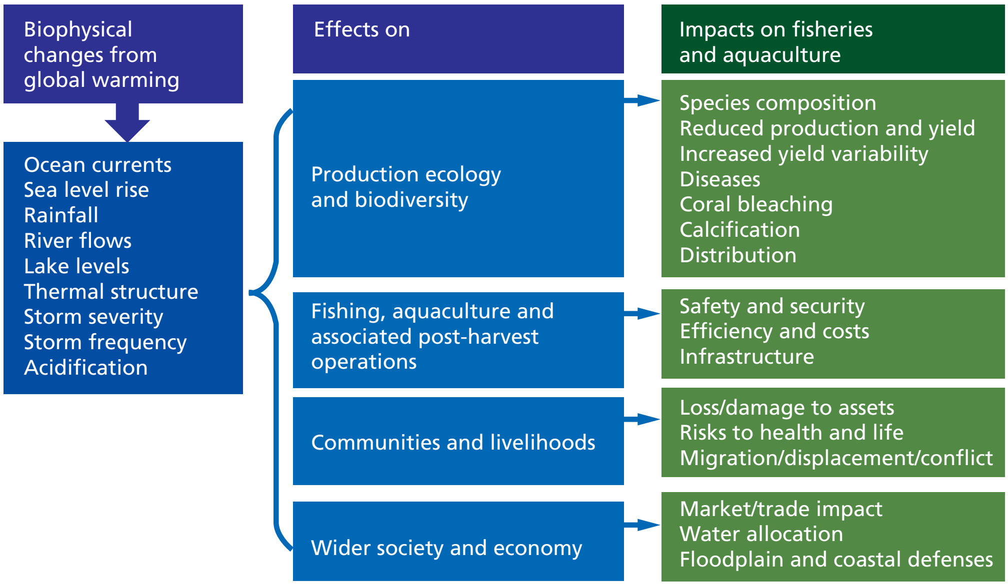
Adaptation is a process of adjustment in ecological, social, or economic systems to actual or expected climate and its effects, which includes actions that moderate, avoid harm or exploit beneficial opportunities (Noble *et al.*, 2014; UNFCCC, 2018). The 2015 Paris Agreement ("the Paris Agreement") is the first global agreement to place climate change adaptation on a par with climate change mitigation (i.e. addressing the causes of climate change). The Paris Agreement specifically sets a goal on adaptation, which consists of "enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change" with a view to contributing to sustainable development and addressing the 1.5 °C to 2 °C targets in the Agreement (Article 7.1). As such, the Paris Agreement requires member countries to plan and implement adaptation efforts and report on the progress of their adaptation efforts via mechanisms such as Nationally Determined Contributions (NDCs), short-term National Adaptation Programs of Action (NAPAs), and longer term National Adaptation Plans (NAPs). The Agreement, in its Preamble and as noted in Chapter 2 of this volume, also emphasizes the intrinsic relationship between climate change actions and the core imperatives of reducing poverty, increasing food security, and ending hunger. These interactions: the nexus of climate change responses with poverty and food priorities, are also noted in recent reports by the World Bank (WB) and the United Nations World Economic and Social Survey (WESS, 2016).

The overarching objective of this chapter is to help to inform national climate change adaptation planning efforts in the context of fisheries and aquaculture. It provides guidance to identify and select appropriate climate change adaptation tools and methods that can be used to respond to the direct and indirect impacts of climate change on the fisheries and aquaculture sector at the local, national and regional levels. It first reviews challenges and opportunities for climate change adaptation, provides examples of fishery and aquaculture adaptation around the world, then presents a climate change adaptation toolbox with a consolidated summary of available adaptation tools and strategies for capture fisheries and aquaculture. It also provides a review of the steps needed for selecting, implementing and monitoring the effectiveness of adaptation tools. Finally, the chapter includes guidance on the phasing and timing of climate change adaptation efforts based on economic analysis and trade-offs.

25.2 CHALLENGES AND OPPORTUNITIES FOR ADAPTATION

Climate change is having profound impacts on fishery and aquaculture-dependent communities and the ecosystems they depend on, especially in tropical regions (Brander *et al.*, 2018). Climate change drivers are causing and are expected to continue to cause potentially significant shifts in primary production, changes in species interactions, shifts in species distribution and abundance, changes in growth and mortality rates as well as change in temperature extremes, precipitation and the intensity and frequency of storms (Doney *et al.*, 2012; Kirtman *et al.*, 2013). In turn, these changes are impacting the socio-economic status of the fisheries and aquaculture sector in many parts of the world and the poverty and food insecurity of areas dependent on fish and fishery products, as well as the governance and management of the sector and wider society (Figure 25.1). While there are many non-climate stressors that also affect these sectors, climate change presents additional, unique challenges because of the uncertainty surrounding exactly which resources and users will be impacted, how they will be impacted and to what degree (Ogier *et al.*, 2016).

FIGURE 25.1
Climate variability and change impact pathways in fisheries and aquaculture



Source: Adapted from Badjeck *et al.*, 2010

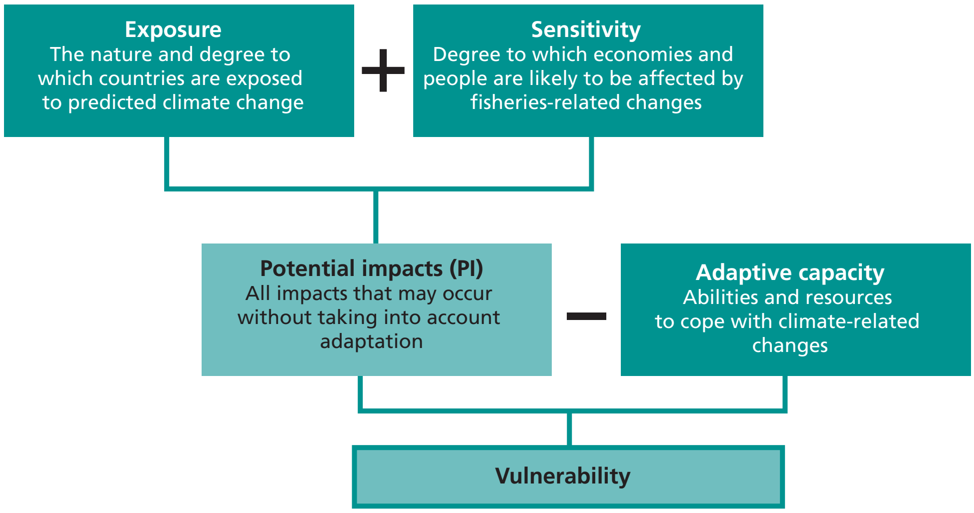
Despite uncertainties in the direction and degree of climate change impacts on fishery and aquaculture systems, the options for responding to climate change are relatively clear (Dulvy *et al.*, 2010). These involve: 1) the reduction of greenhouse gas emissions (climate change mitigation) and/or 2) the building and mobilization of the capacity of natural and human systems (i.e. ecosystems, individuals, communities, sectors, nations and regions), to cope with the impacts from and/or take advantage of the opportunities presented by climate change (climate change adaptation). This chapter focuses on the latter of these two options.

Climate change adaptation is a process of adjustment to actual or expected climate and its effects, which include changes in processes, practices and structures to moderate or avoid potential damages or to benefit from opportunities associated with climate change (Noble *et al.*, 2014; UNFCCC, 2018). The concept of adaptation highlights the notion that instead of trying to control nature, society needs to learn to live with the impacts and uncertainties through learning, experimentation and change. Based on the degree of change required, adaptation can be incremental or transformational (Noble *et al.*, 2014). Incremental adaptation refers to small adjustments to maintain the essence and integrity of an existing fishery and aquaculture system, such as changing gear, fishing method or processing and preservation method. Transformational adaptation involves fundamental changes to the system, often at greater scales and with greater effort than incremental adaptation, and can include migrating or changing livelihoods, as well as governance adaptation. Adaptation actions are taken in the private and/or public sectors, in domestic, regional or global settings and for different types and scales of fisheries and aquaculture systems. Where current adaptation has not been adequate to respond to current climate conditions, it is referred to as the “adaptation deficit” (Noble *et al.*, 2014). Delays in action in both mitigation and adaptation will increase the adaptation deficit in many parts of the world (Noble *et al.*, 2014).

Adaptation is intended to strengthen resilience and reduce vulnerability to climate change and over the past decades, the Intergovernmental Panel on Climate Change (IPCC) has incorporated consideration of resilience and vulnerability into its discussions on climate change impacts and adaptation. Resilience is the ability of a system to absorb a shock, disturbance or change, while essentially retaining the same function and structure. It couples both human and natural elements as linked and dynamic in socio-ecological systems (IPCC, 2014). In a fishery and aquaculture context, a resilient fishery or aquaculture system is comprised of a resilient ecosystem, a resilient management institution, a set of resilient fishing or fish farming communities, and a resilient socio-economic structure (Charles, 2008).

Vulnerability is the "propensity or predisposition to be adversely affected" (IPCC, 2014), and is often described in terms of exposure and sensitivity to negative effects (i.e. susceptibility to harm) mitigated by the capacity to respond, also known as adaptive capacity (Noble *et al.*, 2014). The most commonly used framework for assessing vulnerability is presented in Figure 25.2 below.

FIGURE 25.2
Interpretation and adaption of the IPCC model of vulnerability to the context of fisheries and aquaculture

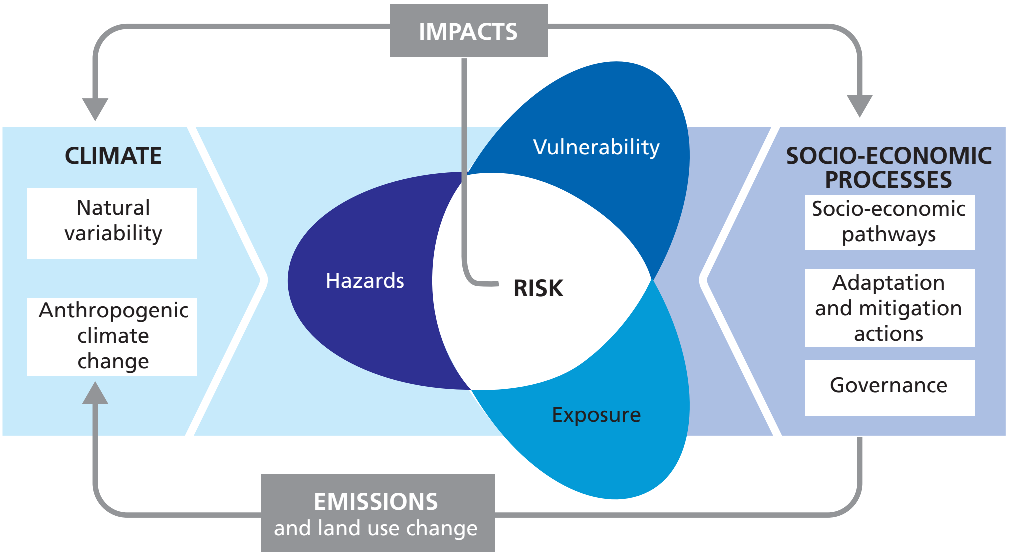


Source: Adapted from FAO, 2015a.

This understanding of vulnerability was applied in the IPCC Third Assessment Report (McCarthy *et al.*, eds., 2001) and is commonly used in climate change vulnerability assessments in the fishery and aquaculture sector (e.g. see Chapter 21) to identify practical adaptation options to assist communities, countries and regions to reduce vulnerability to climate change and optimize opportunities. However, the IPCC has now expanded its definition of vulnerability to consider additional conditions directly and indirectly affected by climate change, such as ethnic composition, age, poverty or socio-economic status (Oppenheimer *et al.*, 2014). This reflects the shift in understanding vulnerability as multidimensional and recognizing the role that structural and social conditions play as factors that contribute to vulnerability. Thus, vulnerability is often higher among marginalized groups, such as indigenous peoples, women, children, the elderly and disabled people who experience multiple deprivations that deprive them of, or reduce, the means to managing daily risks and shocks (Olsson *et al.*, 2014).

The IPCC Fifth Assessment Report (AR5) highlights the role that socio-economic processes and development pathways play in producing risk, including through failures to implement adaptation and mitigation measures (Figure 25.3). In this understanding, hazards are considered as characteristics of climate change and its effects on geophysical systems, while vulnerability refers to the characteristics of human or socio-economic and biological systems exposed to hazardous climatic events or non-climatic events and trends (Oppenheimer *et al.*, 2014). This new approach translates information more easily into a risk-management approach that is meant to facilitate policy-making.

FIGURE 25.3
Conceptualization of the expanded understanding of vulnerability. Vulnerability here includes the impacts of climate and socio-economic processes on risk



Source: Oppenheimer *et al*., 2014.

Finally, fisheries and aquaculture are nested in specific geographical, environmental, and socio-economic contexts that will each have different and unique vulnerabilities. While climate change will impact fisheries and aquaculture as a whole, small-scale and large-scale fisheries, aquaculture and post-harvest operations will experience climate change impacts differently because of differences in scale and different capacities to adapt to climate change impacts. These characteristics are important to consider when evaluating climate change risks, vulnerability and capacity to respond to climate impacts or opportunities. Adaptation requires information on risks and vulnerabilities to identify adaptation options, and these options need to be context specific. Other chapters in this publication discuss in more detail the specific impacts and vulnerabilities in different regions and scales.

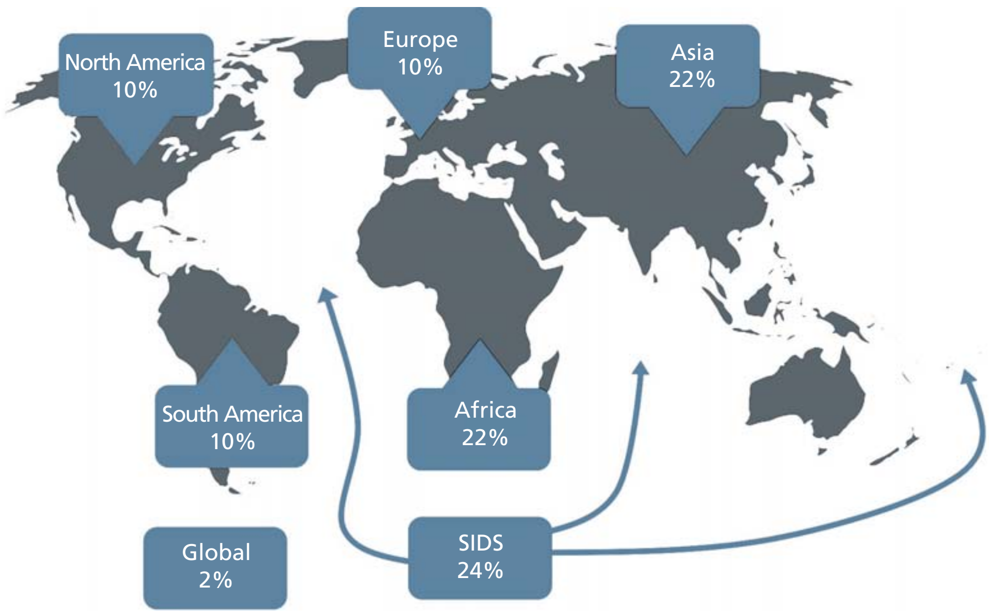
25.3 EXAMPLES OF ADAPTATION RESPONSES TO CLIMATE CHANGE AROUND THE WORLD

A literature review approach was utilized to identify examples of current and recommended adaptations in the fishery and aquaculture sector around the world and inform the development of a toolbox of adaptation measures for each sector. The literature search targeted a diversity of geographic and biophysical contexts, with an emphasis on most vulnerable areas to climate change (e.g. developing countries, low latitude regions, small island states and coastal areas). The search was not intended to be an exhaustive review of all adaptation actions in fisheries and aquaculture to date, but rather to demonstrate the variety of individual and societal adaptation actions employed at different scales around the world. Cases studies were reviewed from all around the world, with approximately 70 percent from small island developing states (SIDS), Africa and Asia (Figure 25.4). Most of the screened case studies came from marine capture fisheries, while there were not as many from inland fisheries (Table 25.1).

TABLE 25.1
Case studies of reviewed adaptation actions by sector

Sector	Proportion
Aquaculture	22%
Marine	44%
Inland	10%
Targets both capture and farmed	24%

FIGURE 25.4
Percentage of reviewed adaptation actions by region



The screened adaptation case studies addressed multiple goals, including food security, vulnerability reduction or resilience building, safety, and income security, in addition to recommendations to improve sustainable management and build capacity to respond to current and future climate variability for individuals, communities or regions. Adaptation goals reflected differences between developing and developed countries, with vulnerability reduction and food security more common goals in developing countries (in 65 percent of all adaptation actions), and improving management, policy and forecasting more frequently cited in developed countries (in 88 percent of adaptation actions in developed countries). In addition, in developing countries, where small-scale fisheries are predominant, adaptation responses often target small-scale and coastal fisheries and fishing communities, while adaptation in developed countries often focused on industrial and large-scale fishing and aquaculture operations. The majority of these case studies (76 percent) made reference to observed or implemented adaptation actions and included initiatives led by governments, the private sector and fishing communities (e.g. MCII, 2013; Musinguzi *et al.*, 2016; NIWA, 2013). Drivers for adaptive responses varied across the case studies. In a number of cases, extreme weather events had initiated the response (e.g. Chang *et al.*, 2013; Defra, 2014). In other cases, it was difficult to disentangle climate and non-climate drivers for adaptation (e.g. overfishing, environmental degradation as a result of human activities) (Adaptation Fund 2014; GEF, 2014a; USAID, 2016). Generally, the reviewed adaptation responses provided examples of institutional changes (including changes in management, legal frameworks, policies and incentives), changes in fishing and aquaculture practices, technologies or livelihoods, and initiatives to reduce and manage climate and non-climate related risks (e.g. harmful algal blooms [HABs]).

25.3.1 Institutional adaptation

Since the adaptations are responses to climate change impacts at the local level, some adaptation actions focus on building-up the capacity of local or national-level fishery and aquaculture managers or individual farmers and fishers to undertake climate change vulnerability or risk assessments and planning (Tan Sinh and Canh Toan, 2012). These elements are often part of initiatives mainstreaming climate change into fisheries and aquaculture planning and management. Adaptation case studies also included recommendations for investment in research and better coordination between fishery agencies and research institutions to assist decision-makers to perform time-adaptive measures (Chang *et al.*, 2013). The vessel day scheme (VDS) is also viewed as an example of an indirect implemented and effective economic response to climate variability. It is a subregional arrangement that brings together eight of the Pacific Island countries, whereby coastal states agree to sell access to their waters at a mutually agreed price (see also Chapter 14). At the onset, the VDS was developed so that the parties to the Nauru Agreement have a single, coordinated – and, hence, stronger – negotiating position regarding access to their waters by distant water fishing fleets. Because the VDS covers and indirectly sets limits to the catch of fish over this vast range, it strengthens the sustainability of their fisheries, and countries are more able to provide an efficient response to increased natural variability in terms of the stock size and the location of the fish (PNA Office, 2014).

Numerous case studies recognize that climate change impacts will be much worse on fisheries that are not well managed (e.g. Bell *et al.*, 2011a). There are efforts to strengthen the ecological resilience of fishery habitat via adaptation actions focused on the community level. Projects that support community-led conservation of mangrove areas and nursery habitats can have not only adaptation benefits but also mitigation benefits when combined with carbon offsets, such as Kenya's Mikiko Pamoja Community Carbon Offset project (Wanjiru, 2017). Reforested and preserved mangrove areas provide carbon offsets as well as important nursery habitat, and the funds from the offsets can sometimes also be used for community projects. Other case studies have also strengthened ecosystem health via management measures, such as formalizing rules for the harvest and use of non-timber forest products to reduce run-off in Senegal (Adaptation Fund, 2015). Benefits for the sector or individuals can sometimes be seen immediately, such as in the case of fishing safety policies, and training and provision of safety gear to reduce injuries at sea (GEF, 2014b; Rezaee, Brooks and Pelot, 2017). Other benefits may only be experienced on longer timescales. For example, benefits from mangrove planting for nursery habitat and shoreline protection can take several years to realize as the mangroves grow and establish roots (Huxman, 2013).

25.3.2 Livelihood adaptation

Livelihood diversification, whether within sectors (e.g. changing target species or using new technology or processing and preserving methods; GEF, 2014a; Musinguzi *et al.*, 2016) or outside the sector (e.g. shifting between terrestrial farming and fishing; IRG, 2008) is a common adaptation strategy across the world. Livelihood diversification is frequently implemented locally and individually, such as changing to farming or livestock breeding when fishery yields decline or migrating to other fishing grounds (IRG, 2008; Musinguzi *et al.*, 2016). These strategies are also supported in adaptation projects, where they can have parallel food security and poverty reduction benefits. For example, a project in Senegal is supporting new opportunities, including training and supporting women's groups with new oyster farms (Adaptation Fund, 2015) and a project in Vanuatu is supporting coastal communities in developing ecotourism (SPC, 2013a). Some of these projects also involve training in business development and planning, supporting a transition to livelihoods that reduce reliance on potentially vulnerable systems such as mangrove or coral reef habitats. Fish aggregating devices (FADs) are becoming a common tool in adaptation in SIDS (GEF, 2015; SPC, 2013a, 2013b). FADs increase access to pelagic species in coastal and rural areas and relieve pressure on inshore and coral reef habitats. They have also been incorporated in community-based ecosystem approach to fisheries (EAF) projects, where FAD siting, construction and management is part of a wider EAF strategy. FADs have been used in conjunction with training activities to increase skills, with local fishers trained in monitoring and identification of species at FADs to collect data in data-poor areas. However, the potential impacts of FADs through increasing catches of juvenile tuna and by-catches of, for example, sharks need to be monitored and managed carefully (see e.g. Chapter 14). Many adaptation strategies, like FADs, can address multiple risks (e.g. increasing sea surface temperatures and ocean acidification, food insecurity, population growth) and provide multiple benefits (e.g. enhance the country's fisheries economy and food security). However, not all livelihood diversification reduces vulnerability. In Madagascar fishers converted from fishing to farming livelihoods as a response to declining catches caused by climate change (IRG, 2008) but agricultural livelihoods in the area are also highly vulnerable to climate change because of erratic rainfall, temperature changes and cyclones and unlikely to able to provide long-term livelihood support.

25.3.3 Addressing climate risks

Adaptation can also address climate risks such as storms, floods and drought, and related-risks such as harmful algae blooms (HABs) through measures that reduce exposure and vulnerability to these risks. For example, the Kosrae Shoreline Management Plan in Federated States of Micronesia involves relocating coastal infrastructure and restricting new development away from coastal hazards. These activities are supported by a government loan programme to build homes outside of risk areas (NIWA, 2013). The Management Plan's planning horizon is also based on a long-time frame (i.e. one to two generations) rather than predetermined dates, reflecting how local people think about the future in more concrete rather than fixed date terminology (i.e. imagining their grandchildren's future rather than a set date). Other climate change adaptation strategies include increased safety at sea through investments in vessel stability, safety equipment, communication, safety information and culture, weather forecasts, and search and rescue planning (Rezaee, Brocks and Pelot, 2017). Reducing exposure to risks at sea, such as storms and winds, can include training and provision of safety gear or GPS devices, and is used in projects in lake and marine fisheries such as in Lake Malawi (GEF, 2014a) and the Caribbean (Chapter 9; GEF, 2014b). Early warning systems for storms, weather, HABs, disease or temperature extremes can reduce exposure and are used in both marine and inland settings and in capture and farmed systems. For example, in response to an extreme cold event leading to high mortality in cage aquaculture in Taiwan, an early warning system connecting marine researchers, fisheries organizations and policy decision-makers, was recommended (Chang *et al.*, 2013). Data and information used to reduce exposure can come from publically or privately funded research and monitoring, such as publically funded projects like ClimaPesca[1] in Central America, ClimeFish[2] in Europe or private companies offering commercial fishing forecasts.

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[1] http://climapesca.org
[2] http://climefish.eu

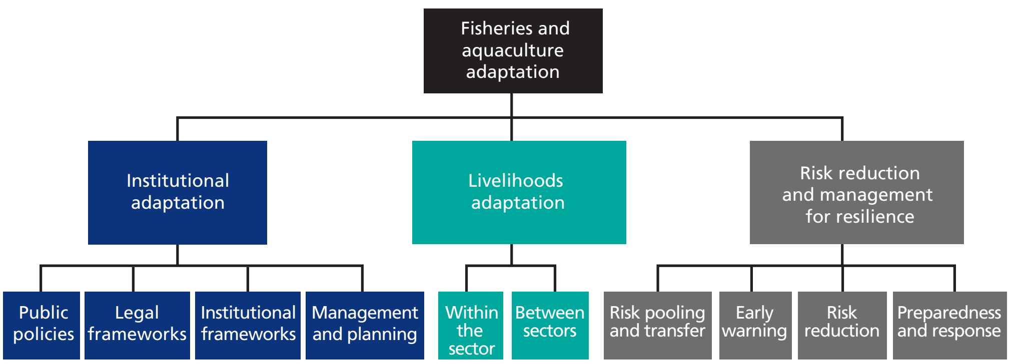
Safety nets and social protection policies can aid recovery and mitigate damage and losses from disasters for fishers and fish farmers. For example, after a stormier than usual season in the United Kingdom of Great Britain and Northern Ireland, the government provided compensation to individual fishers and the fishing industry in the form of grants to replace damaged or lost static gear and allowed temporary flexibility on allocation rules to make up lost income when conditions returned to normal (Defra, 2014). Insurance provision, co-financed by governments, can also be an important tool to compensate fishers and farmers and build back better after a disaster. In Viet Nam, insurance was counted as part of the government's social protection tool to help farmers cope with and recover from natural disasters and fish disease outbreaks (FAO, 2016). There are also examples of informal arrangements between fishers to assist each other during recovery periods. In Bangladesh, fishers pool resources by sharing gear and fishing together following storm events to spread the cost of recovery and improve safety at sea (Chowdhury *et al.*, 2012). These types of responses rely on social connections and can strengthen social ties.

While not all the reviewed adaptation actions explicitly include provisions for them, elements of stakeholder participation, incorporation of traditional knowledge, transparent decision-making and gender sensitivity are important elements in designing adaptation and addressing underlying vulnerabilities, such as socio-economic marginalization and poverty (e.g. Tan Sinh and Canh Toan, 2012). In addition, information relating to the costs or time frames associated with adaptation strategies and evaluations of success were often missing from the reviewed adaptation studies. More research is needed to assess the effectiveness of adaptation tools in fisheries and aquaculture and the timing and cost of adaptation.

25.4 TOOLS AND METHODS FOR ADAPTATION

Different types of adaptation tools have been developed over the last two decades (Biagini, 2014). However, there is minimal guidance available specifically aimed at developing adaptation strategies for the fisheries and aquaculture sector (Cinner *et al.*, 2018). This section aims to contribute to filling this gap by providing a portfolio of climate adaptation tools and methods recommended and currently available to governments, industries and individual fishers and fish farmers. The section groups adaptation tools according to three main categories that are not mutually exclusive: 1) institutional and management, 2) livelihoods, and 3) risk reduction and management for resilience (Figure 25.5).

FIGURE 25.5
Categories of adaptation activities (from analysis of case studies)



Aquaculture, like all agricultural activities, involves partial or complete control of the life cycle and the environment. In a context of global change, it offers the possibility of controlling a certain number of changes or moderating their amplitude. Capture fisheries, on the other hand, are more vulnerable to environmental change induced by climate. Adaptation tools will differ for activities in capture fisheries and in aquaculture, and this section provides two toolboxes with examples of tools and methods that can be implemented by capture fisheries or aquaculture (Tables 25.2 and 25.3 respectively).

Although there are a large number of tools and methods currently available to respond to change in the fishery and aquaculture sector, the increasing influence of climate change requires new perspectives on how to make these sectors sustainable and stable (Lane, 2010). While some of the currently used tools will be sufficient to respond to climate change impacts, many of them will have to be modified to increase flexibility in the face of increased uncertainty about the breadth and significance of impacts. In addition, through the options presented here, decision-makers and fishery and aquaculture stakeholders will have the opportunity to employ new tools that can help the fisheries and aquaculture sectors respond to the effects of climate change more adequately.

Regardless of how adaptation is approached, building adaptive capacity of the fisheries and aquaculture sectors is imperative in order to effectively adapt. Cinner *et al.* (2018) advocates for strengthening capacity across five domains: 1) the assets (i.e. the financial, technological and service resources) that fishers and aquaculture stakeholders can access when needed; 2) flexibility to modify adaptation strategies; 3) the capability to organize and act collectively; 4) learning to recognize and respond to the effects of climate change; and 5) the power and freedom to decide whether to change their behaviour or not. These domains are cross-cutting and need to be considered across three principal areas that can be targeted for successful climate change adaptation in the fisheries and aquaculture sector: institutions, livelihoods, and risk reduction and management for resilience. It is recognized that effectively meeting adaptation objectives will involve a spectrum of options, implemented by public institutions and/or the private sector, within an existing governance framework.

TABLE 25.2
Types and selected examples of adaptation tools and approaches in capture fisheries

INSTITUTIONS
Public policies
Public investments (e.g. research, capacity building, sharing best practices and trials, communication)
Climate change adaptation policies and plans address fisheries
Provide incentives for fish product value addition and market development
Remove harmful incentives (e.g. for the expansion of fishing capacity)
Address poverty and food insecurity, which systemically limit adaptation effectiveness
Legal frameworks
Flexible access rights to fisheries resources in a changing climate
Dispute settlement arrangements
Adaptive legal rules
Regulatory tools (e.g. adaptive control of fishing pressure; move away from time-dependent effort control)
Institutional frameworks
Effective arrangements for stakeholders engagement
Awareness raising and capacity building to integrate climate change into research/management/policy/rules
Enhanced cooperation mechanisms including between countries to enhance the capacity of fleets to move between and across national boundaries in response to change in species distribution

Management and planning	
	Inclusion of climate change in management practices, e.g. EAF, including adaptive fisheries management and co-management
	Inclusion of climate change in integrated coastal zone management (ICZM)
	Improved water management to sustain fishery services (particularly inland)
	"Adjustable" territorial use rights
	Flexible seasonal rights
	Temporal and spatial planning to permit stock recovery during periods when climate is favourable
	Transboundary stock management to take into account changes in distribution
	Enhanced resilience by reducing other non-climate stressors (e.g. habitat destruction, pollution)
	Incorporation of traditional knowledge in management planning and advice for decision-making
	Management/protection of critical habitats for biodiversity and recruitment
LIVELIHOODS	
Within sector	
	Diversification of markets/fish products, access to high value markets, support to diversification of citizens' demands and preferences
	Improvement or change post-harvest techniques/practices and storage
	Improvement of product quality: eco-labelling, reduction of post-harvest losses, value addition
	Flexibility to enable seasonal migration (e.g. following stock migration)
	Diversify patterns of fishing activities with respect to the species exploited, location of fishing grounds and gear used to enable greater flexibility
	Private investment in adapting fishing operations, and private research and development and investments in technologies e.g. to predict migration routes and availability of commercial fish stocks
	Adaptation oriented microfinance
Between sectors	
	Livelihood diversification (e.g. switching among rice farming, tree crop farming and fishing in response to seasonal and interannual variations in fish availability)
	Exit strategies for fishers to leave fishing
RISK REDUCTION AND MANAGEMENT FOR RESILIENCE	
Risk pooling and transfer	
	Risk insurance
	Personal savings
	Social protection and safety nets
	Improve financial security
Early warning	
	Extreme weather and flow forecasting
	Early warning communication and response systems (e.g. food safety, approaching storms)
	Monitoring climate change trends, threats and opportunities (e.g. monitoring of new and more abundant species)
Risk reduction	
	Risk assessment to identify risk points
	Safety at sea and vessel stability
	Reinforced barriers to provide a natural first line of protection from storm surges and flooding
	Climate resilient infrastructure (e.g. protecting harbours and landing sites)
	Address underlying poverty and food insecurity problems
Preparedness and response	
	Building back better in post-disaster recovery
	Rehabilitate ecosystems
	Compensation (e.g. gear replacement schemes)

TABLE 25.3
Types and selected examples of adaptation tools and approaches in aquaculture

INSTITUTIONS	SPATIAL SCALE
Public policies	
Mainstream aquaculture into national and regional adaptation and development plans	National/regional
More effective sharing of and access to water and coastal space with other users	National/watershed
Investments in research and development on aquaculture adaptation technologies; new species, breeding for species tolerant to specific or a combination of stressors (disease, temperature, salinity, acidification) etc.	National, regional, international
Investments to facilitate the movement and marketing of farm products and supply inputs	National, regional, international
Appropriate incentives for sustainable and resilient aquaculture including taxes and subsidies	National, International
Attention to poverty and food insecurity within aquaculture systems	National, international
Legal frameworks	
Property rights, land tenure, access to water	National
Standards and certification for production and for resistant facilities	National
Institutional frameworks	
Strengthening cross sectoral and inter-institutional cooperation and coordination	Zone/national/ regional
Mainstream adaptation in food safety assurance and control	National
Management and planning	
Climate change mainstreamed into ICZM	National/watershed/ regional
Community-based adaptation	Site and community levels
Aquatic protected areas (marine and freshwater) and/or green infrastructure (see ecosystem approach to aquaculture [EAA] guidelines [FAO, 2010])	National/regional
Mainstream climate change in aquaculture area management under the EAA	Zone/watershed/ national
Better management practices including adaptation and mitigation i.e. better feed and feed management, water quality maintenance, use of higher quality seed	Site level/zone/ management area
Mainstream climate change into spatial planning and management for risk-based zoning and siting	Site level/zone/ management area
Integrate climate change in carrying capacity considerations (production, environmental and social)	Site level/zone/ management area
LIVELIHOODS	
Within sector	
Develop and promote new, more resilient farming systems and technologies	Site level/national
Genetic diversification and protection of biodiversity	National
Integrate climate change in microfinance	National
Aquaculture diversification	All
More resistant strains	Site level
More resistant and/or resilient hatcheries and hatchery produced seeds	Zone/national
Value addition	National, regional, international
Better market access; new markets for new species and products	Zone, national regional
Shift to non-carnivorous species	Site level
Fish meal and oil replacement	Site level/national
Empowering farmers' and womens' organizations	Management area/ national
Integrated farming systems and circular economy	Site level/ management area

Between sectors	
Diversify livelihoods	Site level/national
RISK REDUCTION AND MANAGEMENT FOR RESILIENCE	
Risk pooling and transfer	
Social safety nets	National
Social protection	National
Aquaculture insurance	National
Early warning	
Integrated monitoring (relevant aquaculture area), information analysis, communication and early warning of e.g. extreme events, disease outbreaks, etc.	Farm, watershed, zone
Development of national and local vulnerability maps and raising awareness of risks	Subnational/national
Scientific and local knowledge are synthesized and shared; logistics to disseminate information	All
A reliable national risk communication system that supports early warnings	National
Meteorological infrastructure and system that can effectively support crop and farm assets insurance (and particularly weather-indexed or parametric insurance)	National
Risk reduction	
Stronger farming structures (e.g. net pens) and more resilient designs (e.g. deeper ponds)	Site level/national
Enabling adaptive movement between mariculture and inland aquaculture (recirculation aquaculture systems, aquaponics)	Site level/national
Better water management and biosecurity frameworks	Site level/zone/farm clusters
Preparedness and response	
Contingency for emergency management, early harvest and/or relocation	National
Rehabilitation and building back better plans	National/international
Relief programmes such as work-for-food and "work in reconstruction and rehabilitation projects" that offer temporary jobs for farmers and farm workers whose livelihoods have been negatively impacted by climate change	International/national
Emergency assistance to avoid additional damage and loss from climate-related disasters – could include fish feed to avoid massive mortality of stock, etc.	National institutions

Source: Adapted from FAO, 2017.

25.4.1 Institutions

The current fisheries management tools and measures include information gathering (e.g. stock assessment), input controls (e.g. total allowable effort, limited licenses, individual effort restrictions, vessel and gear restrictions), output controls (e.g. total allowable catch limits, catch share programmes, vessel catch limits), technical measures (e.g. area-based conservation measures, size and sex selectivity restrictions), monitoring and enforcement (Cochrane and Garcia, 2009; Lane, 2010). In theory, the current fishery management tools can be expected to meet the objectives of sustainable fisheries management and to respond to the additional challenges posed by climate change. However, Lane (2010) notes some key weaknesses that need to be addressed if resource management institutions are to successfully apply these tools in the face of climate change, including the traditional limitation of stakeholder participation to a consultative role; minimal or ignored stakeholder direct observations and anecdotal information; often conflicting and hard to meet management objectives of ecological sustainability, economic viability and social stability; significant difficulties with applying and operationalizing the precautionary approach; and, considerable influence on governments by industrialized fishing interests.

Despite these weaknesses, the existing tools can still be expected to respond to anticipated climate change impacts but some parts will need to be enhanced to address effectively the complexity and uncertainty of climate change. In particular, effective fishery management approaches need to be participatory, adaptive, and therefore flexible (e.g. FAO, 1997; Lane, 2010). The critical adaptive properties of fisheries management and governance that enable climate change adaptation and resilience building include: an explicit ecosystem level focus; a long-term focus; a learning orientation and adaptive approach; the capacity to cope with complexity and uncertainty; an integration of multiple sectors and scales; monitoring and review capability; and effective and inclusive stakeholder engagement and empowerment. Management approaches such as the EAF and EAA, including adaptive management or co-management, comprise the key enablers and property of good adaptation to climate change and should therefore be applied (EAF: FAO, 2003; EAA: FAO, 2010; Ogier *et al.*, 2016). In addition to this, Miller *et al.* (2010) recommend stronger moves to "integrative science", the process of bringing a plurality of knowledge sources available to support suitable institutional responses, a broader planning perspective, and the development of suitable resilience-building strategies. Chang *et al.* (2013) highlighted the need for enhanced coordination between research institutions and fishery agencies.

For fisheries and aquaculture, setting out a design for change may require a change in existing public policies and legal frameworks, for example with a view to enhancing knowledge, transparency, incentives and adaptation. Decision-makers have a number of tools to achieve this, including public investments in research and learning from climate change adaptation best practices and trials, building the capacity of stakeholders to incorporate climate change into management approaches, developing mechanisms for cross-sectoral coordination at local, national or international levels, creating or removing incentives to reduce the level of fishing pressure or promote flexible adaptation (Hanna, 2010). In addition, fisheries and aquaculture management needs to be integrated with other resource use management (e.g. development, recreation, tourism, oil and gas extraction) to holistically manage river basins, watersheds and the coastal zone. Transparency in resource allocation and transfer of resource access across different sectors will be required and will imply the development of cross-jurisdictional agreements. Furthermore, fisheries management must, where not already in place, shift from top down command and control approaches to a more devolved style of management that shares management responsibilities with resource users (Lane, 2010). This can be accomplished through prioritizing stakeholder participation, building capacity into all levels and aspects of such institutions, ensuring that climate science is incorporated into and available to the relevant institutions, and creating or enhancing institutional cooperation agreements between countries, government agencies and non-governmental organizations (NGOs).

Specifically with regards to aquaculture, changes may also involve drafting a legislative framework that ensures property rights, deals with planning and access, and also with water and waste water, seed, feed, investment, food safety purposes and disease control (Miles, 2010). Self-regulation through voluntary codes of practice and standards should be encouraged and environmental sustainability and social responsibility should be emphasized. In order to work effectively, the management system needs inter-institutional cooperation and coordination, skilled public and private personnel with adequate financial resources to implement, monitor and enforce the legislation and the regulations that flow from there (Miles, 2010).

Fisheries and aquaculture adaptation strategies should be mainstreamed in existing guidelines (e.g. ICZM, EAA/EAF, environmental impact assessment, social impact assessment, national development plans, national budgets as well as in international climate change negotiations). Eighty-seven NDCs address fisheries and aquaculture, of which 78 include climate change adaptation measures for fisheries and aquaculture (see

Chapter 2). Further incorporation of fisheries and aquaculture into national adaptation planning is fundamental for the success of climate change adaptation in these sectors.

25.4.2 Livelihoods

Another area where climate change adaptation occurs is through focus on fishery- and aquaculture-based livelihoods. Climate change is expected to impact fishery- and aquaculture-based livelihoods in a number of ways, for example through changes in the availability and quality of fish for food and less stable livelihoods, including increasing economic instability (e.g. extreme variations in catch, changing distributions and abundance of target species, fluctuations in catch potential). These impacts are expected to be the most significant for the least developed countries in the tropics because of their greater dependence on availability of fisheries resources and their quality for food, and because they have fewer financial resources to invest in climate adaptation and the competition for land and water (Allison *et al.*, 2009; Barange *et al.*, 2014).

Interventions that focus on livelihoods adaptation include activities and strategies that include a mix of public and private activities within the fisheries and aquaculture sector, as well as non-fish related sectors. Many existing adaptation strategies have been developed in response to environmental and regulatory change in general and are not specific to climate change. A common livelihood strategy is diversification within or outside the sector to reduce vulnerability of fisheries-dependent livelihoods to change (Allison and Ellis, 2001). As seen in the case studies, strategies to diversify livelihoods within the sector can include changes to targeted and farmed species (e.g. introducing climate-resilient species or varieties) in order to access new markets or provide higher value products, harvest measures (e.g. gear shifting), technological changes or modifications (e.g. changes in effort or fishing power), improvements in post-harvest storage and preservation and the development of alternative livelihoods (McClanahan, Allison and Cinner, 2015). New opportunities that may arise may also provide new avenues to change consumer preferences.

Many of these tools are individual or community-level responses or actions of the private sector; however, they can be facilitated with government or institutional support. All of these existing tools can be applied to fisheries experiencing impacts from climate change. The sector can also invest in new adaptation strategies, for example, fishers increasing their mobility as fish stock distribution shifts with changing ocean conditions (including seasonal migration), privately investing in new technology (e.g. small-scale monitoring of climate drivers), and developing platforms for sharing knowledge about climate change impacts and adaptation strategies that have been successfully employed (Rathwell, Armitage and Berkes, 2015). Small-scale fishers and fish farmers are often not as well positioned to take advantage themselves of opportunities and adapt to threats as are larger-scale commercial actors. A strong focus should therefore be placed on building general adaptive capacity that supports poor and small-scale producers and value chain actors, in order to enable them to make the most of new opportunities and cope with the challenges related to climate change (FAO, 2017). This broad-based approach to building adaptive capacity can be designed to simultaneously produce benefits in terms of poverty reduction and food security, as well as climate adaptation.

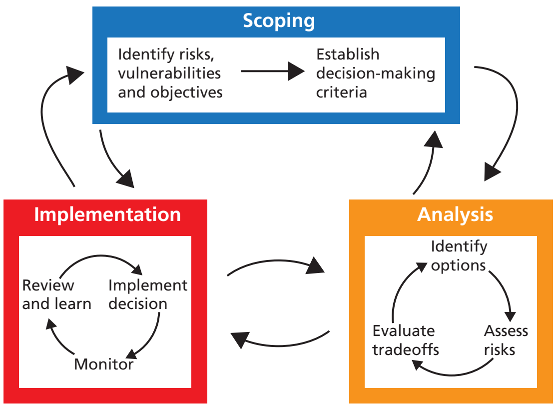
25.4.3 Risk reduction and management for resilience

Finally, climate change adaptation and disaster response can occur through reducing current and future risks, mitigating the potential impacts of climate change and increasing the resilience of the fisheries and aquaculture sector to those impacts, e.g. loss of infrastructure on working waterfronts, loss of fish markets or decreased fishing safety. The existing tools for risk reduction and resilience building include a mix of public and private activities to pool and transfer risk, promote early warning and information systems, improve risk reduction and preparedness, and enhance response to shocks from climate change impacts. In order to improve preparedness for and response to climate change impacts, adaptation and disaster response strategies can be aimed at minimizing the impact of weather-related hazards and extreme events on the fisheries and aquaculture sector and dependent livelihoods through preparation and recovery (e.g. building back better,[3] dissemination of best practices, and capacity building; Cattermoul, Brown and Poulain, eds., 2014). These measures can also help to address poverty and food security issues. In addition, early warning systems can be expanded beyond the traditional weather forecasting to include advance warning for other risks, such as temperature anomalies, algal blooms, market changes (e.g. volume and value) and price fluctuations. Advanced warnings of impending shocks can be used to make timely decisions in order to minimize the damage and loss to aquaculture and fisheries. Lastly, the overall resilience of the fisheries and aquaculture sector to climate change impacts can be strengthened through adaptation focused on enhancing the sustainability of fisheries, avoid overfishing, prevention of impacts, including climate resilient infrastructure (e.g. protecting harbours and fisheries landing sites, stronger farming structures and more resilient designs such as deeper ponds), continued improvements to safety at sea and vessel stability, measures to improve food safety, climate resilient structures, and widespread communication about climate drivers and what tools are available to combat likely impacts.

25.5 USING THE TOOLBOX

A key step in climate change adaptation is putting adaptation tools into practice. Decisions in relation to climate change are not a once-and-for-all event, but an iterative (or adaptive) process that is likely to continue over decades, where there will be opportunities for learning and mid-course corrections in the light of new information (Fisher *et al.*, 2007). The iterative process is represented in Figure 25.6 and explained in the steps below. In addition, Box 25.1 lists examples of guidebooks and tools that are already available for planning and guiding climate change adaptation.

FIGURE 25.6
An iterative risk management framework incorporating system feedbacks



Source: Modified from Jones *et al.*, 2014.

[3] The use of the recovery, rehabilitation and reconstruction phases after a disaster to increase the resilience of nations and communities through integrating disaster risk reduction measures into the restoration of physical infrastructure and societal systems, and into the revitalization of livelihoods, economies and the environment (https://www.unisdr.org/).

BOX 25.1

Examples of online tools and publications for adaptation planning and implementation

- Glick, Stein and Edelson (2011) provide a guide to climate change vulnerability assessment, with due consideration to biodiversity issues (see Table 25.4).
- Brugère and De Young (forthcoming) provide detailed guidance on how to conduct a vulnerability assessment and devise suitable solutions for integrating fisheries and aquaculture in NAPs.
- Raemaekers and Sowman (FAO, 2015b) document their experience in applying participatory rapid vulnerability assessment in small-scale fisheries in southern Africa.
- Brugère and De Young (FAO, 2015a) provide an overview of vulnerability assessment concepts and methodologies, focusing on issues relevant to the fisheries and aquaculture sector.

On line tools include

- UK Climate Impacts Programme Adaptation Wizard
  http://www.ukcip.org.uk/wizard/
- CSIRO's Climate Adaptation Flagship best practices for engaging with stakeholders
  https://research.csiro.au/climate/wp-content/uploads/sites/54/2016/03/3_CAF_WorkingPaper03_pdf-Standard.pdf
- Stockholm Environment Institute – Climate change adaptation toolkit and user guide: a comprehensive guide to planning for climate change adaptation in three steps
  https://www.weadapt.org/knowledge-base/adaptation-decision-making/climate-change-adaptation-toolkit
- EcoAdapt Climate Adaptation Knowledge Exchange
  http://www.cakex.org/
- European Union's project ECONADAPT Toolbox provides easily accessible information on the economic assessment of adaptation
  http://econadapt-toolbox.eu/
- Swiss Re Economics of climate adaptation
  http://www.swissre.com/eca/.

Step 1: Scoping and objective setting

Vulnerability assessment of the fishery and aquaculture sectors to climate change is a relatively recent initiative (see Chapter 21). Table 25.4 sets up the steps needed to undertake a comprehensive scoping of the vulnerability of the fishery and aquaculture human and natural systems in the context of climate change.

Climate change vulnerability assessments are intended to support decision-making, and as such should start with determining clear objectives (i.e. what are the desired goals and objectives), including what is being adapted to and who adapts (e.g. resource users, male/female). In addition, the scope for adaptation should be determined in close consultation with key stakeholders.

TABLE 25.4
Recommended steps to assess vulnerability to climate change

1. Determine objectives and scope:
• Identify biophysical system, resource users and resource user requirements. • Determine spatial and temporal scales. • Engage key stakeholders – internal and external, primary and secondary. • Agree on goals and objectives. • Select assessment approach based on subject, user needs and resources (see e.g. FAO, 2015a for a review of existing approaches).
2. Gather relevant data, information and expertise:
• Review literature, and other sources of available information, gather historical information on the subject. • Obtain climatic projections (or develop the projections) focusing on relevant hazards and on the agreed spatial and temporal scales. • Obtain historical information, make projections on responses of subject to risks.
3. Assess components of vulnerability:
• Determine likely exposure of the relevant biophysical and human system (e.g. community, sub-national area corresponding to a given fishery, etc.) to climate change-induced risks. • Evaluate sensitivity of the above system to climate change-induced (and interacting) risks. • Assess adaptive capacity of the system, which can mitigate risk impacts. • Estimate overall vulnerability of the relevant system taking into account climate risks as well as other risks potentially interacting with climate (e.g. relating to poverty, food). • Estimate level of confidence or uncertainty in the assessments for each of the components.

Source: Adapted from Glick, Stein and Edelson, 2011.

Once these objectives of adaptation and scope are set, decision-makers can begin identifying the relevant data and information that are available or will be needed in further defining an adaptation strategy. Once the relevant data and information are collected, the relevant stakeholders should conduct a vulnerability assessment. Such assessments normally involve an evaluation of the three components of vulnerability, as defined by the IPCC and derived models: 1) the exposure of the designated biophysical and human system (i.e. social-ecological system) to risks spawned by climate variability and change, 2) the sensitivity of the system to these risks, and 3) its capacity to prevent and mitigate likely impacts. Furthermore, assessing vulnerability requires particular attention to those people or groups within the system who are already in poverty or are food insecure, as well as those at high risk of falling into this state. It is expected that climate vulnerability will be highest for those with the greatest levels of poverty and food insecurity. Thus it is advisable to disaggregate the system under consideration (e.g. the given community or region) to ensure that the vulnerability of those with greatest poverty and food insecurity is included and prioritized as necessary. The vulnerability assessment can do this by 1) assessing vulnerability to climate risks for various income, poverty and/or food security "scenarios" within the system, to be clear how climate vulnerability varies between these disaggregated groups and scenarios, and/or 2) examining vulnerability to multiple factors simultaneously, e.g. to both climate risks and food insecurity risks.

The assessment should be grounded in the best available science, including historic observed changes in climate, future modelled projections (prospective assessment), or a combination of the two, as well as build on traditional ecological knowledge (TEK) and other stakeholders' knowledge. Qualitative and participatory, bottom up methods should also be used to gather information from those experiencing impacts, and integrate information on their socio-economic and governance status and systems into the assessment (Glick, Stein and Edelson, 2011). Participatory methods (e.g. participatory/rapid rural appraisals (PRA/RRA) can include expert judgement, mapping and key informant interviews (Brugère and DeYoung, forthcoming; FAO, 2015b). An important component of the assessment is the quantification of uncertainty, which can be done through a risk assessment. Risk assessment involves estimating both the probability of an event occurring, and the severity of the impacts or consequences of that event (see Chapter 21). Brugère and De Young (forthcoming) provides guidance to support countries and communities in ranking their risks. Although the focus is on climate change, other elements not conventionally included within climate-related vulnerability assessments, but that could have an impact on the system's vulnerability, should be considered in the assessment: food security and poverty were noted above; other aspects include power relations, gender, existing governance and management systems, markets and trade and perceptions.

Step 2: Analysis of the results of the vulnerability assessment and development of a climate adaptation strategy

The results of the vulnerability assessment exercise can then be used to develop an overall climate adaptation strategy or plan for a given context. The goal here is to identify a range of potential adaptation options that can be used to meet the objective(s) as identified through the previous step. For each of the identified objectives of climate adaptation, decision-makers and stakeholders should go through the following activities to develop an adaptation strategy.

1. Prioritize and select vulnerable "target groups" for which the adaptation tools will be utilized.
2. Identify adaptation options and required actions for building adaptive capacity.
3. Evaluate adaptation options, in line with agreed objectives and selection criteria (e.g. socio-cultural and technical feasibility, alignment with national development objectives, economic but also social and environment costs, robustness i.e. is the option able to cope with a range of future climate projections).
4. Prioritize and select adaptation tools (e.g. what timeframe; what can be learnt from past, comparable adaptations).

In prioritizing and selecting the adaptation tools that are ultimately going to be used, there are standard methods, which include scoping, expert elicitation, stakeholders' consultation and economic analysis. Further discussion is included in Section 25.6 (below) on how to determine which adaptation tools will provide the greatest benefits with the least costs and how to make robust decisions about adaptation in the face of uncertainty (Charles, 2001; 2008). This analysis should also include the preparation of an action plan and identification of who will pay and be responsible for the implementation and monitoring of each selected adaptation tool.

Step 3: Implementation, monitoring and evaluation

Measuring the effectiveness of adaptation interventions is a key aspect of an iterative process. This is even truer in the context of climate change, where the uncertainty surrounding the extent of climate change impacts is often high. Many of the adaptation case studies currently implemented or recommended (Section 25.3), however, did not explicitly include a plan or approach for measuring adaptation progress and effectiveness. Yet, evaluating the effectiveness of climate change adaptation tools and measures helps to assess the outcomes of adaptation, learn about what works and what does not work, and improve future adaptations. It is key to build measurable goals and indicators into implementation in order to continuously assess whether or not the tools are meeting the selected adaptation objectives. An assessment of the effectiveness of the adaptation tools, particularly in relation to the most vulnerable populations, should happen periodically in accordance with the tools' timeframe in order to modify the tools where needed and build a robust adaptation strategy. This can help to continuously improve the adaptation strategy by understanding how well specific adaptation tools worked, why they worked or did not work and in what context.

BOX 25.2

Example of guidebooks and toolkits that can be used to guide evaluation of adaptation in the fisheries and aquaculture sector

- AdaptME: http://www.ukcip.org.uk/wp-content/PDFs/UKCIP-AdaptME.pdf
- Defra: Measuring adaptation to climate change – a proposed approach http://webarchive.nationalarchives.gov.uk/20130403054913/http://archive.defra.gov.uk/environment/climate/documents/100219-measuring-adapt.pdf
- CLIMAR: Evaluation of climate change impacts and adaptation responses for marine activities http://www.belspo.be/belspo/fedra/proj.asp?l=en&COD=SD/NS/01A
- USAID: Adapting to coastal climate change – a guidebook for development planners http://www.crc.uri.edu/download/CoastalAdaptationGuide.pdf

25.6 FURTHER CONSIDERATIONS REGARDING CLIMATE CHANGE ADAPTATION

When and how should communities, nations, international bodies and NGOs act to develop and implement adaptation actions? The following sections outline some of the considerations to apply in appraising adaptation tools. They also provide guiding principles to limit maladaptation in capture fisheries and aquaculture systems and to inform trade-offs between long-term sustainable use and short-term extractive production goals.

25.6.1 Frameworks for the economic appraisal of adaptation

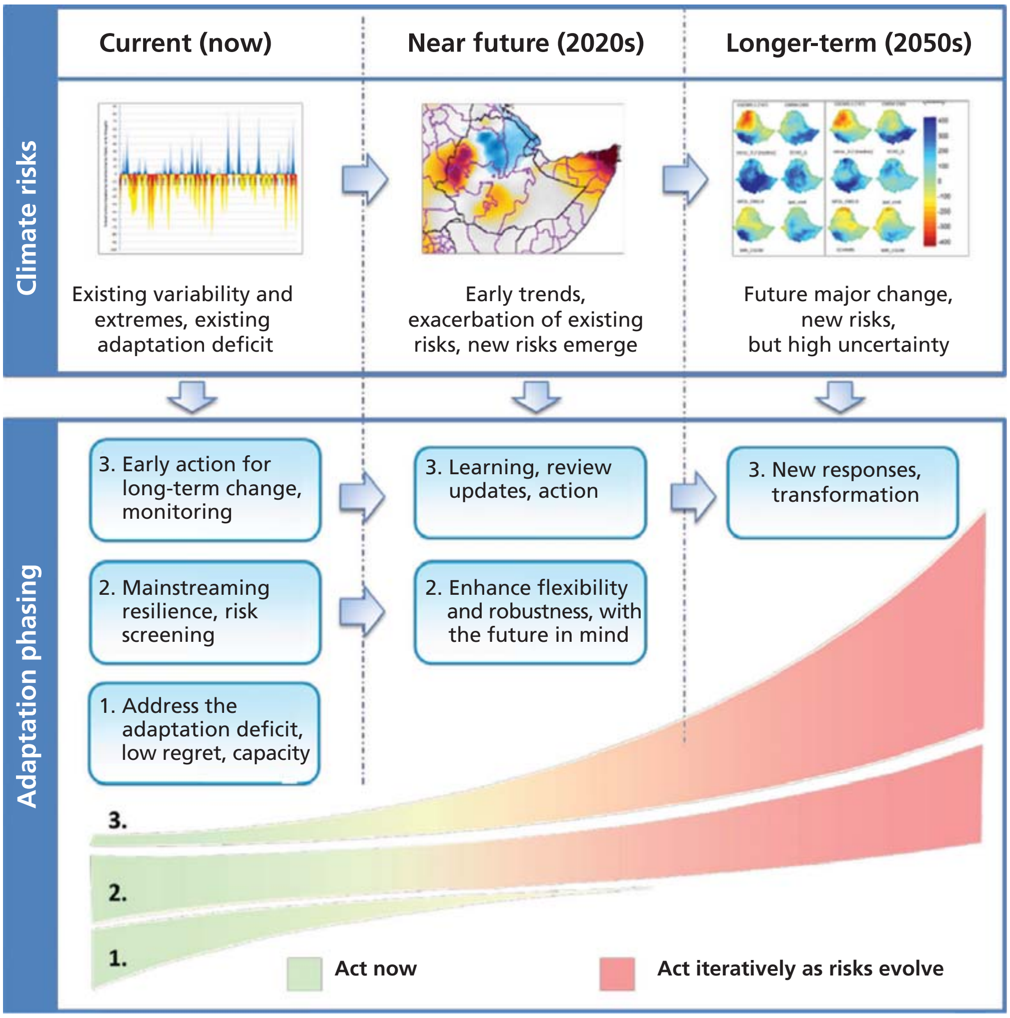
A critical part of the adaptation decision-making process is the phasing and timing of adaptation, taking account of future uncertainty (Watkiss, 2015). A certain number of "light touch" economic decision-making principles have emerged to help with these decisions. In general, these principles encourage immediate low-regret actions, which generate substantial early benefits, combined with an evaluation and learning process to improve future strategies and decisions. An example of these principles is given below:

- **Avoid the cost of inaction,** i.e. avoid cases where future costs are bigger than current costs.
- **Address (current) adaptation deficit,** i.e. actions that are worthwhile (i.e. generate net social and/or economic benefits) irrespective of whether or not anthropogenic climate change occurs. Such actions (also referred to as low- or no-regret actions) are usually grounded in development policies.
- **Mainstream climate change** in cases where future benefits require decisions or activities now (also referred to in the literature as actions with long lead times), e.g. vessel replacement, installation of climate resilient infrastructure.
- **(Take) early action for long-term change** i.e. early monitoring, research and learning to start planning for the future impacts of climate change. This includes a focus on adaptive management, the value of information and future option values and learning so that appropriate decisions can be brought forward or delayed as the evidence and knowledges emerges (Watkiss, 2015).

These principles can be considered together in an integrated adaptation strategy or an adaptation pathway, illustrated in Figure 25.7 below.

FIGURE 25.7

An example of a framework for timing and phasing adaptation using iterative frameworks and low-regret options



Source: Watkiss, P. (2014a). Early value-for-money adaptation: delivering value for money (VfM) adaptation using iterative frameworks and low-regret options. DFID, London. Available at www.vfmadaptation.com

These broad types and principles of adaptation decisions will require the use of particular economic tools. Whereas cost-benefit analysis can be used to address current climate variability (the adaptation deficit), it presents some limitations in the context of adaptation to long-term climate risks, because of the challenges of quantifying the impacts of climate change in the long run (Watkiss, 2015). This point is reinforced by the IPCC AR5, which reports that "economic analysis is moving away from a unique emphasis on efficiency, market solutions, and benefit-cost analysis of adaptation to include consideration of non-monetary and non-market measures; risks; inequities; behavioural biases; barriers and limits and consideration of ancillary benefits and costs" (Chambwera *et al.*, 2014). A number of alternative decision support approaches have therefore emerged to assist with the economic appraisal of adaptation (Table 25.5). These include the extension of conventional decision support tools for adaptation, e.g. cost-benefit analysis, to include new approaches that explicitly address uncertainty. The main methods advanced are real option analysis (ROA), robust decision-making (RBM), portfolio analysis (PA), and iterative risk management (IRM), summaries of which are presented in Table 25.5. None of these tools provide a single best method for all adaptation appraisals; how they are deployed and used is up to the relevant stakeholders according to their own context and assumptions (e.g. whether they apply discount rates, equity weights or non-monetary measures). As the assumptions behind the economic analysis will have a major influence on adaptation results, it is important to be clear about these assumptions to ensure a balanced and reliable comparison between the different options.

TABLE 25.5
Summary of adaptation decision support and appraisal tools

Decision support tool[4]	Description	Potential use
Cost-benefit analysis	Values all costs and benefits to society of all options and estimates the net benefits/costs in monetary terms.	To identify win-win, low- and no-regret options. As a decision support tool with iterative climate risk management.
Iterative risk assessment	Uses an iterative framework of monitoring, research, evaluation and learning to improve future strategies.	For appraisal over medium-longer terms. Also applicable as a framework at policy level.
Real options analysis	Allows economic analysis of future option value and economic benefit of waiting/information/flexibility.	Economic analysis of major capital investment decisions. Analysis of flexibility within major projects.
Robust decision-making	Identifies robust (rather than optimal) decisions under deep uncertainty, by testing large number of scenarios.	Identifying low- and no-regret options and robust decisions for investments with long lifetimes.
Portfolio analysis	Economic analysis of optimal portfolio of options by trade-off between return (net present value, NPV) and uncertainty (variance).	Project based analysis of future combinations. Designing portfolio mixes as part of iterative pathways.

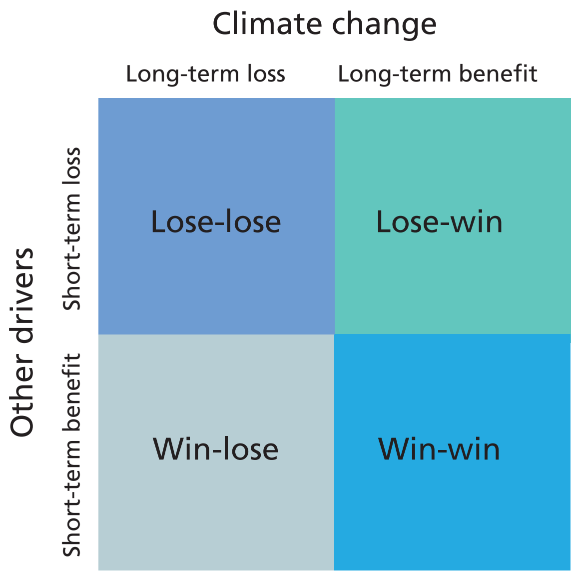
Adapted from Watkiss, 2014b.

With adaptation to climate change occurring in the context of non-climate stressors and existing vulnerabilities (e.g. population growth, food insecurity) that are affecting fisheries and aquaculture, considerations need to be made for addressing both short-term and longer-term stressors associated with climate and non-climate drivers. A framework to identify adaptations to address the effects of climate change and other drivers, like population growth, is presented in Figure 25.8.

[4] See http://econadapt-toolbox.eu/ for additional information.

FIGURE 25.8

Possible outcomes of adaptations to address the effects of climate change in the long-term and other drivers, like population growth, in the short-term



Source: Grafton (2010) adapted from Bell *et al*. (2011a).

Clearly, the best climate change adaptation strategies will include "no-regret," "low-regret" or "win-win" options that provide both short-term and long-term benefits. "Win-win" adaptations could be investments to address, for example, the effects of rapid population growth on present-day availability of fish, and the effects of climate change in the longer-term. "Win-win" adaptations are not to be understood as having no social and economic costs, but as delivering immediate gains (a "win" now) while insulating resources and communities from the effects of continued greenhouse gas emissions (a "win" in the future; Bell *et al.*, 2018). Effective adaptation to climate change is also likely to involve some "lose-win" adaptations, where the economic and social costs exceed the benefits in the short-term, but where investments position economies and communities to receive net benefits in the longer-term under a changing climate (e.g. climate proof infrastructure). In analysing the economic costs and benefits of recommended win-win and lose-win adaptations, social and cultural aspects should also be considered, including the redistribution of the expected benefits from investment (Bell *et al.*, 2018). Win-lose and lose-lose outcomes should be avoided because they represent maladaptation.

25.6.2 Avoiding maladaptation within the fishery sector or between sectors

Another consideration that should be taken into account when developing an adaptation strategy is the potential for maladaptation. Maladaptation can be summarized as "actions, or inactions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in future" (Field *et al.*, 2014). This suggests, for example, that measures addressing climate change, but leading to increased poverty or food insecurity, would be maladaptive (by decreasing welfare). Another way to consider maladaptation in economic terms is to consider maladaptation as lose-lose and win-lose investments, i.e. investments with short-term benefits but long-term losses (i.e. high costs), which should be avoided (Bell *et al.*, 2011b).

Maladaptation can occur between sectors (e.g. agriculture and inland fishery) or within the sector. Maladaptation within the sector may originate in policies and strategies that deliver short-term benefits or economic gains, but lead to greater vulnerability in the medium- to long-term. For example, a subsidy approach that locks in existing and unsustainable practices that would likely increase climate change vulnerability is maladaptive (Grafton, 2010). Other examples of potential maladaptation within the sector include fishing too intensively (beyond sustainability limits) or in new locations (deeper, farther from home) without sustainability assurances, or with non-sustainable changes in gear, such as smaller mesh sizes. These can be the wrong kind of response to reductions in catches, or migration of targeted stocks from traditional fishing grounds or into the exclusive economic zones of adjacent states. The maladaptation responses may increase catches in the short-term, but will have long-term detrimental consequences on stocks and marine ecosystems and will further erode the ability of natural and human systems to adapt to climate and other changes.

In inland fishery ecosystems, maladaptation can originate from the multi-sectoral competition for limited water resources. Inland fishery resources and their freshwater habitats compete for water with other human activities, many of which (e.g. production of food and energy) can be extremely demanding. Impacts arise from changes in both the quantity and flow, as well as the quality of freshwater available for inland fishery production. River regulation for hydropower, water abstraction for agricultural, industrial and municipal uses, and discharge of cooling waters and other pollutants are of particular concern (see Chapter 18). Short-term decisions over allocation to agriculture or power generation may have undesirable long-term ecosystem impacts, the decline in inland fishery resources being only one of these.

In the case of aquaculture, the situation is similar to that of inland fisheries, with maladaptation impacts potentially resulting from competition over both water and land resources and lack of cross-sectoral governance (FAO, 2017). In addition, the future availability of resources for aquaculture feed is likely to be a major constraint to aquaculture growth because of competition with livestock and agriculture sectors as well as use of fishmeals and fish oil for direct human consumption. The shift towards vegetable materials in aquaculture feeds will need to take into account competition with other agricultural human-food crops for water and land. There will also be competition for feed crops from biofuel production. Potential maladaptation risks and trade-offs need to be clearly understood at regional and local levels. The conditions and performance potential of integrated systems also need to be better defined and understood to avoid maladaptation. Table 25.6 provides some concrete examples of where maladaptation has occurred or could occur in the future if consideration is not taken.

TABLE 25.6
Examples of actual incidences or potential risks of maladaptation

		Within or between the sector
Marine fisheries	Ecosystem/ biodiversity impact	• Stocking hatchery bred fish into a disrupted ecosystem after an extreme water temperature event with subsequent damage on wild population (Chang *et al.*, 2013). • Diversification of fishing activity that places pressures on new, more vulnerable stocks.
	Economic and social impact	• Illegal fishing activity (non-compliance with management measures) to compensate for reduced access or reduced catches.
Inland fisheries	Ecosystem/ biodiversity impact	• River regulation, dam construction and abstraction are recognized to stress inland fisheries through habitat degradation and fragmentation, marked shifts in community structure, loss of sensitive species, and of population connectivity (see Chapter 26).
	Economic and social impact	• Investment in an activity benefiting one group, such as catchment management focused on providing irrigation to farmers, may negatively affect downstream aquatic systems and communities reliant on catchment flow for fisheries or navigation (see Chapter 26).
Aquaculture	Ecosystem/ biodiversity impact	• Increasing use of surface and groundwater for irrigated agriculture to compensate for dwindling or unreliable precipitation, for example, may affect the availability of freshwater for aquaculture (see Chapter 22). • Injudicious use of fry for restocking wild environment and enhancing local fisheries may alter or impoverish biodiversity and the genetic pool of resources (Scheraga and Grambsch, 1998).
Markets and infrastructure	Ecosystem/ biodiversity impact	• The destruction of sand dunes resulting from building infrastructure close to the water, which subsequently increases the new building's exposure to storm surges (adapted from Magnan, 2014).
	Economic and social impact	• Heat wave of warm water temperatures leads to greater abundance of catch, shift in fishing season and price collapse due to lower demand (Miller *et al.*, 2017; Mills *et al.*, 2013).

Although maladaptation is of great concern, there are few principles available to help understand and identify risks of maladaptation. Useful principles to design adaptation with a low risk of maladaptation include the assessment questions below, which were initially conceived for coastal areas at a local scale (Magnan, 2014).

Avoid environmental maladaptation

1. Avoid degradation that causes negative effects *in situ*. An ideal initiative would have no collateral effect on assets' exposure to climate related hazards, overexploitation of resources, habitat degradation or pollution of ecosystems.
2. Avoid displacing pressures onto other socio-ecological systems. The aim of any adaptation is to reduce pressures on the environment, not to displace them.
3. Support the protective role of ecosystems against current and future climate-related hazards, so as to maintain natural buffer zones in face of impacts of both sudden (e.g. storms, floods) and gradual changes (sea level rise).
4. Integrate uncertainties concerning climate change impacts and the reaction of ecosystems, so as to maintain enough flexibility to adjust activities in the event of unpredicted environmental changes and new scientific knowledge.

Avoid socio-cultural maladaptation

1. Start from local social characteristics and cultural values that could have an influence on risks and environmental dynamics.
2. Consider and develop local skills and knowledge related to climate-related hazards and the environment.
3. Call on and develop new skills that the community is capable of acquiring.

Avoid economic maladaptation (i.e. avoid creating poverty or investment irreversibility)

1. Promote the reduction of socio-economic inequalities, and implement measures to reduce poverty and increase food security, as these measures can increase system resilience and sustainability of exploitation of natural resources.
2. Support the relative diversification of economic and/or subsistence activities.
3. Integrate any potential changes in economic and subsistence activities resulting from climate change to avoid developing activities that require heavy investment (money, time and energy) but will quickly become obsolete because of climate change.

Initiatives that address many or all the guiding principles will have a lower risk of maladaptation compared to initiatives that address few or none of them (Magnan, 2014).

25.7 CONCLUSIONS

Countries and communities will have to adapt to climate change uncertainty, complexity and risks in fisheries and aquaculture management, governance, markets and livelihoods. Adaptation is a "process of adjustment in ecological, social, or economic systems to actual or expected climate and its effects", which includes actions that moderate, avoid harm or exploit beneficial opportunities. Different types of adaptation tools have been developed. However, there is minimal guidance available specifically aimed at developing adaptation strategies for the fisheries and aquaculture sector. This chapter aims to contribute to filling this gap by providing a portfolio of climate adaptation tools and methods recommended and currently available to governments, industries and individual fishers and fish farmers.

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Chapter 26: Options and opportunities for supporting inland fisheries to cope with climate change adaptation in other sectors

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KEY MESSAGES

- Inland fisheries are an extremely climate-friendly system of food production, with a low carbon footprint.
- Although inland fisheries will be impacted by climate change, there are potential opportunities and gains for inland fisheries that can be captured by its effective integration into the adaptation plans of other sectors.
- Significant adaption approaches will focus on the benefits from integration of inland fish into broader environmental management plans and integrated water and land management (particularly hydropower, irrigation, and the commitment to maintaining environmental flows). An important strategy to achieve this will be basin management plans and the development of transboundary management bodies to develop and implement these.
- Effective integration of inland fisheries considerations into aquaculture adaption is important to limit potential maladaptation issues from interactions relating to invasive species, genetic and health impacts.
- International basin agreements offer the opportunity to provide a framework for the inclusion of inland fisheries considerations in climate change adaption planning and the prevention of maladaptive impacts of other sectors.

26.1 INTRODUCTION

Climate change has, and will continue to affect inland fisheries directly and indirectly (Chapters 18 and 19 and references therein). In order for inland fisheries to continue to support human societies, fishers will have to adapt to the threats and opportunities associated with climate change (Badjeck *et al.*, 2010; De Young *et al.*, 2012; Williams and Rota, 2011). Although changes will primarily be driven by physico-chemical and biological processes, the capacity to adapt will also need to be influenced by cultural, socio-economic and political circumstances.

As global change continues to influence the provision of ecosystem services (Millennium Ecosystem Assessment, 2005), there is considerable need for adaptive management in freshwater fisheries, as increasingly being discussed in marine systems (Brander, 2007). Adaptive management is recognized for its capacity to contribute to successful adaptation to climate change (Kundzewicz *et al.*, 2014; Plagányi *et al.*, 2011; Wilby *et al.*, 2010). Central to adaptive management is the inclusion of stakeholders from a range of backgrounds and the informed assessment of risk and opportunities associated with the putative change in circumstances to develop and implement management measures, which should be subject to regular evaluation and modification (Wilby *et al.*, 2010). There is also a need for policymakers and regulatory agencies to recognize that regulations controlling fisheries' access and activities will have to change to reflect new realities (e.g. changes in species composition, fishable areas, yields) and that this will have to be based on the collection of reliable data.

Climate change will act across different sectors of human life, and each will need to undergo adaptation to change. Freshwaters, or more strictly inland waters, are closely linked to their catchments, and as such, any activities or changes that occur in the catchment (e.g. land use change, over-extraction of water, pollution) are typically manifested in the waterbody itself. Given that inland fisheries are dependent on the integrity of aquatic ecosystems (Millennium Ecosystem Assessment, 2005), they are highly vulnerable to such perturbations, and this extends to human activities to allow adaptation to climate change. Aquatic ecosystems are considered to be among the most threatened on the planet for this very reason (Millennium Ecosystem Assessment, 2005). As detailed in Chapters 18 and 19, the climate-change related stresses on inland ecosystems and their fisheries are largely associated with water-related factors and temperature change. This sensitivity means that freshwater ecosystems and the inland fisheries they support are susceptible to knock-on effects, as human systems respond and adjust to anthropogenic pressures, including adaptation to climate change.

Anthropogenic drivers in freshwater ecosystems are almost entirely linked to growth in human population, economic development and increasing urbanization (this is explored in Chapter 19). This growth translates into increased demands for food, energy generation, water and industrial development. These factors commonly contribute to footprints on aquatic ecosystems and can have a strong climate change component through linkages to the water adaptation actions of the respective sectors. Conversely, other anthropogenic drivers can have positive impacts for inland fisheries, such as environmental initiatives that aim to rehabilitate degraded ecosystems and restore ecosystem services. The large influence of anthropogenic drivers on environmental factors affecting freshwaters means that any actions to allow climate change mitigation or adaptation in the sectors associated with the drivers will also frequently have subsequent impacts on inland fisheries. As such, there is a need for greater awareness of potential impacts and opportunities facing inland fisheries; this chapter explores the options and prospects for adaptation of inland fisheries in response to the threats and opportunities presented by climate change adaptation in other sectors.

26.2 ADAPTATION APPROACHES TO LOST FISHERY OPPORTUNITIES ARISING FROM CLIMATE CHANGE IMPACTS

As described in Chapters 18 and 19, the impacts of climate change will affect the capacity of inland fisheries to continue to provide benefits and services to human society. These may be sufficient to undermine progress over the past few decades in development, poverty reduction, disease mitigation, and food and nutritional security. Table 26.1 shows some of the likely negative impacts on inland fisheries and fishers induced by already observed and predicted future climate change based on the information provided in Chapters 18 and 19. The impacts are numerous and range considerably in severity and indicate that inland fisheries will undergo considerable change. However, fisheries and fishers are characterized by their capacity to adapt, and for many of the observed and predicted changes, new opportunities may arise, if fishers, fisheries professionals and policymakers are able to adapt to the new conditions.

Climate-driven changes in fish availability, quality, processing and trading will affect fish prices and market access, altering fish related income and access to food. There will also be wider impacts on communities, society and the economy. Floods and drought can cause a reduction in households' assets, such as houses, livestock and crops, decreasing their financial and livelihood security. Flooding can also cause displacement and conflict, and climate variation can increase prevalence and distribution of diseases, such as malaria and cholera, and damage hospitals and schools.

Some changes could also be positive, for example where increased precipitation results in increased availability of essential fishery habitats; where previously degraded habitats are restored; or where new species become available from migration (Table 26.1). However, realizing the benefits of any new opportunities will likely require investment in new technology, and provision of advice from fisheries professionals.

As so many of the impacts of climate change on freshwater ecosystems will be indirect and driven by the activities of other sectors, adaption in inland fisheries will need to address multiple sectors in a sustainable way, and should integrate with wider development initiatives to reduce poverty and inequality. Existing local adaption practices should be enhanced and strengthened, and capacity to take advantage of new opportunities should be increased. Where feasible, access to higher-value markets might mitigate against lower values of fish; while more efficient post-production processes could reduce fish losses by up to one third (Allison *et al.*, 2009; Williams and Rota, 2011).

Improvements in infrastructure such as the provision of suitable cold storage and transport systems (Young and Muir, 2008) could also help provide better access to services and markets for fishers, and reduce their vulnerability to climate impacts such as extreme weather events. Adaptive management and an ecosystem-based approach to management would also help maintain and protect ecological functioning and improve water management, while including and informing different stakeholder groups (Nguyen *et al*., 2016). To maximize adaptive capacity in the inland fishery sector, governments and development agencies may need to invest in education for fishers and fishery managers. Furthermore, the provision of credits, loans and insurance to commercial and artisanal fishers could allow equipment to be upgraded and provide flexibility to deal with the increased frequency and intensity of periods of extreme weather e.g. to enable livelihoods to rebuild after climate shocks. Worldwide, there is also going to be a pressing need for flexibility from regulatory bodies, as existing fisheries regulations and fishery management objectives reflect established circumstances, some of which may already be inappropriate as a result of climate change, or could become so in the future.

TABLE 26.1

Key changes and impacts of climate change on inland fisheries (see Chapters 18 and 19) and potential adaptation approaches and opportunities

Impact	Loss	Opportunities	Adaptation
Increases in air and water temperatures			
Increase in temperature & reduction in dissolved oxygen.	Negative shift in conditions for cold-, and in some cases cool-adapted fishes and whitefish (often high value species). Loss of ice cover or reduced ice thickness (preventing access to fishery or transport of catch/gear/personnel). Reduction in average size (where size is not limited by cold water temperatures) as a result of temperature, lower dissolved oxygen and related stressors. Potential local extinction of species in some areas where thermal range is exceeded. Loss of value of traditional and scientific ecological knowledge.	Extended fishing season in those regions currently limited by ice-cover. Lower expenditure on heating houses and business premises. Reduction in illness and injuries associated with extreme cold weather, (e.g. cardiovascular and respiratory deaths), and the number of cold weather associated injuries such as frostbite and traffic accidents. Increase in water temperature allows increased survivorship, growth and production where temperature is currently limiting e.g. high latitudes, and altitudes. Increased potential for warm-water/low dissolved oxygen-adapted fishes, allowing shift in fishery.	Establish long-term monitoring to provide managers, fishers and other stakeholders with relevant information. Apply adaptive management approaches to allow for flexibility to take advantage of opportunities. Develop new ecological knowledge by collaboration between fishery professionals and fishers.
Increase in the frequency and intensity of hot and warm weather.	Increased acute thermal stress on fish. Increased risk of sunstroke. Increased requirement for refrigeration of catch and air-conditioning.	No obvious opportunity.	Produce new norms for worker health and safety/occupational health. Develop infrastructure (cold storage, refrigeration) and biosecurity systems to maintain quality of the catch through the human food chain.
Shifts in isotherms (poleward, altitudinal) following warming.	Shifts in fish distribution will see losses and gains in fish species richness. Novel fish communities formed with no current analogues, and unknown interactions.	Possible new fishery opportunities, may offset losses of existing fisheries.	Train and possibly fund fishers to change their gears and prepare them for new reality. Establish long-term monitoring to provide managers, fishers and other stakeholders with relevant information and to allow for informed adaptive management.
Changes in precipitation			
Shifts in seasonal patterns of precipitation.	Loss of important environmental cues for some fish, with possible detrimental impacts on their ecology. Change in fish community. Loss of value of traditional and scientific ecological knowledge.	Possible opportunities to shift target species to those that respond positively to change.	Develop new ecological knowledge by collaboration between fishery professionals and fishers. Train and possibly fund fishers to change their gears and prepare them for new reality.
Increased frequency and intensity of extreme precipitation events.	Increased hazards for fishing operations. Habitat degradation and fish kills because of run-off.	Flood mitigation measures may include rehabilitation/construction of wetlands/buffer ponds/waterbodies offering potential fish habitat.	Ensure that buffer zones are accessible to fish and promote their survival and growth.

Impact	Loss	Opportunities	Adaptation
Increase in discharge and flooding.	Increased flooding and risk of damage to life, housing, infrastructure and fishing gear/boats. Reduction in fishing opportunities during periods of flood. Scouring of channels, loss of habitat and reduction of non-rheophilic riverine fishes. Increased flux of terrestrial-derived materials (carbon, sediment, pollutants).	Increase in the scale and even the presence of essential habitat (e.g. floodplains, wetlands) – reversing the loss of spawning, nursery and high-productivity foraging habitats. Possible increased productivity from inputs from terrestrially-derived organic material from flooded areas.	Restore environmental cues (environmental flows) and habitats for high value migratory fishes in those catchments that have undergone over-extraction of water. Increase the capacity of fishers to capture those fishes that benefit from the change.
Reduction in discharge, flooding and water levels.	Reduction in the scale and even the presence of essential habitat (e.g. floodplains, wetlands) – resulting in loss of spawning, nursery and high-productivity foraging habitats. Loss of environmental cues and required baseflow for high value migratory fishes. Loss of rheophilic riverine fish. Changes in food web structure and loss of terrestrially-derived energy which greatly subsidizes fish production.	Less flooding may increase capacity to operate fishery throughout the year. Reduction in flood damage to housing, infrastructure and fishing gear/boats, and risk to life. Change in fish community provides new opportunities.	Increase the capacity of fishers to capture those fishes that benefit from the change.
Biological impacts			
Species introductions.	Exotic species compete with native fishes. Co-introduction of parasites and disease. Habitat degradation.	Development of new fishery for non-native species.	Establish long-term monitoring to provide managers, fishers and other stakeholders with relevant information. Allow for flexibility in regulatory agencies to allow fishing for and/or sale of non-native species as their exploitation may not be legal.
Changes in contaminant cycles.	Increased temperatures and changes in discharge result in mobilization of contaminants.	Assessments can be part of a general check on food quality, improving consumer confidence.	Increase assessment of fish quality, but this can be used to increase consumer confidence in general. Establish long-term monitoring to provide managers, fishers and other stakeholders with relevant information.
Changes in parasites and diseases.	Currently temperature-limited parasites and diseases may increase activity, distribution or impact, e.g. reduction of fish condition, spoiling of product or in extreme cases, causing fish mortality and human infections.	Assessments can be part of a general check on food quality, improving consumer confidence.	Need to train and employ specialists and educate fishers, medics and public.
Changes in human populations as a result of climate change induced migration and changes in accessibility			
Migration and increased human population densities.	Increased demand for land, water, food – including inland fishery products. Increased habitat degradation and pollution inputs. Higher fishing pressure.	Better market opportunities and higher prices for inland fisheries products.	Forward planning to accommodate risks of migration. Establishment of management regimes, user rights and access restrictions to protect vulnerable fisheries.
Increased tourism in those areas currently limited by climate.	Increased demand for access to recreational fisheries and possible conflict with existing capture fishery.	Potential for development of economically lucrative enterprises.	Need for fisheries managers and governments to treat all fisheries sectors equitably and recognize importance of inland capture fisheries.

26.3 CAPTURING OPPORTUNITIES PRESENTED BY CHANGING CLIMATE

Climate change is largely considered to have negative consequences for inland fisheries: however, there will be both losers and winners (Harrod, 2016). Here, we briefly outline some opportunities for inland fisheries of which fishery professionals, policymakers, fishers and other stakeholders should be aware.

26.3.1 Potential opportunities presented by changes in water availability

For large parts of the globe, future climate change is predicted to result in increased precipitation (IPCC, 2014a, 2014b; Kundzewicz *et al.*, 2014). Assuming that associated increases in temperature and evapotranspiration do not offset increases in precipitation, it is projected to lead to increases in run-off, river discharge and flooding (Kundzewicz *et al.*, 2014; Poff, 2002; Rouse *et al.*, 1997). Given the close proximity of many human settlements to river systems, this will undoubtedly cause substantial problems for human society. However, where water abstraction and dam construction has resulted in significant loss of wetlands and floodplains, such flooding could also restore degraded (and potentially create new) essential aquatic habitats that support inland fisheries (Poff, 2002). It is important to note that simply restoring flooding in systems where the natural dynamics have been substantially altered does not automatically mean that this will have a positive impact on the ecosystem (Middleton, 2002) and thus on the fish.

Increased precipitation has the potential to increase inland fishery production, if fisheries and the inland water system supporting them can successfully adapt and the increase in water is not removed by other sectors. One means by which access to water is managed is through the construction of multipurpose reservoirs, which are used for flood control, hydropower, irrigation and provision of drinking water for humans and farm animals. Amarasinghe and De Silva (2016) have noted that the potential of these water bodies for inland fisheries is under-valued, and as these constructed habitats become increasingly common, as part of non-fisheries sector adaptations to climate change, they present new opportunities for inland fisheries, especially in association with local small-scale aquaculture.

Changes in precipitation will have the most significant direct impact on river discharge at a global level, and on availability of water for fisheries and other sectors, however, warming and the associated changes in the *type* of precipitation will also affect the volume and pattern of river discharge. These effects will be most pronounced in those rivers fed by glaciers, which include many of the world's major inland fisheries (See Ganges basin case study in Chapter 19). In catchments that drain glaciated or snow-covered areas (e.g. the Andes, Himalayas and Hindu Kush), river flow is typically maintained during warm dry periods by glacial melt or snowmelt. In these systems, predictable seasonal patterns of glacial melt and associated flow regimes have driven the development of human societies reliant on the supply of water for irrigation for agriculture, drinking, power generation and inland fisheries (Milner *et al.*, 2017), and this will be affected by climate change.

As peak glacial melt occurs during warmer summer months, increased discharge following warming has (and will) lead to increased discharge during this period, changing the once predictable pattern of seasonal flooding. Increased flows in glacial-fed rivers during the dry season summer period will increase flooding during a period typically associated with low water levels (see Ganges River basin case study Chapter 19), providing an opportunity for increased fisheries production (Milner *et al.*, 2017), assuming excess water is not removed to support water demands from other sectors, e.g. irrigation-fed agriculture. Fisheries are therefore likely to benefit in the medium-term, but if glacial regression continues, at some point the supply of glacial melt may fail (Hamilton, 2010), with obvious catastrophic impacts on inland fisheries.

26.3.2 Potential opportunities presented by environmental warming

Depending on the particular emissions scenario or the climate model employed, it is considered likely that the world will warm, on average, between 1 °C and 5 °C by the end of the current century (Barros *et al.*, 2014). It is important to recognize that even if emissions were stopped outright tomorrow, warming would continue because of inertia in the climate system.

Increases in air and water temperatures will mean that existing temperature-related controls on fish distribution will likely weaken or even fail, with the likely result of a shift in the distribution of those freshwater fishes that historically have been constrained by climate (Britton *et al.*, 2010; Comte *et al.*, 2013). Warming will transform large parts of the globe, but changes will be especially large in those areas that are currently affected by freezing temperatures, e.g. high latitudes and high altitudes. In these regions, biological production is currently limited by temperature, while fisheries operations are restricted by snow and ice cover. Some freshwater systems and their associated fisheries will be lost, but in other areas new opportunities for fisheries will appear, e.g. through habitat creation as ice cover retreats (Milner *et al.*, 2008), also human populations and their access to potential fisheries will change.

Warming will lead to marked changes in hydrological, physico-chemical and ecological processes in these regions (Wrona *et al.*, 2006, 2016) and flooding and warming will result in the formation of new habitats (Lehtonen, 1996). This will result in changes in species distribution, including both expansions and contractions, and in some cases, the regional and possibly global extinction of some species (Xenopoulos *et al.*, 2005), with subsequent impacts on inland fisheries. As a consequence of warming the range of cold or high-oxygenated water species will contract, shifting their distribution to higher latitudes or altitudes (Hickling *et al.*, 2006; Parmesan, 2006; VanDerWal *et al.*, 2013). The distribution of cool-water-adapted fishes may expand or contract, whereas warm-water fishes (or blackfishes, their tropical counterparts), the biggest winners of climate change, will expand their distributions, such as has been observed in Finland and in the Ganges River basin (see the corresponding case studies in Chapter 19). This will provide new opportunities for inland fisheries, and the sector must be prepared to adapt to this opportunity. However, often these warm-water species are considered of lower economic value than their cold-water or whitefish counterparts, but can often support far higher yields, driving a trade-off for fishers between quality and quantity.

Apart from changes in fish distribution, climate change will also lead to a redistribution of inland fishery activities.

Fisheries operate at human timescales, and the natural speed by which fish have shifted their distributions in response to global geological and climatic shifts may not be fast enough for new species taking advantage of changes to compensate for the decreases in negatively impacted species in order to satisfy future demands from fisheries. For instance, riverine fish in Great Britain responded to recent climate change (warming) with poleward shifts of about 45 km over 25 years (Comte *et al.*, 2013). Given the active role fisheries managers have had in the spread of non-native fishes over approximately 150 years, it is likely that the introduction of fishes to optimize fisheries in new or modified freshwater habitats will be promoted. It is likely therefore that fishery managers will attempt to accelerate the process by the movement and stocking of fish adapted to warming waters into their fishery.

Following climate change, the Arctic will undergo significant change (Smith, 2011), allowing the potential expansion of inland fisheries in that region. Although some aboriginal and commercial fisheries exist high into the Arctic (ACIA, 2004; Lam, 2016) fishery production in the region is currently restricted by temperature, while the remote nature of the region limits fishery activities. As waters warm, and people move into the region there is considerable scope to develop inland fisheries (ACIA, 2004; Wrona *et al.*, 2005) to help to support demands for employment, fresh food and recreation. However, this may put indigenous people, who, to a large extent rely on traditional knowledge and practices, in a difficult position, forcing them to adapt while at the same time competing with new arrivals. Indigenous people have traditionally responded to changes by migrating to new areas. However, modern societies discourage mobility and thereby limit the use of migration as an adaptation measure (Pecl *et al.*, 2017).

26.3.3 Potential opportunities presented by climate impacts on agriculture

Throughout their history, humans have transformed the surface of the earth: today agriculture dominates human land use, with approximately 40 percent of the Earth's ice-free surface devoted to this sector (Queiroz *et al.*, 2014). This has led to repeated wide-scale destruction of natural habitats including forests, prairielands and wetlands, resulting in significant environmental issues, including the degradation of inland fisheries in many places (see Chapter 19). Worldwide, the area of land under agriculture is predicted to continue to increase, especially in low- and middle-income countries, in response to increased demands to feed and employ expanding human populations (Queiroz *et al.*, 2014; Rey Benayas *et al.*, 2007). This is likely to have further impacts on inland fisheries in these regions.

Conversely, higher-income nations in Europe, North America and Oceania have seen recent decreases in the extent of farmland and an expansion of forested areas, through a process known as agricultural abandonment. Although the impacts of agricultural abandonment on biodiversity are subject to considerable debate (Queiroz *et al.*, 2014; Rey Benayas *et al.*, 2007), it is likely that it generally has a positive impact on freshwater ecosystems, and by extension on fish production. This reflects the positive association between forested catchments and hydrological stability, water quality (including reduced inputs of sediments and other pollutants) and increased availability of high quality fish habitat (temperature regulation through shading, increased structural complexity through woody debris inputs), and the provision of allochthonous food subsidies from riparian vegetation (Crook and Robertson, 1999; Larson and Larson, 1996; Pusey and Arthington, 2003; Triska and Cromack Jr, 1980). Any future increases in agricultural abandonment associated with climate change will therefore likely have a positive impact on inland fisheries, although given the regions where it is most common, it will probably be most relevant for recreational fisheries. There is certainly scope for accelerating habitat recovery in such instances, restoring some lost ecosystem services and consequent beneficial outcomes for inland fisheries.

26.3.4 Capturing the opportunities presented by adaption in other sectors

The reactions of other sectors to climate change provides both challenges and opportunities to the inland fisheries sector and these are summarized in Table 26.2. Where climate change actions from sectors external to inland fisheries fail to account for severe consequences for the latter these are to be considered maladaptations (see Chapter 25).

The key to future successful management of inland fisheries will be to limit adverse impacts from other sectors, especially in relation to water. In most cases this will require ensuring adequate environmental flows and habitat maintenance to sustain fisheries. There are some specific direct adaptation measures that are already used to attempt to offset impacts and these include: measures to support fish migration past barriers (such as dams) and restocking and enhancement where recruitment has been impacted.

In general, the impacts of water regulation, abstraction and loss of connectivity that arise from increased water storage, flood control and irrigation of agriculture are already ongoing and climate change will simply exacerbate or accelerate the maladaptation.

There will be some opportunities, which could form the basis of adaptation actions to provide positive outcomes for fisheries. These are mostly related to capturing opportunities that arise from increased water availability and water storage capacity and the improvement of land and soil management in catchments. The establishment of new fisheries in human-made water bodies is the most obvious example and is the typical response to attempt to redress the impact on free-flowing rivers and loss of riverine and floodplain fisheries.

TABLE 26.2

Summary of adaptation in non-fishery sectors, their impacts on inland fisheries and potential emergent opportunities for adaptation in inland fisheries

Sectoral adaptation actions	Potential loss/impact	Opportunity	Inland fishery adaptation
Urban and industrial areas			
Increased abstraction and storage of water to meet demand for potable drinking water.	Restrictions on access to fishing in water bodies.	Water bodies managed for water quality. Increased fish biodiversity. Potentially new food or recreational fisheries.	Develop and manage recreational and food fisheries in accordance with waterbody potential (including potential fisheries enhancements).
Urban/industrial protection demands flood controls and river training.	River flows regulated, and river course managed, leading to homogenisation of the channel, and loss of essential habitat both in-channel and in the floodplain, e.g. spawning, nursery, feeding areas. Reduced flooding and floodplain connectivity reduces productivity. Flood control to protect critical urban developments and agricultural areas.	Possibilities for win-win scenarios through holistic management of floods that preserves river dynamics and ecological flows.	Develop flood management plans that meet the requirements of water managers and the aquatic ecosystem.
Changes in emissions of pollutants in air and water to mitigate climate change.	Possible reduction in productivity thorough reduced nitrogen deposition from NO_x. Potential shifts in fish community structure may affect catch structure.	Improved quality of freshwater and fish.	Establish monitoring programme to provide managers, fishers and other stakeholders with relevant information.
Food and forestry production sector			
Changes in conditions (temperature, precipitation, CO_2 concentrations) drive changes in long-held farming practices, e.g. shifts from pastoral to arable farming, new crops, sowing periods, reduction of fallow periods.	Changes in disturbance and run-off patterns through the agricultural year. Increased exposure to agrichemicals. New crops change inputs of allochthonous materials into waterways.	With awareness and proper planning inland fisheries considerations can be built into development plans.	Develop catchment-level management plans to minimize impacts on receiving waters and allow for overall improved management of fisheries.
Changing precipitation demands increased agricultural irrigation and irrigated areas. Construction of water storage ponds for irrigation.	Increasing abstractions for rivers and water bodies. Extreme removals dewater environment and result in loss of fisheries. Possible loss of natural standing waters to construct water storage ponds.	Increasing construction of water bodies for water storage and movement creates new habitat.	Initiate stocking programmes and stock management.
Flood proofing of roads, and conurbations.	Partitioning of floodplains and loss of connectivity reduce fish productivity. Possible loss of natural standing waters to construct water storage ponds.	Include mitigation actions (to be identified in environmental impact assessments - EIAs) in infrastructure development projects at the planning stage.	Undertake mitigation actions through fish transparent weirs and culverts; restore refuges and habitats within systems; implement holistic, fish friendly water management and ensure minimum flows & water levels. Develop fisheries through enhancements/stocking.

Sectoral adaptation actions	Potential loss/impact	Opportunity	Inland fishery adaptation
Water and resource use efficiency drives intensification of agricultural or livestock production.	When poorly managed, this leads to: increased run-off of nutrients, pesticides, sediment into water courses; increased water abstraction from rivers.		Implement stronger regulatory controls and environmental management measures to limit external impacts on water courses and water bodies. Implement payment for ecosystem services.
Climate-driven land use change – increases/ decreases in agricultural or forested land.	Continued degradation of agricultural land, and associated fish habitat increases.	Minor changes to field boundaries and riparian zones can have major positive impacts.	Rehabilitate degraded land and increase land cover to reduce impacts of erosion and run-off. Implement catchment-based active management to minimize impacts and ensure the participation of the inland fisheries sector.
Farmland abandonment.	Loss of water management and managed wetland habitat (e.g. rice fields, water meadows).	Increased cover of mature vegetation and forest results in improved catchment integrity, improved water quality in run-off, and improved riparian habitat quality. These all benefit fish and result in increased stocks.	Promote reforestation of abandoned farmland.
Increased saline intrusion as a result of water abstraction from rivers or increased storage.	Changing salinity regime may alter fish diversity and food webs in delta areas.	Possible extension of range in deltaic habitats and fisheries for euryhaline adapted species.	Develop new fisheries. Establish monitoring programme to provide managers, fishers and other stakeholders with relevant information.
Energy sector			
Increased hydropower generation.	Impacts on riverine fisheries, flooding and flow. Loss of migratory routes. Changes in habitat from riverine to lacustrine habitats. Impacting largest and most iconic of freshwater species (e.g. sturgeons, giant Mekong catfish, pimelodid catfishes). Reduced sediment and nutrient supply downstream. Loss of nutrients upstream (spawning mortalities). Potential accumulation and liberation of heavy metals and other toxic substances in reservoirs.	Include mitigation actions (to be identified in EIAs) in dam design and operation at the planning stage. New fish habitats become available. Potential to develop cage aquaculture in newly formed reservoir habitats.	Improve fish passages and management of dams to sustain basic ecological flows to mitigate some impacts. Establish fisheries in the reservoirs created as a partial replacement of lost riverine and floodplain fisheries (may require stocking and the introduction of new species).
Biofuel production.	Drainage of wetlands (e.g. peatlands drainage for palm oil leads to loss of fisheries). Loss of riparian habitats to biomass plantations and release of sediments and agrochemicals into the channel.	Few alternatives or opportunities beyond the construction of wetland refuges or management of areas to protect key floodplain or wetland habitats.	
Development of wind energy.	Habitat degradation, land use change and sediment mobilization during the construction phase, especially in upland areas. Changes in local microclimate (warming effect during the night and a cooling effect during the day).	Changes in air temperature may benefit production in some fish species.	Apply catchment-based active management to minimize impacts.
Development of floating solar farms on lakes and reservoirs.	Loss of primary productivity and mixing as a result of shading and change in wind patterns.	If water surface is not totally covered, solar panels may represent a refuge from avian predation, increasing survivorship and fisheries yield.	Develop management regulations taking into consideration that fish may aggregate under floating elements.
Nuclear energy.	Impacts of thermal discharge on receiving waters.	Provision of improved rearing habitat for stocked fishes. Increased growth rates of fish from associated waters.	Develop management regulations taking into consideration that fish may aggregate around the outflow of cooling water.

Sectoral adaptation actions	Potential loss/impact	Opportunity	Inland fishery adaptation
Installation and maintenance of energy-production infrastructure (e.g. pylons, service roads).	Short-term impacts: disturbance, habitat degradation, land-use change and sediment mobilization during the construction phase. Possible increased risk of negative impacts through extended road networks, e.g. construction of housing, the spread of invasive species.	Access to new areas for fisheries exploitation.	Develop management measures for new fishing areas.
Environmental restoration and rehabilitation management as part of flood control, carbon sequestration or rehabilitation of degraded land			
Reforestation & improved watershed management.	Few or no anticipated negative impacts. Potential shifts in water flows. Possible acidification and browning of waters during initial phases of reforestation.	Reduced erosion and sedimentation. Possible improvement in dry season flow by maintaining higher baseflow; reduction in flash flooding. Stream temperature regulation, provision of structured habitats and allochthonous energy and nutrients.	Ensure inland fisheries are consulted before making management decisions.
Wetland construction or rehabilitation (as part of flood control or restoration).	Few or no anticipated negative impacts.	Extension of fisheries habitat.	Restore riparian habitat. Reconnect wetlands and rivers. Actively stock/enhance to develop fisheries.
Restoration of contaminated land.	Possible release of contaminants into waterways during restoration works.	Improvements in habitat quality over the long-term and reduced risk of contamination. More benign conditions for inland fish.	Raise awareness among fishers regarding the dangers connected with the release of contaminants.

In many cases, the benefits to inland fisheries are dependent on successful adaptive management at a catchment or regional level. This will require political will, discussion and cross-sectoral collaboration, and underlines the need for policymakers and regulatory agencies involved in other sectors to be well briefed on inland fisheries and their needs (and their importance to society). Given that inland fisheries are often associated with groups with little political representation, this opens a role for international developmental agencies and non-governmental organizations to help to empower inland fishers and to continue to advocate on their behalf and for greater recognition of the importance of inland fisheries.

26.4 ADAPTATION TOOLS AND APPROACHES

As discussed in Chapter 18, freshwater ecosystems and fisheries are highly driven by temperature, water quality, quantity and seasonal pulses. Conserving inland fisheries will require maintaining all these elements or restoring them where they have been lost. For most watersheds, it is neither realistic nor practical to aim for a complete restoration to a pristine condition. However, there is a range of methodologies and technologies that can be used to mitigate some of the human induced impacts on watersheds when pressures from other users have eased sufficiently to make rectification sustainable. The aim with such rehabilitation should be to restore an ecosystem that favours whole communities of species, rather than specific fish populations. This can only be achieved by restoring ecosystem processes and functions. The habitat characteristics which need improvement must be identified, including all functional units used by fish and especially sensitive parts in the fishes' lifecycles. Available technologies include fish passes, ecological engineering, reconnection of floodplain or backwaters to improve lateral connectivity; shoreline rehabilitation, e.g. reinstatement of riparian vegetation; re-profiling of the river channel and recreating habitat heterogeneity; and creation of spawning grounds (see review by FAO, 2007).

The problems encountered with flow regulation and abstraction of water have resulted in promotion of the concept of environmental flows. An environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits. In most developed countries and in some developing countries, strict regulations for environmental flows and water quality criteria are now in place, however simply defining the minimum flow in the dry season is not adequate. Fish and other aquatic organisms have certain requirements for water quantity and quality, but the timing of hydrological events is equally important to them; environmental flows identify key characteristics of the hydrography that are required by fish species to complete their life cycles and maintain stock levels (Valbo-Jørgensen, Marmulla and Welcomme, 2008). Where river health is deteriorating as a result of disturbances to natural flow regimes by damming and water abstractions, environmental flows must be restored by mimicking the natural hydrological cycle through dam operation to meet these needs and maintain the abundance and diversity of species, which at the same time supports other ecosystems services provided by the river (Tharme, 2003).

Stocking is a common tool used in inland fisheries management (Arlinghaus *et al.*, 2016), especially in human-made water bodies. It is used routinely (Craig, ed., 2016) as a means of providing fishers with fishable stocks. From this viewpoint, it is often considered successful (Jonsson and Jonsson, 2016), but the practice is not without controversy, as many detrimental impacts are associated with the process (Arlinghaus *et al.*, 2016). These include the loss of local genetic diversity, risk of disease or parasite introduction and the introduction of non-native fishes, which can become invasive, change food webs and depress populations of preferred native fishes. Despite these threats, there is little doubt that stocking will be a key tool as fishery managers adapt to climate change. Those funding, directing and advising the inland fisheries sector therefore need to be aware of the need to minimize the ecological impacts of stocking and to maximize the benefits.

As open water stocking has become increasingly controversial, other approaches such as habitat management are seen to be increasingly important in addressing the impacts of climate change (Arlinghaus *et al.*, 2016). The adaptation activities related to management of water, construction or rehabilitation of temperate and tropical wetlands will offer considerable opportunities to restore native fish biodiversity. Whether such actions will be comprehensive enough to restore viable inland fisheries remains to be seen. The creation of new aquatic environments for water storage is more likely to be the norm and in such cases this is likely to be accompanied by some form of stocking or enhancement activity to create fisheries.

Where new fisheries arise, whether this is the result of enhancements or a climate induced shift, it is essential that the fisheries authorities and researchers undertake studies and monitor developments together with the users in order to equip fishers with the knowledge and tools to confront the new situations.

People living in a basin derive different benefits according to their gender, ethnicity, occupation and socio-economic status, and consequently also suffer differently from negative impacts. Decisions that will affect quality or quantity of water resources or aquatic habitats require social, economic and environmental assessment of the risks and trade-offs involved, and projects need to be studied within a basin planning framework. Basin management should lead to the optimization of benefits to society while ensuring a sustainable and equitable development.

If there is no exchange of information between local stakeholders and planners it leads to anxiety and excludes an important source of local knowledge especially on informal activities such as inland fisheries, knowledge which is essential for mitigating negative impacts and avoiding the need for costly and difficult remedial actions. Decision-making processes should be balanced, fully transparent and involve all stakeholders and the approach to management must be multidisciplinary, i.e. involve for example engineers, biologists, socio-economists and the fisheries authority. Although it is complicated and time and resource consuming, decision-making, planning and management must take place through an ecosystem approach i.e. all stakeholders that either directly exploit the resources or whose activities might have an impact upon them should jointly negotiate how they define their interests, set priorities, evaluate alternatives, and implement and monitor outcomes of any development scheme affecting the watershed. Any scheme that seeks to achieve multiple objectives will inevitably involve trade-offs. In this situation payment for ecosystem services (PES) could be used as an instrument to provide incentives to local stakeholders to conserve and manage the ecosystem e.g. maintain drinking water quality and preserving biodiversity (for the benefit of fisheries).

In transboundary basins, adaptation activities in one country may affect the aquatic ecosystem, fish stocks and/or fisheries in other basin countries. This adds a transboundary/international dimension to the issue of governance across water dependent sectors. At the global level, 44 percent of 263 international basins have some form of intergovernmental agreement (UNEP, 2002). Most typically, this includes the formation of a Lake or River Basin Organization e.g. the Mekong River Commission, the Lake Tanganyika Authority and the Amazon Cooperation Treaty Organization. These provide advice on, or deal directly with, basin development and the management of inland waters and living aquatic resources. The agreements provide a framework for joint utilization of the natural resources in the basin in concern, however, this rarely includes the management of fisheries, although there is often a mandate in environmental matters, which may cover biodiversity. Exceptions are the Lake Victoria Fisheries Organization and the Great Lakes Fisheries Commission which are specific transboundary fishery management organizations. Ideally, this environmental aspect would be extended to specifically include the needs of fisheries. Depending upon the basin, this may be justified on the basis of the importance of fisheries for food security and nutrition, and elsewhere as part of a more general indicator of ecosystem health.

Many basin organizations have made climate change impact assessments or developed strategies to adapt to climate change, and although most basin organizations have limited binding powers, they still provide a useful mechanism for the collection and exchange of scientific and other information. In particular, these organizations offer the potential for basin-wide assessment of climate change threats and impacts, elaboration of adaptation measures and strategies to avoid maladaptation impacts (United Nations Economic Commission for Europe, 2015).

26.5 CONCLUSIONS

It is clear that adaption to climate change will impact inland fisheries both directly and indirectly as a result of activities within and outside the sector, and that these impacts include risks and opportunities for the capacity of the inland fishery sector to continue to feed and employ people worldwide.

A major challenge in proposing and implementing adaptation options for impacts from other sectors is how to provide economic (or other values) justification. This is a fundamental requirement in making the case for adaption actions by, *inter alia*, agriculture, water authorities, hydropower generators and irrigation managers, to invest in adaptive mechanisms. Undoubtedly, the greatest challenges lie with the inland fisheries that are primarily aiming at food provision in developing countries (see Chapter 19). It is these fisheries and countries that face the greatest threats to inland fisheries, driven in particular by developments in other sectors, and which simultaneously have limited mature and effective regulatory frameworks to minimize impacts.

The economic argument for investment in adaption for fisheries is typically weak, particularly when it is based merely on the economic value of the volume of fish produced. There are some other hidden values of inland fisheries that are rarely accounted for in a simple economic approach, including failure to consider direct contributions to food security and the less tangible ecosystem services: e.g. biodiversity, maintenance of genetic material for adaptation, as well as aquaculture, cultural and well-being values.

There are relatively few binding international norms that directly support inland fisheries, thus pro-inland fishery adaption actions will tend to be driven by national policy commitments (the EU Water Directive is a notable example of specific policy that covers inland fisheries). Many countries have existing environmental regulations, and these will need to be strengthened to ensure effective adaptation and to minimize the risks of maladaptation. Since the 1950s, regulations have typically been applied on a polluter pays approach, and addressed impacts on resources rather than impacts on ecosystem services (Mauerhofer, Hubacek and Coleby, 2013). This is changing with some commitment from cradle to grave production systems and a move towards PES (Mauerhofer, Hubacek and Coleby, 2013; World Water Assessment Programme, 2009). These approaches can reduce the impact on inland waters and consequently inland fisheries. Some of this change is driven through regulation and some is part of a corporate social responsibility (CSR) commitment (UNESCAP, 2009). Their effective application will do much to create the economic environment for implementation of adaptation that favours inland fisheries.

Inland fisheries are effectively in competition for access to water with other sectors and, as such, an area where inland fisheries would directly and significantly benefit would be from more holistic management in the water sector. The goal should be the routine incorporation of inland fishery considerations into adaptive water management platforms such as the EU Water Framework Directive (Vlachopoulou *et al.*, 2014) and international basin agreements as part of the suite of ecosystems services to be sustained under management targets.

Inland fisheries will also benefit from a broader perspective on the social, economic and environmental costs of climate change and the need for holistic adaptation approaches that address broader ecosystem services such as water and environmental integrity, land and watershed rehabilitation, reforestation, wetland management, water and nutrient cycling, water storage, and carbon sequestration. If properly planned and implemented, these could all have follow-on benefits to freshwater environments and therefore directly or indirectly benefit fish and the fisheries that exploit them. An important starting point in developing effective adaptation approaches is meaningful engagement and consultation with stakeholders at the fishery level (Few, Brown and Tomkins, 2007; Gbetibouo, 2009; Bhave, Mishra and Raghuwanshi, 2014).

This expectation may be overly optimistic, as a certain effect of increased stress on systems from climate change is that overall economic productivity will be impacted. In this situation, increased regulation of any sector is likely to be met with strong opposition and lobbying with the justification that this places an additional burden on economic viability. In the case of CSR, shareholders may simply push to abandon actions that impact the bottom line, potentially eroding any progress made. As such, there is an increased and urgent need for inland fisheries to receive support, recognition and protection from regional, national and international bodies.

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Chapter 27: Countering climate change: measures and tools to reduce energy use and greenhouse gas emission in fisheries and aquaculture

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KEY MESSAGES

- Significant opportunities exist for reducing fuel use and greenhouse gas (GHG) emissions in capture fisheries and aquaculture.
- Reduction of vessel emissions by 10 percent to 30 percent is achievable with efficient engines and larger propellers, better vessel shape and hull modifications, and speed reductions.
- The use of fishing gears that require less fuel for harvesting traditional species may significantly reduce greenhouse gas emissions.
- For towed fishing gears, measures to reduce emissions include multi-rig gear, efficient otter boards, off-bottom fishing, high-strength materials, and large mesh sizes and smaller diameter twines.
- The use of efficient LED lights can significantly reduce emissions in fisheries that use lights for attracting fish.
- Shore-side facilities can take advantage of emerging and maturing renewable energy systems such as wind and solar for reducing emissions.
- The aquaculture industry should progress towards reduced use of energy-intensive feedstuffs, improved feed management, and where appropriate, consider integrating pond aquaculture with agriculture.
- Certain fisheries management measures may have significant impacts on GHG emissions, both positively and negatively. In general, fisheries management that reduces fishing effort and enhances fish stocks will result in reduced fuel use and GHG emissions.
- Fuel use and GHG emission should be an important consideration in devising fishery management strategies and other related management controls.

27.1 INTRODUCTION

Global capture fisheries and aquaculture produced an estimated 167.2 million tonnes of fish in 2014 and contributed 17 percent of animal protein intake by humans (FAO, 2016). The production of fish requires the input of fossil fuel, which results in the emission of GHGs into the atmosphere. According to data in IMO (2015) and FAO (2015, 2016), globally, fishing vessels (including inland vessels) consumed 53.9 million tonnes of fuel in 2012, emitting 172.3 million tonnes of CO_2. This is about 0.5 percent of total global CO_2 emissions that year. For the aquaculture industry, it was estimated that 385 million tonnes of CO_2 equivalent (CO_2 *e*) was emitted in 2010 (Hall, *et al*., 2011). Overall, the energy use of protein production per unit mass of fish is comparable to chicken, but is much less than that from other land-based systems such as pork and beef (Parker and Tyedmers, 2015).

In capture fisheries, Mitchell and Cleveland (1993) defined carbon intensity as the amount of CO_2 emitted per unit weight of fish landed. While GHG can be released through non-fuel use processes in fish production and associated activities, such the loss of refrigerants, the main source of GHG is from the use of fossil fuel. Therefore, the following two concepts related to fuel consumption are often used as indicators of GHG emissions: fuel use intensity, or fuel intensity, (FUI) and fuel efficiency. FUI is defined as the quantity of fuel used per quantity of fish landed (Parker and Tyedmers, 2015). Fuel efficiency is simply the inverse of FUI and defined as the weight of fish landed per unit weight of fuel used.

Fuel use occurs in all stages of fish production including wild harvest in marine and fresh waters, aquaculture, shore-side operations, and in post-harvest processes. This chapter is limited to fish production up to the first landing point, including landings infrastructure, but does not include fish processing, transportation and marketing. Every stage of fish production, especially capture fisheries, is impacted by local, national and international fisheries management rules and regulations. We will therefore discuss fuel use intensity, fuel efficiency, and fuel-saving options from the following five perspectives: fishing vessel, fishing gear, aquaculture, shore-side infrastructure at the first landing, and fisheries management.

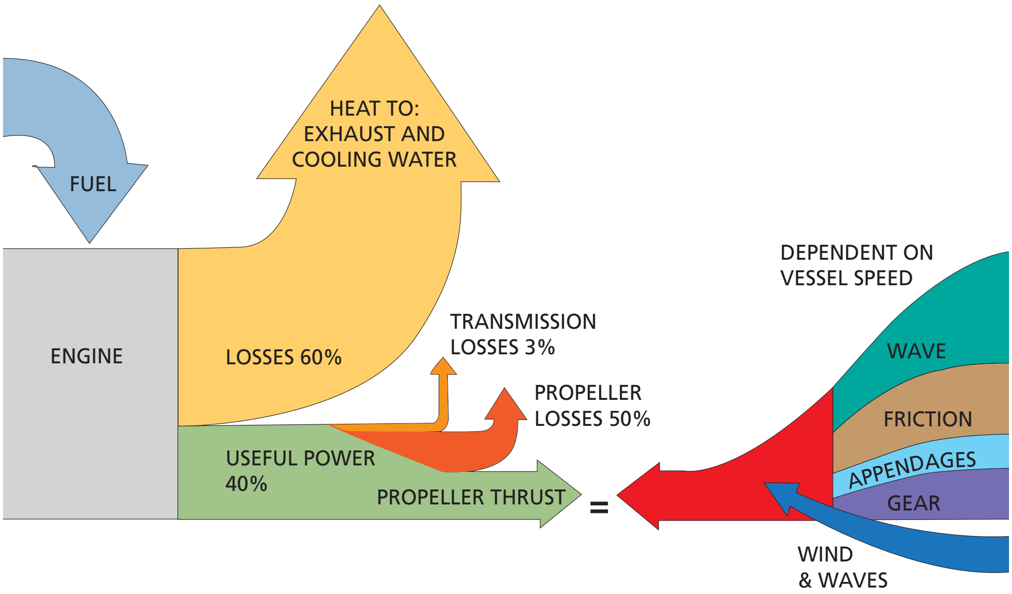
There are several cross-cutting means that can improve fuel efficiency or reduce GHG emission which are applicable to all sectors of fish production and shore-side activities. For example, newer and more efficient engines can save fuel compared with old engines, whether they are used on board fishing vessels, in aquaculture operations, or in shore-side facilities. Renewable energy, such as wind, solar and tidal power may be feasible in some fish production sectors and at some stages, especially for aquaculture and shore-side activities. Energy auditing of fishing vessel, aquaculture operations, and shore-side facilities can help to identify opportunities for energy-saving (Thomas, *et al.*, 2010).

27.2 FISHING VESSELS

The global fishing fleet is estimated at around 4.6 million vessels (FAO, 2016), of which about 65 percent are motorized. Of all motorized vessels, about 85 percent are small vessels less than 12 m in length overall. Currently motorized vessels use outboard and inboard internal combustion (IC) engines for propulsion and onboard power; all producing waste heat and gas, including CO_2.

The power generated by combustion is used to propel the vessel and tow fishing gear, and to a lesser degree, power onboard equipment and facilities, as illustrated in Figure 27.1. The left side of the figure shows factors affecting thrust: the force propelling the vessel, and the right side shows factors affecting vessel resistance: the forces resisting movement of the vessel. The vessel will move at a speed where thrust is equal to resistance. Propulsion efficiency is improved by increasing thrust components and reducing resistance components. Note that power for onboard equipment and facilities may also be provided by a diesel generator which suffers the same losses as the primary engine; the resistance in this case is the electrical loads.

FIGURE 27.1
Illustration of energy output from an engine, and the portion for propeller thrust, and the components of the resistance of and to the vessel. Thrust and resistance must be balanced for the vessel to steam at certain speed



27.2.1 Existing vessels

Fishing vessels may be grouped into three technology levels: traditional, evolved, and contemporary. The first group has changed little over time, the second group has evolved to suit developments and the third employs modern technologies. Many small vessels, as well as large vessels, are of traditional or evolved designs and may not be optimized for propulsion efficiency using contemporary technologies.

Practical actions can be taken with existing vessels to increase their propulsion efficiency. Several actions may be combined to gain significant improvements in fuel efficiency (Table 27.1), which may depend on vessel size, fishing gear and activity.

Retro-fitting a bulbous bow may be applicable for some designs and has the potential to reduce fuel consumption. Generally, such a bow is fitted only on larger vessels because of the cost of installation; but may technically be applied to vessels of any size. Potential fuel savings of 5 percent to 15 percent can be achieved (Notti and Sala, 2012a).

TABLE 27.1

Measures to improve fuel efficiency in existing vessels, with typical ranges of fuel savings calculated or reported across vessels from 10 m to 40 m in length. Achievement of true fuel savings depends on detailed engineering and careful installation of each item

ITEM	ACTION	FUEL SAVING	
		Low	*High*
HULL RELATED			
Bulbous bow	Retro-fit installation	5%	15%
Hull appendages	Reduce/smooth/align appendages	2%	5%
PROPULSION RELATED			
Vessel speed	Reduction	5%	20–30%
Engine	Replacement with new	7%	20%
Engine	Correct design/installation including exhaust		4%
Gearbox & propeller	Replacement	5%	15%
Propeller nozzle/duct	Install	0%	15 – 20%
Trim & weight	Correction	0%	5%
Fuel meter	Install & keep records		
NON-PROPULSION RELATED			
Hydraulics	Upgrade pumps and controls		
Refrigeration	Upgrade compressors & pumps Improve insulation		
Heating/cooling, electrical & lighting	Utilise waste heat. Improve insulation		
Parasitic loads such as pumps & motors	Upgrade controls, switch off all above	0.5%	1.5%
Operational awareness	Improve by training & record keeping		<10%

Small improvements can be made by paying attention to hull appendages including rudder, skeg, keel, sonar transducer enclosures and bilge keels. The key is to reduce the size and area of these appendages, and to streamline the shape to allow smoother water flow. Poor vessel balance can increase resistance and fuel consumption, and should be corrected by shifting weight and equipment, or in high speed vessels by transom modifications. Fuel savings from such corrections are small but important when combined with other measures. For example, transom modifications can have a resistance reduction potential of around 5 percent (Salas and Tampier, 2013).

Refitting and replacing an old and inefficient engine with a modern design can reduce fuel consumption by taking advantage of technology developments such as turbocharging, common rail injection and electronic control. Further, replacing a petrol outboard with a diesel inboard engine can significantly save fuel, by perhaps 30 percent to 40 percent. Diesel engine size selection is critical because most are designed to run efficiently at about 70 percent to 85 percent of maximum rating. When outside of this range, fuel efficiency may be reduced by 5 percent to 20 percent (Curtis, Graham and Rossiter, 2006).

Replacing an engine may require a replacement of gearbox and propeller, providing further opportunities for improvements. The use of a large and slow turning propeller can produce significant fuel savings of 15 percent or more (Gulbrandsen, 2012). A propeller installed with a nozzle or duct (ring around the propeller) can result in fuel savings of up to 20 percent and can be particularly effective for vessels operating towed fishing gears (Laurens and Dasira, 2014; Notti and Sala, 2012b).

On larger vessels, diesel generators supply power to many non-propulsion functions, including hydraulics, refrigeration, heating and cooling, lighting, pumps and others. As an example, 25 percent of fuel consumption of a 44 m Danish purse seiner was not attributed to propulsion and included 11 percent to hydraulics and 7 percent to refrigeration. Improving efficiency of these non-propulsion types of equipment can also contribute to fuel-saving.

Therefore, existing vessels can reduce fuel consumption by combining several smaller improvements to achieve a significant overall improvement, potentially of as much as 30 percent (Siddle, 1984).

27.2.2 New and future vessels

Optimizing design and propulsion

A new fishing vessel designed to optimize fuel consumption should aim to maximize thrust components and minimize resistance as shown in Figure 27.1. For an IC engine, more than half of the input energy is lost to waste heat. The remaining useful power is further diminished by gearbox, shaft and propeller losses so that the final output may only be 20 percent of the input.

The largest contributor to efficient propulsion is the selection of a matched main engine, gearbox and propeller. The hull should be designed to accommodate the largest possible propeller, shaped to allow clear water flow into the propeller, and where applicable to accommodate a propeller nozzle.

IC engines require specific operating conditions to operate at peak efficiency including effective cooling, adequate combustion air and a correctly designed exhaust system (Gulbrandsen, 2012). Engine selection and position (influenced by location of the shaft and propeller) may also affect the hull design. Engine selection should take account of power, appendages and the resistance of active fishing gear (Section 27.3) and bad weather. The selected engine should operate at its peak efficiency at the desired operating speed (or speeds in the case of trawling).

Hull resistance increases with speed and mainly depends on hull form, length, underwater area and weight. An efficient design should optimize hull size and shape to provide safety, speed, hold capacity and weight; and to match the intended fishing operation. The hull length to width ratio has great impact on hull resistance, and generally increasing hull length (but not width) can reduce resistance. Whilst keeping fishing capability equal, the power requirement for a 12 m vessel would theoretically be reduced by 21 percent if the length were increased to 14 m (Tourret and Pinon, 2008). Similarly, lengthening a 17.5 m vessel to 21.5 m would reduce power requirements by 27 percent according to the same authors. Therefore, authorities should carefully reconsider regulations which result in vessels that are too short in relation to their width. A vessel classification system that takes into account installed power and hull or fish hold volume rather than vessel length alone is likely to allow more efficient designs.

Improving overall vessel fuel efficiency should address all energy consumers on board, including equipment design, use and maintenance. Beyond propulsion, power generators, heating and lighting, hydraulics, refrigeration and insulation need to be designed and installed for minimal energy consumption (Table 27.2).

Existing and emerging technologies

Several fuels and propulsion technologies, some established and others developmental, could be adopted for the propulsion of fishing vessels and result in reduced GHG emissions (Table 27.3). Resistance to adoption includes high costs, which will likely be lowered rapidly with technical developments.

TABLE 27.2
Options for improving fuel efficiency in new and future vessels

ITEM	ACTION
THRUST COMPONENTS	
Engine selection	Advanced design, correct power selection
Engine installation	Correct intake and exhaust design. Include fuel meter
Gearbox & propeller	Gearbox for largest possible propeller, RPM <1000
Propeller nozzle/duct	Included where vessel size & speed is appropriate
RESISTANCE COMPONENTS	
Hull dimensions	Increased length. Hull to suit speed, capacity, displacement & operation
Trim & weight	Correct balance to match hull design
Hull shape	Correct shape especially bow & stern areas
Bulbous bow	Included where vessel size & speed is appropriate
Hull appendages	Reduce appendage number & size. Smooth shapes for water flow
ADDITIONAL CONSUMERS	
Hydraulics	Upgrade pumps and controls
Refrigeration	Upgrade compressors & pumps. Good insulation
Heating/cooling, electricity and lighting	Utilise waste heat. Good insulation. Good controls, switch off
Parasitic loads such as pumps & motors	Reduce by design & engineering

TABLE 27.3

Current and emerging technology that has potential for reducing GHG emission. NO_x – nitrogen oxides, SO_x – sulphur dioxide, PM – particulate matter, CO – carbon monoxide, HC – hydrocarbons

POWER SOURCE	USAGE	EMISSIONS
INTERNAL COMBUSTION		
Diesel	Fishing vessels over 7 m in length. Generators for electric power, refrigeration and hydraulics	Greater engine efficiency (+30%) thus CO_2 lower than petrol, but higher NO_x & SO_x & PM
Petrol/gasoline	Small fishing vessels, mainly in outboard motors	Lower engine efficiency thus CO_2 higher than diesel, but lower NO_x, no PM and only trace of SO_x
Liquid natural gas	Some adoption in shipping especially where NO_x emissions are taxed	CO_2 25% less than diesel, 85% less NOx & no SO_x or PM, but methane produced[1]
Kerosene	Small fishing vessels where cheaper than gasoline. Use in two-stroke outboards	Not as efficient as gasoline thus higher CO_2 emissions and dirty exhaust
Biodiesel	IC engines converted to burn biodiesel or blended with gasoline or diesel	Reduces pollutants such as PM, CO & HC but can increase NO_x compared to diesel
Hybrid electric[2]	Some adoption in small vessels, mainly leisure	Similar to diesel if well designed
Diesel electric[3]	Frequent in shipping	Similar to diesel
Ethanol	Vehicles, may be adapted to vessels	CO_2 possibly lower than diesel & gasoline
Propane	Cooking, heating & vehicles, may be adapted to vessels	Lower emissions than diesel & gasoline but methane produced[1]
ALTERNATIVES		
Battery electric	Small vessels in nineteenth century superseded by IC engines in the twentieth century	Zero if batteries charged from renewable electricity.
Fuel cell	Very limited experimental applications. Systems at early stage	Zero other than O_2 and H_2O but hydrogen should be produced from renewable electricity
Solar	Limited in small vessels. Output small so suitable for small consumers or combined with other technology	Zero[4]
Wind propulsion	Historically common in fisheries but rare today	Zero[4]
Wind and other renewable electric	Used to charge batteries or produce hydrogen for fuel cells	Zero[4]

Notes:

[1]Methane's global warming potential is 21 times higher than CO_2.

[2]Combination of internal combustion engine (ICE) and electric propulsion from batteries. Two types – serial where electric motor provides propulsion and parallel where either ICE or electric propulsion are available.

[3]Combination of ICE and electric propulsion without batteries. Propulsion is electric powered direct from diesel generators. Used where loads other than propulsion are high.

[4]Manufacture & installation of technologies creates some emissions.

27.2.3 Vessel maintenance and operation

Maintenance

Undertaking regular maintenance of engines and other machinery is a simple low-cost action that can improve fuel efficiency. For example, if an engine is suffering from a dirty air filter and turbocharger, worn injector nozzles and injection pumps and has water in the fuel, its fuel consumption could be as much as 6 percent higher (Irish Fisheries Development Division, 2008).

Marine growth, including micro-organisms, can accumulate rapidly on a hull, increasing roughness and resistance. Ensuring that the hull and propeller are cleaned regularly can improve vessel efficiency by up to 30 percent (Curtis, Graham and Rossiter, 2006).

Operations

A small reduction in speed in steaming and/or towing, perhaps by 0.5 to 1 knot, can dramatically reduce fuel consumption and may only have a minor impact on production. Potential fuel savings of 5 percent to 30 percent can be expected (Gulbrandsen, 2012).

Fuel consumption meters indicate instant and cumulative fuel consumption of the vessel, and provide feedback on operational behaviour of the vessel to the skipper during steaming and towing. Reports indicate that installing a fuel consumption meter on a fishing vessel can reduce fuel consumption by up to 30 percent. With judicious use of the throttle to adjust engine speed during steaming, up to 35 percent of fuel saving is possible (Eayrs, Chokesanguan and Suuronen, forthcoming; van Marlen, 2009).

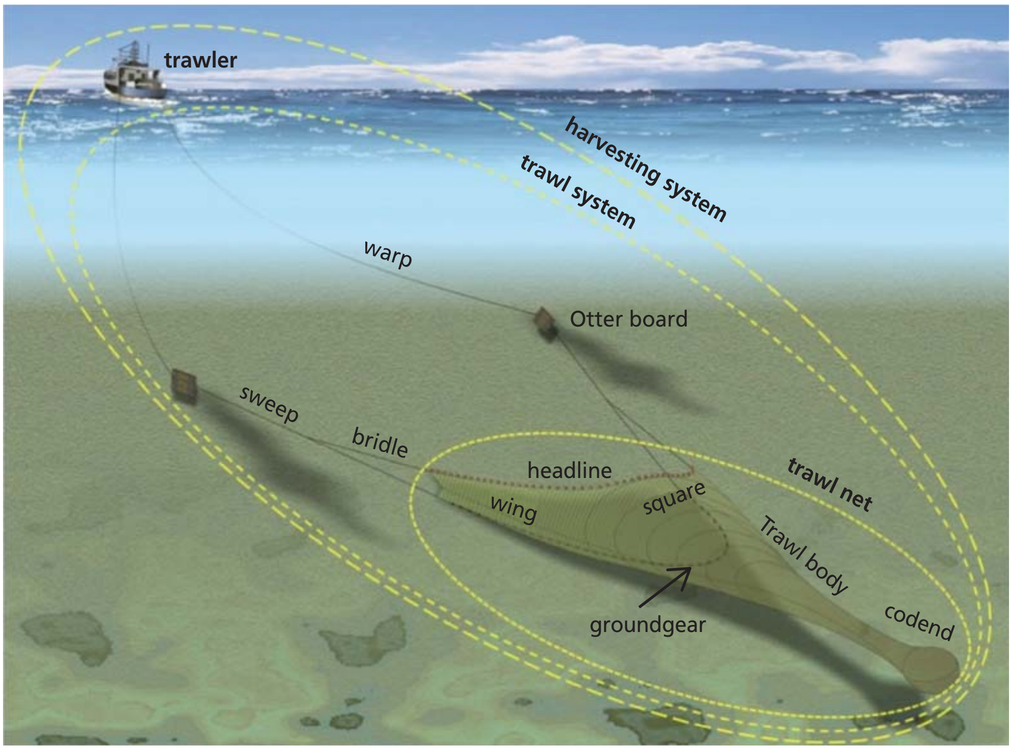
Providing information to the skipper and crew regarding options for fuel conservation can be an effective means to reduce emissions. Where a vessel owner is not the operator of the vessel, properly designed methods of sharing revenue and costs may offer incentives for skippers and crew to reduce fuel use.

27.3 FISHING GEAR DESIGN AND OPERATION

Capture fisheries extend from freshwater to coastal waters and to the high seas beyond national jurisdiction. In general, fishing gear can be divided into two broad categories: mobile gear and stationary gear. From the point of view of energy use and GHG emission, mobile gears are typically more energy-intensive compared with stationary gears. Among mobile gears, bottom trawl, beam trawl and shellfish dredges are among the fuel-intensive fishing gear types as they are towed on or dig into the substrate, thus producing high resistance.

Trawls, especially otter trawls, are one of the most important fishing gear types in terms of the amount of fish harvested from the sea. A typical trawl harvesting system and its components are shown in Figure 27.2. When considering energy use during fishing with an otter trawl, it is generally considered that two-thirds of the energy is consumed by the trawl system and one-third by the vessel. Within the trawl system, the trawl net is responsible for 60 percent of energy use, with otter boards (trawl doors) at 30 percent, and warps and other cables at 10 percent (Vincent and Roullot, 2006). As the trawl system is the major component of the resistance that is responsible for fuel use, improving design, construction and operation of trawls to reduce fuel use has great potential.

FIGURE 27.2
Illustration of an otter trawl harvesting system that includes the trawler and the trawl system



Source: FAO drawing. The trawl system includes towing warps, otter boards, sweeps and bridles, and the trawl net. The trawl net is composed of wings, square, trawl body, and codend. The headline (usually with floats) is the upper limit of the trawl, while the groundgear is the lower limit of the net, and is usually equipped with rollers and bobbins that protect the net while towed over the seabed.

27.3.1 Alternative fishing gears

Many fish species can be harvested by multiple gear types or methods, which include modifications to the existing gear or changes to its operation, or may mean a complete switch away from fuel-intensive gear. Changing to an alternative fishing gear is often the primary response when facing an energy shortage or fuel price increase (FAO, 2015).

Purse seine vs. pelagic trawl

In the Northeastern United States of America, Atlantic herring may be harvested by purse seines, midwater otter trawls, midwater pair trawls, and by weirs and traps. Analysis carried out by Driscoll and Tyedmers (2010) found that purse seines were much more fuel-efficient (by fivefold) than either otter or pair trawls for that species.

Pair trawl vs. otter trawl

Probably in response to high energy costs during the energy crisis of the late 1970s, many Faroe Islands otter trawl vessels targeting pelagic species were converted to pair trawling between 1981 and 1982. Over the last 30 years, fuel use intensity for these pair trawls was only about 50 percent of that for otter trawls (Thomsen *et al.*, 2010).

Semi-pelagic trawl vs. demersal trawl

Depending on whether the trawl system contacts the seabed or not, trawls may be divided into pelagic trawls that are off-bottom, semi-pelagic trawls where either the otter boards or trawl groundgear touches bottom, or bottom trawls where most bottom-tending components touch the bottom (He, 2007). Traditional groundfish species such as Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) are commonly harvested using bottom trawls. With concerns over discards and the impact of bottom trawling on the substrate, tests have been carried out on semi-pelagic trawls with doors off-bottom to harvest traditional groundfish species. Coincidentally, semi-pelagic trawls also have less resistance because of reduced friction with the bottom and more efficient otter boards, and require less fuel to tow. A recent study found that semi-pelagic trawl rigging used for targeting haddock reduced fuel use by 17.2 percent compared with the same trawl but with traditional bottom otter boards (He *et al.*, 2016).

Multi-rig trawls

An otter trawl vessel usually tows just one trawl with two otter boards, except those towed from outriggers where two otter trawls may be towed independently. Multi-rig trawls, such as twin trawls, triple trawls, or quad trawls, are efficient in catching certain species and at the same time saving fuel. Sterling (2009) compared prawn trawls with single-rig, twin-rig, triple-rig and quad-rig configurations, and found that for the same gear width, the resistance for the quad-rig was only 45 percent of the single-rig, potentially saving more than 30 percent of fuel when the vessel resistance is also considered. This was also demonstrated in Gulf of Mexico shrimp trawls which saved 20 percent to 39 percent (24 percent median) of fuel by replacing the traditional single-rig with a quad-rig (Haby and Graham, n.d.). It should be noted that multi-rig trawls may be more suitable for shrimp, prawn or other similar species that do not require a high vertical opening.

27.3.2 Fishing gear designs and operation

Strong synthetic warp

High tensile strength synthetic ropes are stronger than steel cables of the same diameter, but when in water, only 2.5 percent of the weight of steel cable. Preliminary trials replacing steel warps with Dynex warps of similar strength reduced resistance by 10 percent to 20 percent (van Marlen, 2009). However, the drag of warp is highly dependent on the length of warp used, which is related to fishing depth.

Efficient and matching otter boards

Otter boards are horizontal spreading devices used to keep a trawl net open underwater. Since their invention more than century ago, the shape, design, and material of otter boards have undergone dramatic changes. Early solid wooden boards were soon replaced by metal boards to increase durability and sinking velocity especially when operating in deep waters. Oval, V-shaped, and slotted boards were then invented and offered increased efficiency and stability. In Gulf of Mexico shrimp trawls, the replacement of flat wooden boards by cambered steel boards reduced their size (area) by 50 percent and fuel use by 28 percent (Haby and Graham, n.d.).

The earlier low-aspect otter boards spread the net through contact and friction with the sea floor, which produced shear that spread the boards. Efficient high-aspect-ratio boards initially designed for pelagic trawls rely solely on fluid dynamics to expand the trawl. Today, bottom otter boards also utilize these design features to improve fuel efficiency while remaining stable operating both on or off the seabed. Sala, Buglioni and Lucchetti (2010) tested Danish high-lift boards for Italian bottom trawls and reduced fuel use by 15 percent to 20 percent compared to traditional otter boards. Similarly, Hansen (2013) tested pelagic boards for Baltic bottom trawls and saved fuel by 14 percent.

The Batwing design places the expanding surface of the boards on a skid that moves parallel to the towing direction, thus reducing the friction of the board (Sterling, 2009). With this new design fuel savings of 20 percent to 25 percent were reported in experimental trials.

The size of otter boards should match the size of trawl so that the boards can operate at the most efficient condition and achieve the optimal spread of the net. When a new trawl design uses stronger netting materials that allow for thinner twines (see below), the total trawl drag will be reduced; this in turn requires smaller otter boards to expand the gear, further reducing fuel use (Sterling and Balash, 2017).

Trawl design

Balash *et al.* (2016) reported a new trawl design, called the "W Prawn-Trawl", for the Australian prawn fishery, and found that the new design reduced resistance by about 20 percent without reduction in catch of the target species, when compared to a traditional net. In general, trawl designs with steep cuts in the wing and use of large mesh netting on the front end have less resistance.

The use of smaller twines in net construction can reduce trawl resistance. For example, a UK study that compared 4 mm twine with 3 mm twine showed that the thinner twine reduced resistance by 6 percent (Cutis *et al.*, 2006). However, thinner twines are more likely to suffer damage. New, stronger and more durable materials allow for the use of thinner twines without increasing the risk of net damage. For example, compared with regular polyethylene twine, smaller twines with equivalent strength of ultra-high molecular weight materials, such as Dyneema, Dynex, or Spectra, reduce twine surface area, and can reduce trawl resistance by about 20 percent (Parente *et al.*, 2016; Sterling and Balash, 2017). Knotless netting which has much less "knot" surface area can further reduce resistance (Sterling and Balash, 2017).

27.3.3 Fishing with electricity and light

Electric stimuli for beam trawls

The relevant merits of using electrical stimuli in trawls are still in debate in Europe in terms of their impact on target and non-target species. However, energy saving can be substantial when using electrical pulse in beam trawls in the North Sea. Dutch research demonstrated 40 percent to 50 percent reduction in fuel use when lighter and slower pulse trawls were used compared with heavy and faster traditional beam trawls because of the drag reduction in the pulse trawl (Percy, 2016; Taal and Hoefnagel, 2010). Some reduction of catch of target species was also reported, but with improvements in technology, the catch rate has been gradually improved (van Marlen, 2009).

Energy-efficient fishing lights

Fishing operations based on light attraction are widely used in East Asian countries and in some inland fisheries in Africa. These fishing methods include purse seines for small pelagic fish, stick-held lift nets for Pacific saury, and jigging for squid (Inada *et al.*, 2010). Fuel used to generate electricity to power fishing lights constitutes a major part of total fuel consumption, sometimes more than 70 percent in coastal squid jigging fisheries (Matsushita, Azuno and Yamashita, 2012). Light sources have evolved from torch lights in ancient times, to kerosene and acetylene lamps a century ago, to more advanced incandescent and halogen lamps from the 1950s, and metal halide lamps from the 1980s (Inada and Arimoto, 2007). These lighting methods all waste substantial amounts of energy as heat. More recently, energy-efficient light emitting diode (LEDs) lights are gradually replacing MH and incandescent lights, and have shown great potential for fuel reduction. For example, Katsuya *et al.* (2010) reported a 47 percent reduction in fuel used for lighting when LED replaced other lighting types in squid jigging. Matsushita, Azuno and Yamashita (2012) reported 24 percent fuel savings when LED lights were used together with MH lights in Japanese coastal squid jigging. More recently, An *et al.* (2017) demonstrated that hairtail jigging with LED lights was more than three times higher in "catch intensity" i.e. the amount of hairtail landed per kilowatts of energy used by lights.

27.3.4 Fishing instrumentation

Seabed-discriminating acoustic devices
The Canadian scallop fishery off Nova Scotia used three-dimensional topographic charts overlaid by geological features and sediment characteristics obtained from multi-beam sonar to accurately identify productive scallop beds. This charting allowed the fishing effort to be directed on top of and in the same orientation as the scallop beds. Because the total catch was limited by quotas, total fishing time for harvesting a quota of 13.46 tonnes of scallop was reduced from 162 hours when not using multibeam mapping information to 43 hours when using the information. Consequently, fuel consumption was reduced by 36 percent using the new technology (Robert *et al.*, 2002). However, it should be noted that the use of advanced technology to increase fishing efficiency is only beneficial when adequate management to prevent overfishing is in place.

Gear monitoring and catch sensors
Catch information is typically only known when a trawl is brought on board, often resulting in wasting fuel by catching the wrong species, size or an undesirable amount of fish. Modern fishing gear monitoring devices can identify fish species and size, and measure gear geometry as well as the amount of catch during the capture process in real time and before the gear is retrieved. The Norwegian DeepVision system (Rosen *et al.*, 2013) can identify species and measure sizes of fish as they pass through a trawl, providing information if the skipper should continue towing the trawl. Catch sensors inform the skipper when the gear should be hauled, which avoids catching an excessive amount of fish that can reduce quality and waste energy (Grimaldo, Sistiaga and Larsen, 2014).

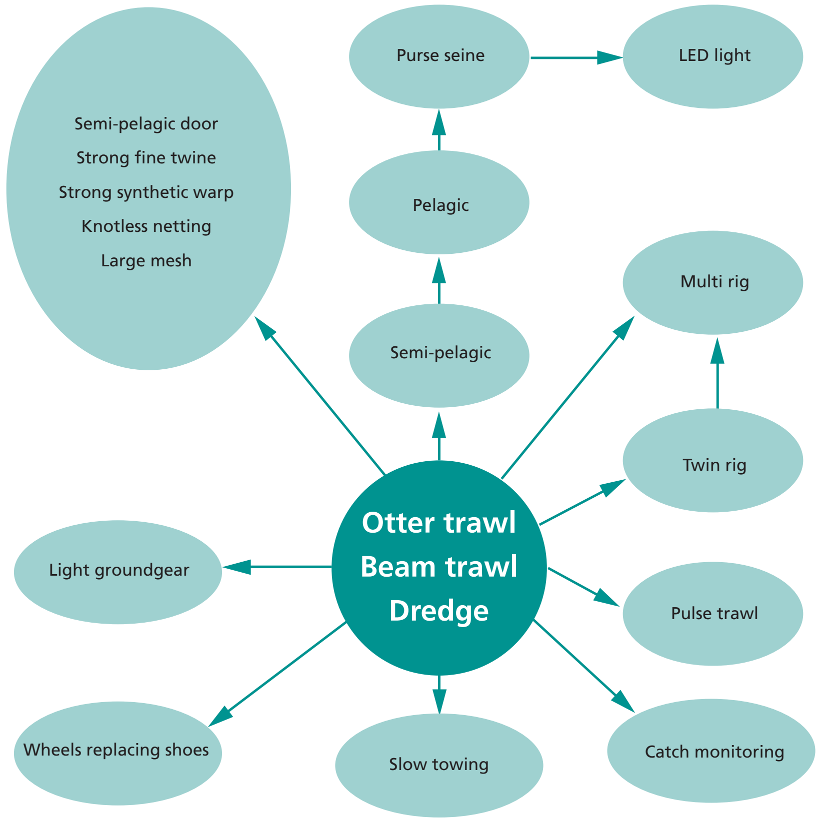
Acoustic gear geometry sensors inform skippers if the gear is operating in its desired geometry, thus avoiding fuel-wasting "faulty" sets from poor gear deployment. They also help skippers adjust towing speed or wire out so as not to overspread when towing against the current. Otter board attitude (pitch, roll and yaw) and altitude (height) sensors make it possible for near-bottom trawling or semi-pelagic trawling, saving fuel as well as reducing the seabed impact of trawling.

Positioning and tracking systems
Global positioning systems and computerized electronic plotters allow for marking the positions of stationary gear such as gillnets and longlines set in the sea, saving fuel when relocating the gear during retrieval. Radio buoys and satellite buoys installed on drifting fish aggregation devices (FADs) reduce search times for the owner vessel to relocate the FAD, thus reducing fuel use.

27.3.5 Combination of "best technologies"

Options for fuel-saving in mobile fishing gears are summarized in Figure 27.3, based on the discussions above and suggestions of "best available technologies" for trawls from Hansen (2013) and "Smart" trawl designs by Valdemarsen (2013). Overarching "Smart" trawl designs and operations may include 1) less bottom interaction, 2) reduced drag of netting and otter boards, 3) monitoring of fish behaviour and trawl performance, and 4) adjustment of gear parameters while fishing.

FIGURE 27.3
Illustration of fuel-saving strategies for otter trawl, beam trawl and dredges. Not all strategies are applicable to all gears



27.4 FISHING PORT INFRASTRUCTURE

The carbon footprint of a port is the sum of direct and indirect GHG emissions expressed as CO_2 *e*. When designing a new port or upgrading an existing facility, the first step should be an energy audit to calculate the power requirements. Power requirements may range from a few kilowatts for an artisanal landing site (light-duty power) to hundreds of kilowatts for a medium-sized fishing harbour with ice producing facilities and cold storage (heavy-duty power). Light-duty power is required for water extraction and storage, hygiene facilities, lighting and security, and slipway winches. Heavy-duty power is required for ice production facilities, cold storage, and workshop equipment.

The light-duty power requirements of an artisanal landing site may be fully accommodated with renewable solar/wind hybrid systems, consisting of solar photovoltaic (PV) panels, wind turbines and storage batteries. The heavy-duty power requirements for a medium to large fishing port cannot be economically accommodated, with currently available technology, solely through solar/wind systems, and need to be integrated with a regional or national electrical grid or a diesel generator to form a hybrid system.

27.4.1 Cold stores and ice plants

Fishing ports may need to have facilities for storing fish products on a short- or long-term basis, and for making ice for fishing vessels. These are high energy-demand operations that need considerable attention in reducing energy costs and GHG emissions.

Cold stores

Cold stores demand considerable amounts of power. Energy savings in cold storage may be best achieved through operational standards, including best overall design at the design stage and best practice at the operational stage, such as:

- Ground insulation to prevent wastage of power through freezing of ground water.
- Internal partitions inside the cold store to reduce the cooling capacity requirement when the supply of fish is low.
- Vertical door strips to reduce ingress of heat when the doors are open.
- Ensuring door seals are in good working order and seal properly.
- Using climate-controlled antechambers so that the cold rooms do not open directly on to non-cooled areas.
- Ensuring that the fish are pre-chilled before entering the cold store.

Ice plants

Ice plants come in two basic designs: 1) block ice plants that produce 25 kg to 50 kg blocks, and 2) flake ice plants that produce flake ice as required. Large block ice plants are the most energy-efficient. Therefore, in some areas, blocks of ice delivered by outside suppliers in insulated trucks directly to the departing vessels may be more energy efficient than those produced locally by a smaller plant. However, flake ice plants are often preferable as they vary in size, can be operated on demand, and require a smaller footprint and investment.

As with cold stores, energy savings in ice plants can be achieved through "best practise operations", such as ensuring that the physical characteristics of the feed water (temperature and salinity) comply with the manufacturer's guidelines, using a good PVC strip door, and having good rubber seals around the door of the ice store. No matter what size of flake ice plant is required, measures should be taken to connect to an electric grid rather than running on an independent generator, as these are less efficient, more erratic in power quality, and more locally polluting, as well as requiring expenditure for maintenance.

27.4.2 Alternative energy

Alternative energy sources may be more suitable for land-based port facilities than for fishing vessels because of space limitations and the changing orientations of a vessel to sun and wind. PV and wind energy systems have matured over the years, and can complement each other to form a PV-wind hybrid system. Tidal energy systems are still in development, but could in the future be a part of a renewable energy source for ports as the tide is more predictable than either wind or solar power in duration and intensity.

Recent advances in solar powered technology have given rise to integrated infrastructure solutions for use in remote areas. Solar-powered water supply is now a proven and established technology. There are two basic types of solar pumping systems, 1) lower-flow deep well direct current (DC) submersible pumps, and 2) higher yield alternating current (AC) surface pumps. Solar pumps are equally suited to any off-grid application, whether as a stand-alone system or a part of an off-grid energy solution.

Solar-powered lights, both wired indoor systems and autonomous outdoor systems, are also commercially available as stand-alone integrated systems, with each area or building equipped with its own solar PV panels and storage batteries obviating the use of trenching and heavy cabling around the port. All light fittings should be in LED units to reduce the energy requirement by 90 percent.

27.4.3 Building design for a low carbon footprint

Port buildings should be designed for a low-carbon footprint at the inception stage, both through design features as well as installed equipment. In hot climates, design features should include the following considerations, while opposite considerations may be true in cold climates:

- Correct orientation of buildings to make the best use of shade.
- Eaves or shades to prevent the build-up of heat from direct sunlight.
- Large windows with white internal paint schemes to cut down on lighting requirements.
- Abundant landscaping to absorb reflected light, provide shaded areas and absorb treated wastewater.
- Rain water harvesting.

Equipment features should include:

- Installation of two separate power circuits, one for heavy loads and one for solar-powered loads.
- Ceiling fans to reduce the use of air-conditioning systems.
- Smart energy systems to conserve power, e.g. trip switches on windows/doors to shut down air-conditioning automatically if windows or doors are opened, and motion sensors to switch off lighting.
- Systems that sense and mix in outside air when desired.

27.5 AQUACULTURE

Like capture fisheries, aquaculture is not a major global producer of GHG; emissions from the sector amount to around 7 percent of those from agriculture even when boundaries in the definition of aquaculture are extended to incorporate feeds (Hall *et al.*, 2011). From a per-unit biomass production perspective, GHG emissions associated with aquaculture are greatest in intensive production of finfish and crustaceans, which is heavily reliant on feeds and on aeration and pumping of water to provide additional oxygen and to disperse wastes (Hasan and Soto, 2017; Robb *et al.*, 2017). In contrast, the farming of seaweeds is relatively benign in terms of GHG emissions (Waite *et al.*, 2014), while that of molluscs is somewhat mixed (Bonaglia *et al.*, 2017).

Modelling by Waite *et al.* (2014) suggests that the greatest reduction of GHG emissions in aquaculture is by improving efficiency of input use (e.g. better technologies), shifting energy supply (from fossil fuel to renewable), adopting best practices (improving feed conversion rates), and replacing fish-based feed ingredients with crop-based ingredients. When all four approaches are combined, the projected 133 percent increase in global aquaculture production from 60 million tonnes (2010 baseline year) to 140 million tonnes by 2050 would only result in an 83 percent increase in GHG emissions (i.e. from 332 million tonnes to 609 million tonnes CO_2 *e*), a reduction of 21 percent in CO_2 *e* emission per tonne of fish production.

A recent study of farmed fish production in three countries has further confirmed that most of the GHGs are associated with the production of raw feed materials and, secondarily, with the transport of raw materials to the mills and finished feeds to the farms (Hasan and Soto, 2017; Robb *et al.*, 2017). Recommendations on mitigation are summarized in Table 27.4. To identify the most cost-effective mitigation measures, emission reductions through measures identified in Table 27.4 and the costs of implementing them must be quantified. Models such as the one developed by Robb *et al.* (2017) can help to identify and partially quantify the systemic effects of mitigation measures.

TABLE 27.4
Key measures for mitigating GHG emissions from aquaculture (modified from Robb *et al.*, 2017)

OBJECTIVE	ACTION
Reduce emissions from production of feed materials	• In compounding aquaculture feeds, select feedstuffs with lower associated emissions (e.g. locally-sourced oilseeds, which are much lower than fishmeal and fish oil sourced from capture fisheries)
Reduce emissions from feed mill energy use	• Improve management efficiency of feed mills • Substitute high emission intensity fuels with low emission intensity alternatives
Improve the efficiency of FCRs	• Optimize the nutritional content of feed and their availability • Improve feed management • Increase dissolved oxygen levels to increase feeding efficiently
Improve fish health	• Reducing farmed aquatic animal mortalities, especially among older fish, is an important means of reducing GHG emissions per unit farmed aquatic food production · Improve water quality management · Maintain appropriate fish stocking densities · Implement effective biosecurity measures · Use medicines properly
Reduce on-farm N_2O emissions	• Reduce the amount of nitrogen available for conversion to N_2O by, for example, adhering to fertilization guidelines in pond aquaculture and by improving feed management that targets reducing uneaten food

Integrated food production systems, such as that of fish with rice, address both food and energy needs in a sustainable manner while also contributing positively to climate change adaptation and mitigation. Although largely determined by system details and choice of system boundaries, such systems were found to mitigate GHG emissions from rice fields, which are typically among the highest emitters for any crop production system (Lipper *et al.*, 2017).

Mangroves are the most carbon-rich of tropical forests, storing on average three to four times more carbon than tropical upland forests (Ahmed, Thompson and Glaser, 2017; Alongi, 2014; Donato *et al.*, 2011). Mangroves are also one of the most threatened of tropical ecosystems, declining by an estimated 30 percent to 50 percent over the past half century (Donato *et al.*, 2011; FAO, 2007). As a result, emissions of blue carbon, which refers to carbon sequestered, stored and released in coastal mangroves, seagrass and saltmarshes, have markedly increased (Ahmed, Thompson and Glaser, 2017; Alongi, 2014; Kauffman *et al.*, 2014).

One of the most important causes of mangrove loss has been shrimp aquaculture, which is widely practiced in countries such as Bangladesh, Brazil, China, India, Indonesia, Malaysia, Mexico, Myanmar, Sri Lanka, the Philippines, Thailand, and Viet Nam (FAO, 2007; Hamilton, 2013; Primavera, 2006; Thomas *et al.*, 2017). In a recent literature review, Ahmed, Thompson and Glaser (2017) estimated that shrimp farming has accounted for some 40 percent to 50 percent of the losses of mangroves, most of which took place during the 1980s and 1990s. Integrated mangrove-shrimp cultivation, however, is now emerging as a potential solution to blue carbon emissions (Ahmed, Thompson and Glaser, 2017; Bosma *et al.*, 2017; Jonell and Henrikkson, 2015). Table 27.5 provides projections of the amount of carbon that may be sequestered when different percentages of mangrove areas can be integrated with shrimp culture. Integrated mangrove-shrimp farming can also be certified as organic aquaculture, according to Naturland organic aquaculture standards[1]. Under these standards, no mangrove destruction is allowed and former mangrove areas in the shrimp farm must be reforested to at least 50 percent within a period of five years.

[1] https://www.naturland.de/en/naturland/naturland-standards.html

Seaweed farms, in addition to their potential to provide more low carbon food from the sea, release carbon unless it is buried in sediments or exported to the deep ocean where it acts as a CO_2 sink (Duarte *et al.*, 2017). If used for biofuel production, farmed seaweed reduces emissions from fossil fuels. Seaweed aquaculture can also help reduce emissions from agriculture by replacing synthetic fertilizer as a soil quality improver and, when included in cattle feed, lowering methane emissions from cattle. However, the scope to expand seaweed aquaculture is limited by the availability of suitable areas, competition for sites with other uses, engineering systems capable of coping with rough offshore conditions, and increasing market demand for seaweed products. Seaweed farming practices can be optimized to maximize climate benefits, which, if supported by carbon credits, may also improve the income of seaweed farmers (Duarte *et al.*, 2017).

TABLE 27.5

Estimated potential for sequestering blue carbon by restoration of mangroves through integrated/organic shrimp cultivation, assuming 1.5 million ha of global mangrove are lost to shrimp culture

Restoration of mangrove area through integrated/organic shrimp culture (%)	10	20	30	40	50
Restoration of mangrove area through integrated/organic shrimp culture (million ha)	0.15	0.30	0.45	0.60	0.75
Annual carbon sequestration rate (tonnes/ha)	1.50–1.39				
Total carbon sequestration (million tonnes/year)	0.17–0.21	0.35–0.42	0.52–0.63	0.69–0.83	0.86–1.04

Source: Ahmed, Thompson and Glaser, 2017.

27.6 FISHERIES MANAGEMENT

Fisheries, especially ocean fisheries, are subject to the well-known common property problem (Gordon, 1954; Hardin, 1968). As a result, the majority of the world's fisheries suffer from excessive fishing fleets and fishing effort, and depressed fish stocks compared to what would maximize the net production (World Bank, 2017). The level of these inefficiencies is estimated to be very high. Recent studies have found that the global fishing effort is almost twice what is needed to maximize the net yield from ocean fisheries (World Bank, 2017; World Bank and FAO, 2009). This excessive fishing effort combined with depressed stocks also results in much more use of fossil fuel and, hence, GHG generation, than would be necessary to produce the same level of catch on a sustainable basis. It follows that effective fisheries management that would reduce fishing effort and increase fish stocks would substantially reduce the GHG emissions generated by the world's fishing fleets.

Fisheries management measures vary among fishing nations; some lead to reduction in fishing effort and, thus, GHG emissions, while many others can increase GHG emissions. Well-conceived and implemented fisheries management measures generally reduce fishing effort and improve stock abundance, both of which result in increases in fishing efficiency and reductions in GHG emissions, a win-win situation. In fact, this may be the most effective way to reduce fuel use and emission from capture fisheries (Waldo *et al.*, 2014; Ziegler and Hornborg, 2014). Poorly conceived fisheries management, including many so-called input controls (such as vessel and gear restrictions and limited fishing days) that are designed to conserve fish stocks may lead to increased fuel consumption and GHG emissions. As already stated in other parts of this chapter, fuel consumption can be considerably reduced through improved design and optimized operation of fishing vessels and gear. However, many rigid input management regimes hinder or deny fishers' flexibility to adopt energy efficient designs and strategies (Suuronen *et al.*, 2012). Consequently, emission-inclusive fisheries management policies are likely to be more effective in reducing the use of fuel and GHG emissions from the global fisheries than attempts to optimize fisheries outcomes only.

It is also important to recognize that governments sometimes provide the fishing industry with tax incentives or subsidies of various kinds, including fuel subsidies, to sustain otherwise unprofitable and unsustainable fishing. These measures generally lead to increased fishing effort and therefore GHG emissions, in addition to discouraging fuel saving.

27.6.1 Input control measures

Fishing capacity control

One of the major challenges in world fisheries is overcapacity and excessive fishing effort. The excessive fishing effort, as measured by the number of active vessels, vessel tonnage, engine power, vessel length, and amount of gear used, has led to excessive fuel use.

A study by the World Bank and FAO (2009) on the economic performance of global fisheries highlighted the weak economic performance of the sector, estimating lost economic benefits compared to what is attainable at about USD 50 billion per year (2004 dollars). An updated study in 2012 concluded that in order to reach the sustainable optimal state, global fishing effort would have to be reduced by 44 percent. In addition to other benefits, such as recovered fish stocks, an increase of the annual harvest and improved safety at sea in the fisheries sector, the impact of such a reduction in effort would also be a substantial reduction of fuel use in the sector, with a consequent decrease in GHG emissions.

Area and season closures

Area closures imposed by management authorities may have a contrasting effect on fuel efficiency. On the one hand, closures may contribute to stock rebuilding, which may ultimately increase fishing and fuel efficiency. On the other hand, area closures often include productive areas, especially areas and times of spawning concentrations. Exclusion from areas and times of high concentrations of fish can result in vessels fishing in suboptimal areas, reducing fishing efficiency and increasing fuel consumed per kg of fish harvested (Farmery *et al.*, 2014). Area closures can also result in vessels having to travel further from home ports, decreasing their overall fuel efficiency (Kitts, Schneider and Lent, 2008).

Vessel and gear restrictions

Fisheries management authorities sometimes impose restrictions on the length and engine power of fishing vessels to limit fishing effort. These types of restrictions tend to distort investments and, often lead to less fuel-efficient designs. The same applies to various gear restrictions that hinder innovation for higher efficiency and lead to less fuel-efficient operations.

27.6.2 Output control measures

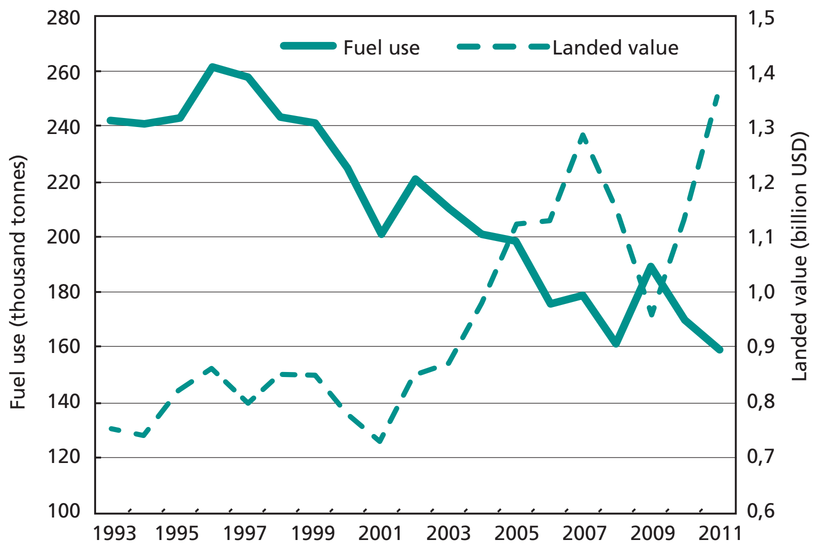
Rights-based fishery management

In some parts of the world, rights-based fisheries management regimes have been adopted to strengthen the economic viability of the fishing sector and improve the sustainability of the fish stocks. The most common of these rights-based regimes are individual quotas and individual territorial user rights fisheries. There are also examples of industry sector/quota share/cooperative programmes. Individual transferable quota (ITQ) systems have been adopted in over 23 fishing nations (Arnason, 2013). One of the earliest nations to do so was Iceland in the early 1980s. The Icelandic ITQ system seems to have been very effective in improving the efficiency of the Icelandic fisheries and rebuilding the fish stocks (Arnason, 2005). Among other things, the system has led to a reduction in vessel number and capacity which, together with other factors such as technological advances in vessel engine and gear technology, has resulted in a reduction of fuel consumption of 35 percent from 1993 to 2011 (Figure 27.4). Similar findings have also been observed in other previously overexploited fisheries subject to ITQs.

Decreases in fuel use intensity have also been reported in the Australian banana prawn (*Penaeus merguiensis*) fishery when a government buyout in 2005 of fishing licenses reduced overcapacity (Parker *et al.*, 2015; Pascoe *et al.*, 2012). A reduced number of licenses often leads to an increase in the fishing efficiency of those remaining in the fishery, and therefore higher fuel efficiency.

FIGURE 27.4

Landed value and fuel use in Icelandic fisheries between 1993 and 2011. Improved fisheries management such as implementation of an ITQ system, capacity control, and technological developments may be the cause of the fuel reduction in the fisheries



Source: Drawn from data in Icelandic National Energy Authority.

Daily and trip landing limits

Some management measures limit the amount of fish that can be landed per day or per multi-day trip. These limitations may result in shorter trips, and an increase in the relative proportion of fuel use for non-fishing (steaming) activity, and, consequently, decreased fuel efficiency (Kitts, Schneider and Lent, 2008).

Selective fishing and landing obligation

All fishing is selective, catching and retaining only certain species and sizes, and allowing others to escape and reproduce. Selective fishing gear, whether it employs large mesh codends, grid devices in trawls, or other designs, may result in lower overall fishing efficiency, and, consequently, increase fuel use intensity. The landing obligation (or discard ban) that is being implemented in the European Union will likely decrease fuel intensity initially because all fish brought on board, with some exceptions, are supposed to be landed. However, as a result of reduced overall prices for the landed fish, and costs of quotas, it was predicted that the ban would result in wider use of selective gears (Batsleer *et al.*, 2016; Breen *et al.*, 2016; Ziegler and Hornborg, 2014), resulting in increased fuel use intensity.

Maximum sustainable yield vs maximum economic yield

Fisheries management decision-making that targets the stock level producing the maximum economic yield (MEY) rather than the traditional maximum sustainable yield (MSY) generally results in higher fishing efficiency and greater fuel efficiency. For example, Farmery *et al.* (2014) analysed the Australian southern rock lobster (*Jasus novaehollandiae*) fishery, and found that building the stock to the level that produces MEY instead of MSY, together with relaxing the trap-limit rule, reduced the carbon footprint by more than 80 percent. However, this may be an extreme case; other fisheries may not experience such a great reduction from this management change.

27.6.3 Fuel subsidy and incentives

Global fuel subsidies, in the form of tax exemptions and/or direct subsidies, have been estimated at USD 4.2 billion to USD 8.5 billion per year (Sumaila *et al.*, 2008). Fuel subsidies effectively reduce fuel prices to fishers and, therefore, will encourage increased fuel consumption and reduced fuel efficiency (Waldo *et al.*, 2014). On the other hand, governments can also offer positive incentives to promote fuel-efficient technologies to reduce GHG emissions. For example, the Korean government subsidizes the purchase of LED light equipment for use in fishing which has made the purchasing of LED equipment more affordable with shorter pay-back times for fishers (An *et al.*, 2017).

27.7 SUMMARY AND CONCLUSIONS

Global fish production from capture and culture operations accounted for about 17 percent of animal protein intake by humans in 2014, and contributed up to 1.5 percent to the world's CO_2 emission. While overall fish production is relatively energy-efficient compared with other high-quality animal protein production on land, opportunities for further reduction in energy use and emissions are available.

In capture fisheries, the vessel and gear are two main sources of energy consumption. In stationary gear fisheries, energy consumed by the vessel travelling to and from fishing grounds may constitute much of the energy use. In mobile gear fisheries such as trawling and dredging, resistance from the fishing gear consumes much of the energy. For fishing vessels, vessel design, size of engine and choice of propeller should match the speed of the vessel at which most energy is consumed. Proper vessel length to width ratio, smooth hull painting and fairing, bulbous bows, high efficiency internal combustion engines, and larger diameter propellers with nozzles are some of the important features for a highly fuel-efficient vessel. For fishing gears, especially towed fishing gears, the use of efficient otter boards, off-bottom fishing, high-strength materials, large mesh sizes, and smaller diameter twines are some of the measures that reduce fuel consumption. Shore-side facilities should take advantage of maturing renewable energy systems such as wind and solar. In aquaculture, GHG emissions are greatest in intensive production of finfish and crustaceans, which is heavily reliant on feeds and aeration. Integrated food production systems such as that of fish with rice, and shrimp-mangrove cultivation can substantially reduce overall GHG emissions from aquaculture production systems.

Fisheries management has a great impact on all aspects of fish production, especially in capture fisheries and can therefore affect efficiency of fuel use. In the past, fisheries management attempting to avoid overfishing has often impeded efficient fishing. At the same time, fuel subsidies intended to support fisheries generally discourage the promotion of fuel-efficient vessels, gears and operations. Management measures that reduce overall fishing effort and improve stock abundance, such as individual harvesting quotas and other similar rights-based regimes have made significant contributions to fuel efficiency in capture fisheries. Fuel efficiency and GHG emissions from fisheries should be considered as an integral part of fisheries management to sustainably reduce fuel use and GHG emission in fisheries.

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Chapter 28: Impacts of climate change on fisheries and aquaculture: conclusions

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28.1 INTRODUCTION

Globally, fisheries and aquaculture make substantial contributions to the food security and the livelihoods of millions of people. Total global production from the combined sectors peaked in 2016 at 171 million tonnes, with 53 percent of this total coming from capture fisheries and 47 percent from aquaculture (reaching 53 percent if non-food uses are excluded; FAO, 2018). The total landed value of the production in 2016 is estimated to have been USD 362 billion, of which USD 232 billion came from aquaculture production (FAO, 2018). Marine capture fishery production has been relatively static since the late-1980s and there has been limited growth in inland capture fisheries. This has meant that growth in aquaculture production has been largely responsible for the average annual increase in global food fish consumption, between 1961 and 2016, of 3.2 percent, twice the human population growth rate of 1.6 percent. In per capita terms, food fish consumption grew from 9.0 kg in 1961 to 20.2 kg in 2015. An estimated 200 million people are employed, directly and indirectly, in the two sectors. Women account for about 19 percent of those employed in the primary sector, but this rises to 50 percent if the secondary sector is also included (FAO, 2018). The food security and livelihoods provided by fisheries and aquaculture are thus crucially important in many coastal, riverine, insular and inland regions. At the same time, the state of marine resources monitored by the FAO continues to decline. The fraction of marine fish stocks fished within biologically sustainable levels has exhibited a decreasing trend, from 90.0 percent in 1974 to 66.9 percent in 2015 (FAO, 2018), with developing countries faring particularly worse than developed ones (Ye and Gutierrez, 2017). Considerable uncertainty remains over the status of many inland capture fisheries, which provide important contributions to global food demands, in particular to some of the poorest, most food insecure countries in the world. These facts demonstrate the high stakes in providing adequate responses to the threat of climate change: not only are fisheries essential for food, livelihoods and trade, but the generally poor state of the resource base limits their capacity to absorb climate shocks, particularly in developing regions where dependency on fisheries is greatest (Barange *et al.*, 2014).

28.2 CLIMATE CHANGE IMPLICATIONS FOR FISHERIES AND AQUACULTURE: APPLYING A POVERTY LENS

Approximately 11 percent of the global population, or about 767 million people, live in extreme poverty, and 815 million go hungry every day (FAO *et al.*, 2017). Many of these people can be found in small-scale fishing and fish farming communities where they are commonly marginalized politically, economically and socially, even in countries with a generally good status in human development. Highlighting this problem, Chapter 2, on "Climate change implications for fisheries and aquaculture: applying a poverty lens", focuses on the relationship between climate change, poverty and vulnerability. The chapter emphasizes that the impacts of climate change on fisheries and aquaculture will affect individuals and communities that depend on the sector for their livelihoods, and thus contends that efforts to adapt to and mitigate climate change must be human-centred. The authors propose that strategies for adaptation to climate change should emphasize the need for poverty eradication and food security, in accordance with the relevant international agreements, including the Paris Agreement.

A key message coming from Chapter 2 and elsewhere in this volume is that small-scale fishers and fish farmers are especially vulnerable to climate change because of both their geographical locations and their economic status. The latter means that a crucial part of increasing the resilience of these individuals and communities must be to eradicate poverty and provide food security for them, as emphasized by the Paris Agreement, the UN Agenda 2030 and other international agreements. Achieving this requires that adaptation to climate change be multi-dimensional and multi-sectoral. Strategies should allow for flexibility in practices and opportunities for those impacted by climate change and ensure that they have opportunities for diverse livelihoods, allowing them to respond to the changes. Strategies and measures need to address any imbalances in power amongst stakeholders and stakeholder groups as well as inequities in, for example, gender, market access, tenure rights and others. People need to be empowered to participate effectively in co-management arrangements and thereby safeguard their legitimate rights. Active support for adaptation is required at national, regional and local levels of governance and a stronger emphasis should be placed on the contribution of fisheries and aquaculture to poverty reduction and food security in countries' Nationally Determined Contributions (NDCs).

28.3 CURRENT SUPPLY AND DEMAND FOR FISHERY AND AQUACULTURE PRODUCTS AND THEIR FUTURE EVOLUTION

As mentioned above, there has been a major expansion in production, trade and consumption of fishery and aquaculture products in recent decades, although the rate of expansion has slowed down in recent years, and shifted from capture to culture sectors (Chapter 3). Fish is an important source of protein in many countries, especially small island developing states (SIDS) and some coastal countries in Africa and Asia, where it can contribute 50 percent or more of animal protein in diets. Furthermore, fish and fishery products are important sources of nutrients and micronutrients, including vitamins, several minerals and omega-3 fatty acids. Globally, an estimated 36 percent of total fish production is exported, making fish and fishery products among the most traded food commodities (FAO, 2018). This means that the sector can be considered globalized but, especially in the case of inland fisheries and aquaculture, production tends to be concentrated in certain countries and regions. Developing countries, in particular in Asia, have a growing share of production and trade, increasing from 21 percent in 1950 to 70 percent in 2015, with a significant contribution coming from small-scale and artisanal fishers and fish farmers. In particular, in 2016 China produced more cultured fish than all other countries put together. These facts highlight the shifting nature of the fisheries and aquaculture sector in recent decades, both in terms of the geographical distribution and the contribution of each sector to global production.

Climate change is expected to lead to changes in the availability and trade of products from fisheries and aquaculture, with potentially important geopolitical and economic consequences, as well as for food security, especially for those countries most dependent on the sectors for food and livelihoods. Exacerbating these climate-driven impacts, human population growth is likely to increase demand, and potentially increase prices in the coming decades. However, if prices increase this may be expected to lead to a decrease in fish consumption globally (but with regional variability

[Chapter 3]). At the same time, higher prices should provide an incentive for those engaged in fisheries and aquaculture to increase their production, and efficiency.

28.4 CLIMATE CHANGE IMPACTS ON MARINE CAPTURE FISHERIES

Chapter 4 of this collection provides projections of the changes in marine catches (estimated as maximum catch potential) between now and the end of the twenty-first century. The projections are derived from two models, which were selected because they are characterized by a significantly different way of modelling ecological processes. The first is a species-based dynamic bioclimate envelope model, while the second is a dynamic size-based food web model. Both of them are driven by the same outputs from earth system models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5), and are thus comparable. Projections were made under two contrasting scenarios of greenhouse gas emissions, according to representative concentration pathways (RCPs) from the Intergovernmental Panel on Climate Change (IPCC): RCP2.6 (low) and RCP8.5 (high) (see Chapter 1).

Application of these two models resulted in projections indicating that the total maximum catch potential in the world's exclusive economic zones (EEZs) is likely to decrease by 2.8 percent to 5.3 percent by 2050 (relative to 2000) under RCP2.6 or by 7.0 percent to 12.1 percent under RCP8.5. Extending these projections, the projected decrease does not change much by 2095 under RCP2.6 but is forecast to be considerably greater, at 16.2 percent to 25.2 percent, by 2095 under RCP8.5. These projected decreases, with the exception of the latter, may not seem particularly large at the global level and have a significant variability range, but the projected changes showed substantial variation across regions and the impacts could thus be much greater for some regions. The biggest decreases can be expected in the EEZs of countries in the tropics, mostly in the South Pacific regions, as also noted elsewhere (Barange *et al.*, 2014; Blanchard *et al.*, 2012; Cheung *et al.*, 2010). The catch potential in the temperate Northeast Atlantic was also projected to decrease between now and the 2050s. For the high latitude regions, catch potential is projected to increase, or show less of a decrease than in the tropics, but there was much higher variability between the two models, time periods and the EEZs in the projected maximum catch potential in these high latitudes regions than those from low latitudes.

An important consideration is that the above projections are not reflecting potential changes *from current catch levels*, but rather changes in the capacity of the oceans to produce fish in the future compared to their current capacity. Fish catches reflect the productive capacity of the ocean, as well as the management decisions taken in response to this productive capacity. For example, as noted in Fig. 4.1, future catches in an area where the productive capacity is expected to decline may actually increase, if management measures restore currently over-exploited stocks (see also Brander *et al.*, 2018). Alternatively, higher future catches in an area where potential production is expected to increase may not be realized if management measures are not properly implemented. The interactions between ocean changes and management responses are thus crucial to determine future directions of change.

28.5 REGIONAL ANALYSIS OF CLIMATE CHANGE IMPACTS, VULNERABILITIES AND ADAPTATIONS IN MARINE CAPTURE FISHERIES

28.5.1 Observed and predicted ocean impacts

Chapters 5 to 17 present case studies on the implications of climate change for marine capture fisheries from many regions of the world. Although it was not possible to provide complete coverage of all countries and regions in this volume, the case studies presented provide near comprehensive coverage of the types of environmental and ecological conditions, diversity of fisheries, stages of social and economic development, governance capacity and degrees of dependence on fisheries that can be found around the world. Collectively they provide unequivocal evidence of the significant impacts that climate change has already had on marine fisheries in some regions and the need to take measures to adapt to current (in many regions) and future (in all regions) climate change. They also provide valuable examples of how different countries are already responding in order to minimize the negative impacts on a sector that provides vital social and economic benefits for many countries.

The observed impacts of climate change reported in these case studies are broadly consistent with the expectations arising from global projections such as those provided in Chapter 4. Warming in ocean temperatures is reported in most regions of the world and has been arguably most obvious in higher latitudes (see also Chapter 1). In the North Atlantic as a whole (Chapter 5), sea surface temperatures (SST) increased at a rate of 0.1 °C to 0.5 °C per decade over the past century, with particularly rapid warming since the 1980s, while temperatures across the North Pacific increased by 0.1 °C/yr to 0.3 °C/yr from 1950 to 2009. As would be expected, given their size and oceanographic complexity, changes in both these regions showed considerable spatial diversity. At the opposite end of the globe, in the Southern Ocean, the picture is not as clear and, while there have been some examples of warming and reductions in sea ice in this region, the South Pole has undergone cooling in recent decades, probably related to a low-pressure system that is associated with the ozone hole, and annual sea ice cover in the Antarctic has increased over the past two or three decades (Chapter 17).

In the mid-latitudes, the southeast and southwest coasts of Australia are reported as having experienced a nearly 2 °C increase in temperatures over the last 80 years (Chapter 16) and over the last 30 years, SST in the Southwest Atlantic warmed at an average of between 0.2 °C and 0.4 °C per decade (Chapter 15). Changes in the major upwelling regions are more complex. The Humboldt Current system has been cooling from the early nineteenth century to the present, in association with more intense upwelling, while those areas of the Benguela Current ecosystem that are dominated by upwelling have shown different trends: SST has increased by between 0.2 °C and 0.5 °C per decade over the past three decades in the northern parts of the Namibian EEZ, the central regions around Walvis Bay have shown no meaningful change, while the southern Benguela has cooled over the last four decades, possibly driven by stronger wind-driven upwelling (Chapter 11). This evidences the complex relationship between climate change and coastal upwelling (see Box in Chapter 1), not just in terms of changes in upwelling strength, but also the timing and the geographical variability of upwelling processes (Bakun *et al.*, 2015; Sydeman *et al.*, 2014; Xiu *et al.*, 2018). Notably, coastal upwelling is poorly represented in the global climate models used to drive the ecosystem models described in Chapter 4, which means their projections do not take into account changes in coastal upwelling and associated processes. This remains one of the larger sources of uncertainty in our knowledge of the impacts of climate change on global fisheries.

Turning to the lower latitudes, warming has been taking place in the Western Indian Ocean at a comparatively rapid rate over the last 100 years or so, and SST increased by an estimated 0.6 °C between 1950 and 2009, with some spatial variability (Chapter 12). Chapter 13 reported an increase in SST of 0.2 °C to 0.3 °C over the previous 45 years along the coast of India. In the Western Central Pacific, SST increased by more than 0.7 °C between 1900 and the early twenty-first century, while differing trends were reported for the Northeast Tropical Pacific. Trends have shown similar diversity across the Western Central Atlantic region (Chapter 9) ranging from warming on the North Brazil shelf to cooling along the southeastern shelf of the United States of America.

The projected changes in ocean temperatures again differ across the regions and show spatial trends that are broadly compatible with the global forecasts reported in Chapter 4. For example, in the Northwest Atlantic under RCP8.5, a scenario of long-term high energy demand and high greenhouse gas (GHG) emissions in the absence of climate change policies, SST is forecast to rise a further 2.0 °C to 4.0 °C by 2100, accompanied by increasing incidence of storms and sea level rise, while temperatures are expected to rise in the North Pacific by between 3.0 °C and 3.2 °C between the end of the last century and 2050 to 2099 under the same RCP scenario, or by 1.4 °C to 2.2 °C under a more moderate emissions scenario. The Arctic Pacific is expected also to experience warming but at a slower rate than further south. Some other examples are: an increase of less than 1 °C by 2100 relative to 2000 to 2010 for the Western Central Pacific under RCP2.6 or by 2.5 °C to 3.5 °C under RCP8.5; warming of between 1 °C and 2.0 °C (depending on locality) in the oceans around Australia over the next 100 years under RCP2.6, or between 2 °C and 5.0 °C under RCP8.5. In the Mediterranean, estimates of future increases in SST range from 1.7 °C to 3.0 °C by the end of this century in comparison to those experienced in the second half of last century, and the Black Sea is also projected to warm by 2.8 °C and 0.5 °C for summer and winter respectively by 2100. The rates vary, but temperatures are changing, in most cases warming, and will continue to do so for the remainder of this century.

The wider ramifications of climate change are also well described in the chapters on the different marine regions and show a similar common theme of change, albeit with considerable regional diversity. The interactions between warming oceans, increased stratification and their implications of reduced dissolved oxygen concentrations are referred to for several regions including the Eastern (Chapter 8) and Western Central Atlantic (Chapter 9) regions, Northeast Tropical Pacific (Chapter 10), Western Indian Ocean (Chapter 12), and Southwest Atlantic (Chapter 15). At the same time, upwelling is reported to be strengthening in the Canary Current (Eastern Central Atlantic) and, under the RCP8.5 scenario, is projected to continue to do so until the end of the century (Chapter 8). This is consistent with information in Chapter 6 that there is evidence that upwelling could be intensifying in some of the bigger coastal upwelling systems. However, the overall effect of such changes on future ecosystem productivity is uncertain.

Striking decreases in the pH of the North Atlantic (about 0.0035 pH units per year for the last 30 years) are highlighted as a key message for Chapter 5, together with forecast ongoing declines in the future that raise concerns about the potential impact on harvested shellfish and early life stages of some finfish species. Declining pH is also referred to in Chapter 12 on the Western Indian Ocean, Chapter 16 on Australia and others. Projections for the Western Central Atlantic (Chapter 9) and Western and Central Pacific (Chapter 14) indicate that, depending on how much the concentration of CO_2 in the atmosphere increases, aragonite saturation values (Ωar) could possibly fall below 3.0 (extremely marginal), which would likely lead to net erosion of the coral reefs in the areas. However, while there is certainty in the direction and magnitude of ocean pH decline, and of its largely negative impacts on marine organisms (Kroeker, Kordas and Harley, 2017), most projection models do not incorporate the potential impacts of ocean acidification (OA) on the marine food web and thus on fish and fisheries. This is because we seem to lack sufficient understanding of the capacity for marine organisms to adapt through acclimation, transgenerational and evolutionary adaptation (Gaylord *et al.*, 2015; Munday *et al.*, 2013; Munday, 2014), to reliably predict OA impacts on marine populations and ecosystems.

Sea level rise is another phenomenon driven by global warming that is being experienced in many regions, albeit at different rates. Chapter 13 reports that two-thirds of Bangladesh lies less than five metres above sea level and, with projected sea level rise, saline water could penetrate 50 km further inland than at present, with serious consequences for the country, and similar risks are reported for coastal areas in the Eastern Central Atlantic (Chapter 8). The mean sea level in the Western Central Atlantic could rise by between 0.35 m to 0.65 m by the end of this century depending on the extent of GHG emissions in the future. In the Mediterranean projections indicate a likely continuation in the recently observed rate of between 2 mm/yr and 10 mm/yr.

28.5.2 Effects on ecosystems and fisheries

Chapters 5 to 17 present a disturbing array of the impacts of climate change on marine ecosystems and fisheries and an even more disturbing picture of potential future trends. Only a few examples are presented here to try to illustrate what is occurring and could take place in the future. At the ecosystem level, common impacts emphasized in the different regions are shifts in distribution by fish species and other taxonomic groups, increasing incidences of coral bleaching with serious implications for the affected ecosystems as a whole, and increasing frequency in outbreaks of harmful algal blooms.

Serious incidences of bleaching of coral reefs are reported from, for example, the Western Central Atlantic (Chapter 9), Western Indian Ocean (Chapter 12), Western Central Pacific and Australia (Chapters 14 and 16). Increasing frequency and intensity of such events is expected to lead to substantial reductions in the extent of live coral cover, and could lead to a loss of coral reef species, changes in the dominant species assemblages and, in some cases, a complete phase shift to algal dominated reef communities. These changes will lead to significantly altered ecosystem services (Chapters 9 and 14). The forecast increases in acidification could exacerbate this problem, at least in some regions. There are several examples of increasing frequencies in the incidence of HABs. For example, Chapter 13 reports more frequent incidence, greater intensity and wider areas of occurrence of HABs in the Arabian Sea and the Bay of Bengal, while the incidence may also be increasing in the coastal waters of South Africa (Chapter 11) and the Western Central Atlantic (Chapter 9). HABs are often associated with mortality of fish and give rise to food safety concerns for humans.

Shifts in the distribution of species of fish of importance to fisheries are one of the most widely recognized and acknowledged impacts of climate change on the oceans. All the marine chapters make references to such shifts but those that have taken place in the North Atlantic are arguably the best known and studied case. Chapter 5 describes the profound changes in the distribution and production of fish species that have been observed in both the Northeast and Northwest Atlantic, which have had important impacts on fisheries and their management in the region. This trend is expected to continue and changes in the distribution and production of species are forecast to lead to substantially increased yields in high-latitudes but decreased yields in areas south of about 50 °N. Two other regional examples that perhaps justify singling out in this summary, because of both the extent of the shifts and the extent to which they have been monitored, are the changes in distribution in the oceans of Western Australia (Chapter 16) and those that have and are occurring in the Mediterranean (Chapter 7).

The research on the distribution and likely impacts of climate change on future distribution of tuna, and the implications for fisheries management also warrants highlighting in both the Western and Central Pacific (Chapter 14) and Western Indian Ocean (Chapter 12), particularly for some SIDS. Climate change has already caused noticeable shifts in distribution and abundance of tuna, and substantial future changes can be expected under a warming climate, with important impacts on national incomes of dependent countries and for the harvest strategies currently being used for their management. The most important adaptations recommended to address these changes are somewhat different in the two regions but involve actions aimed at ensuring, as far as possible, that the current social and economic benefits obtained from these fisheries across the value chain are maintained. The chapters in this volume did not examine the impacts of climate change on tunas in the Atlantic but, as would be expected from the results for the Pacific and Indian Oceans, tuna in the Atlantic have also been reported to have shown significant shifts in distribution in recent decades (Monllor-Hurtado, Pennino and Sanchez-Lizaso, 2017) and climate change is expected to lead to changes in the spatial and population dynamics of the species group in the future (Muhling *et al.*, 2015).

28.5.3 Vulnerabilities and responses

The impacts of climate change are expected to be heaviest for small-scale fishers in several regions, but there are also possibilities that changes in distribution could create new opportunities for them (e.g. Chapters 7, 10 and 15). In the Northeast Tropical Pacific (Chapter 10) small-scale fishers have some advantages because they are able to adapt quickly to take advantage of available resources, but as many of the species they typically harvest are considered to be vulnerable to habitat degradation, new opportunities may be limited. Similar considerations probably apply to the small-scale sector in most regions. Small-scale fishers are also considered to be among the most vulnerable groups in the Southeast Atlantic, Southwest Indian Ocean and Western and Central Pacific. In the Mediterranean and Black Sea, the developing countries in the south and southeast of the region are considered to experience higher exposure to the changes and to have lower adaptive capacity to cope with them and therefore to be more vulnerable to climate change. These examples all highlight the importance of adaptive capacity, or limitations in adaptive capacity, as a key driver of vulnerability.

A further important conclusion coming from a number of chapters, and including the tuna examples, is that the expected changes in distribution are likely to cause new, or exacerbate existing conflicts between users, both within countries and when the distribution of important species changes across boundaries between neighbouring countries or between country EEZs and the high seas. Where fish resources are shared or straddle international boundaries, changes in distribution could lead to disagreement about allocations, as occurred when Atlantic mackerel distribution shifted northwards and westwards, decreasing in abundance in Norwegian waters and increasing in the waters of Iceland and the Faroe Islands. This led to a dispute over allocations between the affected nations (Jensen *et al.*, 2015) that resulted in the scientific recommendations for the total allowable catch being exceeded for a number of years (Chapter 5), and serves as a good example of the need for flexibility in management and allocation arrangements, both national and international, to enable rapid, responsible approaches to such changes.

Adaptation in fisheries and aquaculture is analysed in some depth in Chapter 25 and only a few examples from the marine chapters are discussed here to illustrate the types of threats and responses to them that are being planned or implemented in marine fisheries. In addressing climate change, it is essential to recognize that, almost invariably, it is not the only threat or stressor on a fisheries system but an additional, possibly unidirectional one, adding to what is typically a range of other stressors and uncertainties from anthropogenic and natural causes. These can include, for example, overfishing, pollution, habitat loss, competition for space and environmental variability. Adaptation to climate change must thus be undertaken within that multi-faceted context and any additional measures or actions taken in response to climate change should complement and strengthen overall governance and sustainable use. This principle is widely recognized in the marine regions and fisheries addressed in Chapters 5 to 17, and there are frequent references to efforts to ensure effective management of the fisheries and to reduce the impacts from other stressors. These include implementation of the FAO Code of Conduct for Responsible Fisheries and related instruments, ecosystem approaches to fisheries, spatial planning including effective systems of marine protected areas, ensuring participatory systems of governance and strengthening control and enforcement in the fisheries sector. The additional uncertainty arising from climate change reinforces the importance of adaptive approaches to management that include monitoring of conditions and performance of the fishery, with feedback to management decisions and actions. This enables adjustment, or adaptation, to accommodate any important changes in the system and ensure performance is maintained in relation to agreed objectives (which may also need to be adjusted, within the bounds of sustainability, if changed conditions require it).

As stated above, small-scale and artisanal fisheries and fishers are identified as being particularly vulnerable to the impacts of climate change and a number of the adaptation options referred to in these chapters are aimed primarily at them. They include implementation of the FAO *Voluntary guidelines for securing sustainable small-scale fisheries* (FAO, 2015), and the *Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests* (FAO, 2012) to promote secure tenure rights and equitable access to fisheries as a means of eradicating hunger and poverty and supporting sustainable development. Other specific options include wider use of community-based approaches to fisheries governance, flexibility to enable switching of gears and target species in response to changes, creation of alternative livelihoods, product beneficiation, capacity-building to enhance resilience in different ways, and improving the economic stability of small-scale fishers and those involved in associated activities through, for example, improved access to credit, microfinance, insurance services and investment. Some of these measures require institutional adaptation, whether it is to set new transboundary processes, or to facilitate the changes in primary target species or to accommodate changes in the timing of processes such as fisheries recruitment. Noting the likelihood of increasing incidence of extreme events, measures to improve early warning systems, safety at sea and for protection of fisheries-related infrastructure such as safer harbours, landing sites and markets are also being considered or implemented.

Finally, a number of the marine fishery chapters referred to the need to reduce the uncertainties associated with climate change and its impacts through improved monitoring and research. In addition to providing valuable information for research into climate change, improved monitoring could be linked in some instances to the establishment of early warning systems to alert fishers and the stakeholders of imminent extreme events, including the incidence of HABs, and also to inform fishers of changes taking place, thereby potentially strengthening their adaptive capacity. Research to support adaptation efforts is also required to facilitate more effective adaptation and to reduce the risk of maladaptation.

28.6 INLAND FISHERIES

Chapters 18, 19 and 26 address the impacts of climate change on inland fisheries, a highly diverse sector that occurs on every continent apart from the Antarctic. Inland capture fisheries make important contributions to livelihoods and economies around the world, generating recorded catches of over 11 million tonnes in 2015, equivalent to just over 12 percent of total production from marine and freshwater capture fisheries. They provide high quality, affordable food to some of the particularly poor and vulnerable people globally and are a source of employment and livelihoods to tens of millions of people, as well as being a foundation of cultural systems in many places (Chapters 3 and 18).

Freshwater is a crucial commodity used in or affected by many sectors of human life ranging from human consumption to agriculture, recreation and others. As a result, the world’s limited resources of freshwater are subjected to many anthropogenic pressures including extraction, river regulation, damming, pollution, habitat degradation, fishing and others. The already high demand for water is expected to increase in the future as a result of human population growth and development, which, unless urgent remedial action is taken, will have serious negative impacts on inland fisheries and the benefits they provide. Unfortunately, in the competition for this scarce resource the valuable contributions of inland fisheries are frequently not recognized or are under-valued and priority is given to other more visible demands for water, with serious consequences for the sustainability of inland fisheries.

As an additional stressor, climate has a strong controlling influence on the physical, chemical and biological processes in freshwater ecosystems, which leads to changes in distribution, abundance and production of inland fishery resources. Climate change is also changing the global hydrological cycle, through changes in precipitation and evaporation (Settele *et al.*, 2014). Overall, climate change is driving changes in the composition of species assemblages, the abundance, biomass and distribution of species, fish yields and the efficiency of fishing methods and gears.

Chapter 19 explored the likely impact in the future of these climate-induced changes in combination with other stressors including population growth, demand for freshwater from other sectors, construction of dams and others for 149 countries with inland fisheries. The results indicated a wide range in magnitude of current and future stressors, extending from eight countries that are currently facing high stresses that are projected to become even higher in the future (including Pakistan, Iraq, Morocco and Spain) and, at the opposite end of the range, 17 countries that were found to be under low stress at present and are projected to remain under low stress in the future (including e.g. Myanmar, Cambodia, Lao PDR, Papua New Guinea, the Congo, the Central African Republic, Gabon and Colombia). The remaining 124 countries fell within these two extremes, of which the largest group, 60 countries currently accounting for 46.9 percent of the global inland fishery catch, were found to be facing medium stress now, which is expected to continue in the future. The results indicated that the category of stress is expected to increase by a grade (e.g. medium to high) in 59 countries that currently account for 36.4 percent of the global catch. Thirty-nine countries, accounting for 26.3 percent of the current catch, are forecast to experience high or very high stress in the future compared to 14 countries at present accounting for only 1.8 percent of the global catch.

The case studies described in Chapter 19 present a mixed picture of current and future impacts. In all these cases, non-climate stressors are considered to be the more serious threats to the inland fisheries of these regions than climate stressors. For example, in the Yangtze River basin, over-exploitation, habitat degradation and pollution are thought the be main threats to the future of inland fisheries, while the large variability in precipitation, the already dense population and the rapidly developing economy mean that the basin is highly vulnerable to climate change. In the Ganges River basin, the increasing human population and difficulty in maintaining ecological flows in the river because of increased water demand is expected to be the primary factor impacting inland fisheries. The picture emerging from the other cases examined in Chapter 19 is similar, highlighting threats such as changes in the size, duration and timing of flow events, economic development, agricultural development, deforestation and increasing modification of river floodplain habitats, all of which will have serious impacts on these inland water bodies and systems and their fisheries.

In most inland fisheries climate change will be an addition to already heavily stressed systems, but with large variability. For example, in Finland, climate-driven temperature increases are likely to result in higher productivity of the fisheries but with large changes in dominant species and other fishery attributes. In the Lower Mekong River basin however, climate change is expected to affect air and water temperatures and precipitation, the volume and flow of the river and the agricultural practices that will collectively impact the resources supporting this globally large collection of fisheries. Observed and projected climate impacts in other case studies included increasing water temperatures leading to changes in fish species, potentially from higher to lower value species, changes in precipitation (as rain or snow) and consequently water flows, and more frequent and intense extreme events such as floods. In some cases, (e.g. La Plata River basin) the increasing precipitation and run-off could extend and improve connectivity between fish habitats, while decreased precipitation and more extreme events will negatively impact flows and habitats in others (e.g. the Amazon River Basin).

The implications of the changes for individuals, communities and countries will depend on their exposure, sensitivity and adaptive capacity but in general can be expected to be profound. Their ability to adapt to them will be determined by a range of factors including, for example, the extent of their dependence on the activity, the wealth and assets they possess, their education, location and other factors (Chapter 18; Aswani *et al.*, 2018; Williams and Rota, 2011). In their favour is that the uncertainty and variability that have always characterized inland fisheries mean that the fishers and other stakeholders are accustomed to the need for adaptation and have developed strategies to assist in doing this such as changing exploitation rates, altering their fishing operations, migrating and having diverse livelihoods. Nevertheless, the poverty and food insecurity of many of them seriously constrains this ability and for many, the future impacts of climate change, coupled with increasing pressure from multiple other anthropogenic pressures, are likely to exceed their existing adaptive capacity unless far-reaching action is taken to increase it.

Examples of the action that will be required to facilitate and support adaptation are provided in Chapters 18, 19 and 26. Adaptive management within the framework of an ecosystem approach to fisheries is essential for maintaining, and restoring ecosystem integrity and resilience to the coming changes. This must be done with the engagement of stakeholders and in a participatory manner. Some of the impacts of climate change are certainly likely to be positive. For example, increased precipitation could reduce current water stress in some regions and also lead to the expansion of habitats available to fish, leading to higher abundances and potential yields. Taking advantage of new opportunities could require investment in infrastructure and equipment, for which external support may be required. In cases of both new opportunities and negative impacts, a key requirement for nearly all countries and regions will be to ensure flexibility (within the limits of sustainable use) in policies, laws and regulations that will allow fishers to switch between target species and adjust their fishing practices in response to changes in the ecosystems they utilize for fishing. Adaptation in post-harvest processes will also be important through, for example, the development or improvement of storage and processing equipment and capacity and implementation of robust biosecurity systems in order to ensure the quality of fish and fish products through to the consumers, as well as facilitating possible access to higher value markets.

As reported above, an overriding theme in inland fisheries globally is that they are susceptible to the activities and impacts of other sectors and that these impacts are generally of greater concern than the direct effects of climate change *per se*. These other sectors are also being impacted by climate change and their efforts to adapt or mitigate their contributions to climate change may result in further impacts, primarily negative, on inland fisheries. As a result, it is critical for ensuring the resilience and sustainability of inland fisheries that adverse impacts from other sectors are minimized, particularly in terms of water. This requires, in particular, taking steps to ensure adequate environmental flows and the maintenance of the habitats that sustain ecosystems and the fisheries that depend on them.

An important requirement is that the role and goals of inland fisheries must be adequately addressed in catchment, basin and regional management plans that involve or have implications for water supplies and systems. This implies the need to develop and implement integrated, holistic approaches at appropriate scales, and that address the range of ecosystem services, including support of inland fisheries. They also need to encompass water and environmental integrity, environmental rehabilitation, wetland management, water storage and quality and carbon sequestration. For transboundary basins and systems, such holistic plans should be incorporated in the relevant regional and international agreements.

28.7 AQUACULTURE

Aquaculture is making an increasing contribution to global production of fish, crustaceans and molluscs and thereby to the livelihoods, food security and nutrition of millions of people. By helping to meet the growing demand for these products aquaculture also alleviates the price increases that would otherwise result from any escalating gap between supply and demand. Aquaculture no longer enjoys the high annual growth rates of the 1980s and 1990s (11.3 percent and 10.0 percent, excluding aquatic plants), but remains the fastest growing global food production system. Average annual growth declined to 5.8 percent during the period 2000 to 2016, although double-digit growth still occurred in a small number of individual countries, particularly in Africa from 2006 to 2010. Overall, between 1950 and 2015 global aquaculture production grew at a mean annual rate of 7.7 percent and by 2016 had reached 80.0 million tonnes of food fish and 30.1 million tonnes of aquatic plants (FAO, 2018), equivalent to 53 percent of global production of fish for food by capture fisheries and aquaculture combined (Chapter 3).

Climate change can have direct and indirect impacts on aquaculture, and in the short- and long-term. Some examples of short-term impacts described in Chapter 20 include losses of production and infrastructure arising from extreme events such as floods, increased risk of diseases, parasites and harmful algal blooms, and reduced production because of negative impacts on farming conditions. Long-term impacts include reduced availability of wild seed as well as reduced precipitation leading to increasing competition for freshwater. Climate-driven changes in temperature, precipitation, OA, incidence and extent of hypoxia and sea level rise, amongst others, will have long-term impacts on the aquaculture sector at scales ranging from the organism to the farming system to national and global.

It is clear from the information presented in Chapter 20 that these changes will potentially have both favourable and unfavourable impacts on aquaculture, but the available information indicates that unfavourable changes are likely to outweigh favourable ones, particularly in developing countries where adaptive capacity is typically weakest. The threats of climate change to aquaculture have been recognized by some countries and, as of June 2017, of the 142 countries that had submitted their NDCs, 19 referred to aquaculture or fish farming. Nine of those included a focus on adapting aquaculture to climate change, while ten included proposals to use the development of aquaculture as an adaptation and/or mitigation measure in their efforts to address climate change.

Chapter 20 also presents a number of vulnerability assessments, with examples at national level (Chile), local (salmon aquaculture in Chile and South Sulawesi, Indonesia) and at the watershed scale (Mekong). Assessments at national scale provide useful guidance for governments and decision-makers at global and national levels but there is also usually high diversity within countries. Vulnerability assessments and therefore adaptation planning also needs to be to be conducted at finer, localized scales where the specific practices, stakeholders and communities, and local environmental conditions can be taken into account.

Chapter 21 reports on global assessments of vulnerability of aquaculture to climate change, referring particularly to a study by Handisyde, Telfer and Ross (2017). The assessments considered sensitivity, exposure and adaptive capacity as the components of vulnerability. For freshwater aquaculture, that study found Asia to be the most vulnerable area, influenced strongly by the high production from the continent, with Viet Nam being the most vulnerable country in Asia, followed by Bangladesh, the Lao People's Democratic Republic and China. Belize, Honduras, Costa Rica and Ecuador were assessed as being the most vulnerable countries in the Americas, while Uganda, Nigeria and Egypt were found to be particularly vulnerable in Africa.

In the case of brackish water production, Viet Nam, Egypt and Thailand emerged as having the highest vulnerabilities but the chapter draws attention to the countries with the lowest adaptive capacity to cope with the impacts of climate change, which included Senegal, Côte d'Ivoire, the United Republic of Tanzania, Madagascar, India, Bangladesh, Cambodia and Papua New Guinea. For marine aquaculture, Norway and Chile were identified as being the most vulnerable, reflecting the high production of those countries in comparison to others. China, Viet Nam, and the Philippines were found to be the most vulnerable countries in Asia, while Madagascar was the most vulnerable country in Africa. Mozambique, Madagascar, Senegal and Papua New Guinea were identified as countries with particularly low adaptive capacity.

Chapter 21 presents a number of options for adaptation and building resilience in aquaculture and emphasizes that they should be applied in accordance with an ecosystem approach to aquaculture. They include:

- improved management of farms and choice of farmed species;
- improved spatial planning of farms that takes climate-related risks into account;
- improved environmental monitoring involving users; and
- improved local, national and international coordination of prevention and mitigation.

According to the fifth assessment report of the IPCC (Jimenez Cisneros, Oki, Arnell *et al.*, 2014), climate change is projected to result in a significant reduction in renewable surface water and groundwater resources in most of the dry subtropical regions, which can be expected to lead to greater competition between different types of agriculture and between agriculture and other sectors. As with inland fisheries, this expected trend, and other inter-sectoral interactions, means that focusing only on adaptation within aquaculture is unlikely to be sufficient and effective reduction of vulnerability in the sector requires the integration of aquaculture into holistic, multi-sectoral watershed and coastal zone management and adaptive planning.

Building on this principle, Chapter 22 examines the interactions that can take place between aquaculture and fisheries and agriculture in the context of climate change. Interactions between these sectors can either exacerbate the impacts and problems of climate change or help to create solutions for adaptation. Potential interactions and measures to address them include:

- The expected increase in frequency and intensity of extreme weather events could lead to an increase in the number of escapees from aquaculture farms. This impact could be minimized by measures such as regulating the movement of aquatic germplasm originating from outside the area, certification of cage equipment that minimizes the risk of escapes, modifying pond systems, and developing the capacity of farmers and implementing management measures to address the problem.
- Consumption of water by aquaculture will add to competition for the resource in places where availability and quality of freshwater is reduced by climate change. This problem can be alleviated by reducing water consumption by aquaculture through technological and managerial improvements. Measures such as these need to be complemented by similar actions across sectors and users, and should be a part of integrated, multi-sectoral policies, legal and regulatory frameworks and actions.
- Aquaculture could be negatively affected if the impacts of climate change on the availability of fishmeal and fish oil are negative, as these are important components of feeds for some species. This problem could be reduced in the longer-term by increasing the use of fish processing wastes in feeds as well as by use of new feedstuffs, the production of which is already increasing.

Aquaculture can also contribute to climate change adaptation in other sectors. For example, culture-based fisheries could be used to alleviate the effects of reduced recruitment in capture fisheries as a result of change. Aquaculture is also frequently seen as a promising alternative livelihood for fishers and other stakeholders when capture fisheries can no longer support them because of climate change, over-exploitation and other factors.

A common message across the three chapters on aquaculture is that there are important gaps in current knowledge and understanding of scientific, institutional and socio-economic aspects of the sector and the likely impacts of change. These gaps, examples of which are presented in the chapters, hinder the effectiveness of adaptation in the sector, particularly in developing countries. In general, ensuring that adaptations are consistent with the ecosystem approach to aquaculture (FAO, 2010) would provide a good foundation for success and effectiveness.

28.8 IMPACTS OF CLIMATE-DRIVEN EXTREME EVENTS AND DISASTERS

A formal definition of an extreme event is "the occurrence of a value of a weather or climate variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable" (Chapter 23). Even if not extreme in a statistical sense, a (weather or climate) event, or two or more events occurring simultaneously, can be considered to be extreme, if they have high impacts or consequences for people, the environment or their infrastructure. While the attribution of extreme events is frequently difficult, there is growing confidence that the number of extreme weather events being observed in a number of regions is on the increase, and that this increase is related to anthropogenic climate change. Climate-related disasters now account for more than 80 percent of all disaster events, with large social and economic impacts, including both short- and long-term displacement of people and populations (UNISDR, 2015). Fisheries and aquaculture are sectors frequently exposed to the impacts of climate change and therefore, as can be seen from many examples in the preceding chapters, face serious threats from extreme events. A recent FAO review of 74 post-disaster needs assessments conducted in 53 developing countries indicates that, while between 2006 and 2016 fisheries bore only three percent of the total impact of medium to large-scale natural disasters, including climate extremes, on the agriculture sector there are significant information gaps on the impacts on the sectors and more specifically on aquaculture.

The evidence that the climate is getting warmer is overwhelming. A warmer climate can be expected to disrupt the hydrological cycle, resulting in changes in the frequency and intensity of extreme events, as well as to their timing, duration and geographic distribution. Not all extreme events necessarily result in a disaster and the extent of their impacts on fisheries and aquaculture will be dependent on how exposed and vulnerable the socio-ecological systems are as well as their capacity to respond. It is to be expected, whatever actions are taken, that there will be extreme events in the future and an important message from Chapter 23 is that existing approaches to damage and loss assessment from climate related disasters in fisheries and aquaculture need to be improved, and should be linked to the evaluations under the Warsaw International Mechanism on Loss and Damage. With the increased and increasing number of extreme events and the likelihood of resulting disasters, there is an urgent need to invest in coherent and convergent disaster risk reduction and adaptation measures and preparedness for climate disaster response and recovery in the fisheries and aquaculture sectors. This should lead to a shift from reactive management after disasters have occurred to proactive management and risk reduction of climate risks and hazards.

28.9 HAZARDS IN FOOD SAFETY AND AQUATIC ANIMAL HEALTH

Climate change is leading to changes in, amongst other features, the temperature, pH and salinity of water and the incidence and intensity of extreme weather events, all of which can have impacts on food safety (Chapter 24). For example, the growth rates of pathogenic bacteria that occur in the marine environment have been found to increase at higher water temperatures, while changes in seasonality and other environmental conditions can influence the incidence of parasites and some food-borne viruses. Changes in the environment can also modify the population dynamics of the hosts of food-borne parasites. These impacts of climate change on food safety require modifications to the existing approaches for assessment of food safety risks to ensure that they also address new and emerging hazards in food safety. Coping with climate-driven changes will require giving greater attention to monitoring of key environmental parameters, including water and air temperature, pH and salinity, to enable advance prediction of imminent problems related to food safety such as the incidence of toxins, pathogens and contaminants in bivalve molluscs and the fish species that are more susceptible to such threats. Implementation of effective early warning systems will need collaboration between the relevant sectors and stakeholders, including those responsible for aquatic animal health, the marine environment and food safety and public health, at both national and international levels.

Climate change also brings increased risks for animal health. Aquaculture development is leading to more intense production so as to ensure economic sustainability but this has the effect of increasing the probabilities of disease outbreaks as well as the challenges in controlling them (Chapter 24). Climate change frequently exacerbates these problems and risks. It can have impacts on the production environment, for example on the occurrence and virulence of pathogens, the susceptibility of the organisms being cultured to pathogens and infections, and the risk of escapes from production systems impacted by extreme events. The likelihood and consequences of events such as these need to be minimized by ensuring implementation of an effective biosecurity plan that includes key elements such as emergency preparedness and communication, and emphasizes prevention, biosecurity and health management practices. As with risk management in food safety, managing risks for animal health will require collaboration, sharing of responsibilities and active, long-term engagement of all the relevant authorities and other stakeholders. In accordance with international standards, and relevant regional and national instruments, addressing these challenges requires the implementation of best practices so as to reduce the risk of transfer of disease, and responsible movement of live aquatic animals if harmful impacts on wild and cultured stocks are to be avoided.

28.10 ADAPTATION IN FISHERIES AND AQUACULTURE

In the face of the current and future impacts and threats from climate change, the viability and sustainability of socio-economic and ecological systems that make up the fisheries and aquaculture sectors will be determined by their ability to adapt to them. Chapter 25, "*Methods and tools for climate change adaptation in fisheries and aquaculture*" provides guidance on the identification and selection of tools and methods to facilitate and strengthen such adaptation. Planning for, and implementation of effective adaptation can only be done if there is adequate information on the prevailing and future risks and vulnerabilities. Each specific fishery, community or fishery/aquaculture enterprise will exist within a particular and probably unique geographical, environmental, and institutional and socio-economic context, which means that each will have different and unique risks and vulnerabilities. Climate change adaptation must therefore start with a good understanding of a given fishery or aquaculture system and an accurate assessment of current climate variability and likely future change, and the impacts these could have on the environment and the people. Inevitably there will be uncertainties in this information but decisions still need to be made, and must take those uncertainties into consideration.

Chapter 25 provides information on the tools available to inform decision-making and trade-offs between the present and the future and consideration of the risk and returns of adaptation investments. The chapter describes a process for undertaking a vulnerability assessment, and for developing and implementing an adaptation strategy. The first step in the process is to undertake a scoping of the case under consideration and, in close consultation with the stakeholders, to set the objectives for the strategy and to conduct the assessment. The second step is to develop the strategy. The individuals and groups with highest levels of poverty are almost invariably the ones who are most vulnerable to climate change and the assessment should therefore give particular attention to those people and groups. For this reason, it is preferable to identify and assess the different groups within the system, according to, for example, socio-economic status, poverty and food security, and gender, so as to ensure that the most vulnerable are recognized and addressed. Participatory processes are essential. Thereafter, available and relevant adaptation options need to be evaluated, prioritized and selected on the basis of suitability for achieving the objectives and other criteria such as national development objectives, social and environmental costs and robustness. The chapter presents examples of tools within three primary entry categories: institutional and management, those addressing livelihoods and, thirdly, measures intended to manage and mitigate risks and thereby strengthen resilience.

Adaptation should be seen and implemented as an on-going and iterative process, equivalent in many respects to adaptive management in fisheries. Flexibility, ongoing monitoring of key indicators of conditions and performance, and correction or "tuning" of measures when they are not performing as expected should be an inherent part of any adaptation strategy. The impacts of climate change do not respect human-made boundaries, and implications for transboundary issues, such as changing stock distributions (see, for example, Chapter 5) need to be anticipated, as far as possible, and suitable measures put in place to address them with a minimum of conflict.

28.11 MEASURES AND TOOLS TO REDUCE ENERGY USE AND GHG EMISSION IN FISHERIES AND AQUACULTURE

Chapter 27 reports that in 2012 the estimated global emission of carbon dioxide by fishing vessels, both marine and inland, was 172.3 megatonnes, which was about 0.5 percent of total global emissions that year. The aquaculture industry, including the emissions involved in capturing fish for feed, was estimated to have led to the emission of 385 megatonnes of carbon dioxide in 2010. Fisheries and aquaculture are therefore only minor contributors to emissions but, nevertheless, there are options for reducing fuel use and GHG emissions, which should be seen as important objectives in operations and management in the sector.

In the case of capture fisheries, reductions of between 10 percent and 30 percent could be attained through use of efficient engines and larger propellers in fishing vessels, as well as through improving vessel shapes and other hull modifications and simply by reducing the mean speed of vessels. Further opportunities include using fishing gears that require less fuel, for example switching from pelagic trawl to purse seine or from otter trawl to pair trawl, would reduce GHG emissions, although they could have impacts on catchability and fishing efficiency, which would need to be considered. In the case of towed fishing gears, the use of multi-rig gear, efficient otter boards, fishing off the bottom, use of lighter high-strength materials, and larger mesh sizes can all increase fuel efficiency and reduce carbon intensity (the amount of carbon dioxide emitted per unit weight of fish landed), as can using LED lights in those fisheries that attract fish with lights. Opportunities also exist in the facilities on land, with an obvious gain from using energy from renewable energy systems such as wind and solar-powered generation of electricity.

The choice and application of management measures in capture fisheries can play a role in fuel consumption and GHG emissions and, as a general rule, measures that lead to reductions in fishing effort and enhance fish stocks, thereby enabling higher catches per unit effort, will result in reduced fuel use and emissions. As an example of potential impacts, area closures are a widely applied measure that can contribute to ensuring high and sustainable stock biomass, and therefore fuel efficiency, but can also result in vessels having to fish in more distant or sub-optimal areas, thereby decreasing efficiency. Chapter 27 provides other examples that demonstrate the importance of including impacts on fuel efficiency as an objective in fisheries management planning.

There are also opportunities to reduce GHG emissions in aquaculture, which include improved technologies to increase efficiency in the use of inputs, greater reliance on energy from renewable sources, improving feed conversion rates, and switching from feed based on fish to feed made from crop-based ingredients. The integration of pond aquaculture with agriculture is also a potential option for reducing fuel consumption and emissions.

28.12 CONCLUDING COMMENTS

The structure and contents of this publication illustrate the multi-faceted and interconnected complexity of fisheries and aquaculture, and the interactions between this sector, other human sectors and activities, and the wider environment. The impacts of climate change ramify through these systems and the impacts of physical changes, for example in temperature or pH, can have impacts, direct or indirect, on any or all of the different facets from target or cultured species through to human health and well-being. One of the most important messages coming from this volume as a whole is that efforts to adapt to and mitigate climate change should be planned and implemented with full consideration of this complexity and how any new interventions will affect not only the immediate targets of the actions but the system as a whole. Failure to do this will increase the risks of inefficiency, failure of the actions, and of maladaptation. The consequences of such inefficient, poorly planned adaptation are likely to exacerbate the impacts of climate change, while appropriate adaptations will do much to counteract such impacts.

A second important message is the reminder, recurring through many of the chapters, of the critical importance of fisheries and aquaculture for millions of people struggling to maintain reasonable livelihoods through the sector. These are the people who are most vulnerable to the impacts of climate change, which adds to the many threats and obstacles that already confront them in their day to day lives. Effective adaptation will be required across all scales and sectors of fisheries and aquaculture in order to strengthen and maintain productive and resilient aquatic ecosystems and the benefits derived from them, but particular attention needs to be given to the most vulnerable if the sector is to continue to contribute to meeting global goals of poverty reduction and food security. In addition, as their poverty and marginalization are primary causes of their vulnerability, the eradication of poverty and provision of food security for the world's poor are fundamental to building their resilience to climate change.

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This FAO Technical Paper is aimed primarily at policymakers, fisheries managers and practitioners and has been prepared particularly with a view to assisting countries in the development of their Nationally Determined Contributions (NDCs) to the Paris Climate Agreement, the next versions of which are to be submitted by 2020. The Technical Paper provides the most up-to-date synthesis on the impacts and risks of, and the opportunities and responses to climate change in the fisheries and aquaculture sector, in the context of poverty alleviation.

It covers marine capture fisheries and their environments (Chapters 4 to 17), inland waters and their fisheries (Chapters 18, 19 and 26), as well as aquaculture (Chapters 20 to 22). The Technical Paper also includes chapters on disasters and extreme events (Chapter 23) and health and food safety hazards (Chapter 24). Guidance and tools are presented for planning and implementing effective and explicit adaptation (Chapter 25), while taking into consideration the impacts on fisheries and aquaculture of potential adaptations to climate change in other sectors (Chapter 26). Mitigation is addressed in Chapter 27, which provides quantitative information on the fisheries and aquaculture sector's contributions to greenhouse gas emissions, as well as strategies and tools for mitigation.

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