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Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture

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An overview of satellite remote-sensing (SRS) operational applications in fisheries is presented, and includes two case studies illustrating the societal benefits of SRS. The first describes the use of satellite-based vessel monitoring systems (VMS) and SRS data in a skipjack tuna (*Katsuwonus pelamis*) fishery, including a simple algorithm for determining fishing activity from vessel speed. The second case study illustrates the application of remotely sensed information in determining the impact of climate change on site suitability for scallop (*Mizuhopecten yessoensis*) aquaculture. Global warming simulated according to Intergovernmental Panel on Climate Change scenarios had a significant impact on sites with the greatest suitability for scallop aquaculture. Some challenges in the field of fisheries information systems are also discussed.

Keywords: climate change prediction, GIS, marine aquaculture, operational fisheries oceanography, remote sensing.

Introduction

Global capture fisheries production was relatively stable during the past decade, whereas aquaculture production continued to rise (FAO, 2009). Both sectors are very important for global food security, yet face a growing array of challenges that threaten their sustainability (FAO, 2009). For capture fisheries, overfishing, degradation of key species' habitats, erratic global fuel prices, and climate change are fundamental challenges. Aquaculture faces increasing competition for space, feed, and labour, as well as disease outbreaks and potential impacts of climate change. The solutions to some of these problems can involve applying satellite remotely sensed (SRS) information, so we provide a brief overview of selected SRS operational applications, followed by two case studies, one in capture fisheries and the other in aquaculture. The first discusses the application of SRS environmental data and vessel monitoring technology in a skipjack tuna (*Katsuwonus pelamis*) fishery in the western North Pacific. The second focuses on the impact of climate change on scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, Hokkaido, Japan, using SRS imagery. Finally, we highlight challenges and provide a perspective on the future of fisheries information systems in this field.

Brief overview of operational fisheries oceanography in pelagic fisheries

Operational oceanography has been defined as the branch of marine sciences that routinely provides high-quality observational and modelled data for practical applications (Pinardi and Coppini, 2010). These applications include *inter alia* the provision of services that minimize search time by directing fleets and fishing vessels to areas of optimum availability of targeted species, based on the knowledge of their behaviour under different environmental conditions (Petit *et al.*, 1994). SRS measurements of sea surface temperature (SST), ocean colour, sea surface height anomaly (SSHA), currents, and winds are the most important datastreams that shape operational oceanography. Previous reviews of the application of SRS information in marine fisheries were provided by Simpson (1992, 1993) and Santos (2000), and they include a detailed discussion of data types, operational systems, and fisheries applications. The scope here precludes such detail, but much has changed during the past decade (Barale *et al.*, 2010).

In pelagic fisheries, two themes stand out in operational application of SRS: (i) identification of potential fishing zones (PFZs), which takes advantage of the relationships between target species and environmental factors, and (ii) development of management measures, particularly minimizing the bycatch of endangered species. Modelling fish habitat (Valavanis *et al.*, 2008) used fishery and SRS environmental datasets to demonstrate that the identification of oceanographic features such as PFZs is feasible in different ocean basins, including the Atlantic Ocean (Zagaglia *et al.*, 2004), the western Pacific Ocean (Zainuddin *et al.*, 2008; Mugo *et al.*, 2010), and the Arabian Sea (Solanki *et al.*, 2010). Integration of electronic tags and SRS data to study behaviour and habitat utilization has added an interesting dimension to operational fisheries oceanography (Teo *et al.*, 2007; Weng *et al.*, 2009; Dewar *et al.*, 2010) and has demonstrated the utility of SRS in science-based fishery management (Hobday and Hartmann, 2006; Howell *et al.*, 2008; Teo and Block, 2010). For example, Howell *et al.* (2008) demonstrated a tool (TurtleWatch) that facilitated the avoidance of loggerhead turtle (*Caretta caretta*) bycatch while fishing for swordfish (*Xiphias gladius*) and tuna (*Thunnus* spp.) in the North Pacific (see also Kobayashi *et al.*, 2011). Hobday and Hartmann (2006) developed a tool for decreasing southern bluefin tuna (*Thunnus maccoyii*) bycatch in the eastern tuna and billfish fishery with limited or no southern bluefin quota. This demonstrated the feasibility of designing near-real-time fishery management boundaries using SRS SST, modelled data, and thermal habitat signatures from pop-up satellite tags. Hartog *et al.* (2010) also considered how management decisions based on SRS-derived habitat preferences of southern bluefin and yellowfin tuna (*Thunnus albacares*) could be influenced by ocean warming. These examples are by no means exhaustive, but illustrate some of the research directions that operational application of SRS information has taken in the recent past.

Commercial fishing applications of operational oceanography mostly aim to minimize search times and to save fuel (IOCCG, 2009). Advances in communication systems and data-processing methodology continue to diversify the products delivered to fishing fleets in real or near real time by fisheries information services. These include, among many others, Miami-based Roffer's Ocean Fishing Forecasting Service, Inc. (http://www.roffs.com/), providing fisheries forecasts derived from SRS since 1987; the SeaStar Commercial Fishing Service run by GeoEye (http://www.geoeye.com), featuring three-dimensional oceanographic maps; and Catsat (www.catsat.com), which provides similar services. The Indian National Centre for Ocean Information Services (INCOIS; http://www.incois.gov.in) provides PFZ forecasts for the seas around India. The Japan Fisheries Information Service Centre (JAFIC; www.jafic.co.jp) and the Environmental Simulation Laboratory Company (www.esl.co.jp) disseminate fisheries information services to Japanese fishers. A private company, SpaceFish LLP (http://spacefish.co.jp), recently established a fishery information system and service known as "TOREDAS" (Saitoh *et al.*, 2009), whose stated goals are to (i) facilitate near-real-time data transfer via internet and satellite connection during fisheries operations, (ii) predict PFZs based on scientific findings, and (iii) provide high value-added fisheries oceanographic information (Kiyofuji *et al.*, 2007). All the information systems listed above rely on SRS data to provide forecasts for various species in different parts of the world oceans.

Material and methods

Work on both case studies was conducted in the western North Pacific (18–50°N 125–160°E) for the skipjack tuna fishery and in Funka Bay (southern Hokkaido Island) for Japanese scallop aquaculture (Figure 1).

Skipjack tuna fishery

High-resolution spatial (1-min logging interval) VMS (vessel monitoring system) data were obtained via TOREDAS from a pole-and-line fishing vessel for the period 2007–2009. These data consist of latitude and longitude positions logged by the vessel's GPS and a date–time stamp. The distance between adjacent positions was calculated in ArcGIS 9.2, assuming that the vessel moved between each logged position along a straight line. Vessel speed (knots) was calculated using the distance travelled between adjacent polling points and the time taken (usually 1 min). A histogram of estimated vessel speeds was plotted and used to categorize vessel activity. A spatial filter excluded all VMS data received from within 10 km of the Japanese coast, so eliminating movement into and out of ports, which trigger the false fishing activity because of slow vessel speed. Only data transmitted between 06:00 and 18:00, when skipjack tuna fishing is normally conducted, were retained. Finally, a speed filter retained all data associated with speeds of 0.1–3 knots, indicative of fishing activity as inferred from the VMS speed histogram.

SST and chlorophyll *a* (Chl *a*) from monthly Aqua MODIS standard mapped images (resolution ~4 km), and the delayed time and merged SSHA products from AVISO (http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/index.html) were downloaded for the period 2007–2009 and mapped in ArcGIS 9.2. The data were re-gridded to uniform resolution, matched with the VMS-derived fishing positions, and sampled in ArcGIS 9.2.

Scallop aquaculture

The case of Japanese scallop aquaculture was used to demonstrate the use of SRS in exploring the potential impact of climate change on aquaculture resources. Model construction and analysis consisted of two steps (Figure 2). First, the suitability of sites for scallop aquaculture was determined using integrated remote

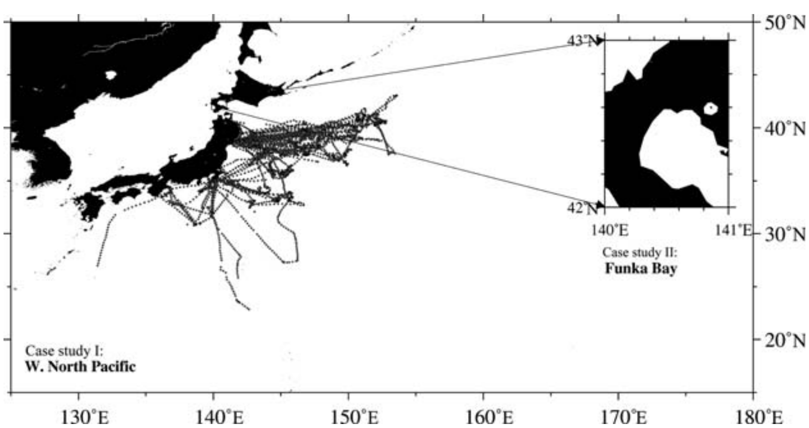

Figure 1. Study areas for the two case studies in the western North Pacific, including the plotted trajectories of a skipjack tuna fishing vessel (dotted lines) off the east coast of Japan in 2008, and Funka Bay scallop area (inset), south Hokkaido Island, Japan.

sensing and a model based on a geographic information system (GIS). Multicriteria evaluation was adapted to the GIS model to rank sites on a scale of 1 (least suitable) to 8 (most suitable), according to Radiarta *et al.* (2008). Second, from the final site-suitability model, we modelled the effect of SST warming on the site-selection model using temperature increases of 1, 2, or 4°C, i.e. scenarios given in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007). The approach is recognized as a valid framework for evaluating climate change impacts on fisheries/aquaculture resources (Brody and Hlohowskyj, 1998; Perry *et al.*, 2005).

Results and discussion

VMS, SRS oceanography, and skipjack tuna fishing

Application of SRS and GIS can help meet the management and harvesting challenges of the important skipjack tuna fishery, whose catches rank third in the world after anchovy (Engraulidae) and Alaska pollock (*Theragra chalcogramma*; Mugo *et al.*, 2010). The search for tuna schools is the most time-consuming step in the fishing operation (Miyake *et al.*, 2004; Majkowski, 2010), significantly affecting fuel and labour costs. Satellite-based VMS was first introduced for surveillance purposes (FAO, 1988; Deng *et al.*, 2005), but more recently became an additional data source in fishing ground location and forecasting systems, such as TOREDAS (Saitoh *et al.*, 2009). VMS data also have potential uses in fisheries science and management (Lee *et al.*, 2010), providing logbook-independent, high-resolution temporal and spatial information on fishing activity (Witt and Godley, 2007). VMS data have advantages over fishing logbooks in that they can be accumulated in near real time and are more objective, accurate, and complete (Mullowney and Dawe, 2009). They have been used to estimate fishing effort mainly in trawl fisheries (Mills *et al.*, 2004; Mullowney and Dawe, 2009; Palmer and Wigley, 2009; Lee *et al.*, 2010). For pelagic fisheries, simultaneous analyses of VMS and SRS data can be used to study skipper behaviour relative to target species. This type of information can improve operational fishery forecasting models and management measures, e.g. in the design of dynamic marine protected areas or effort-control measures. However, in the western North Pacific tuna fishery, little has been done with VMS information.

Daily vessel trajectories and associated speed graphs for a complete fishing trip conducted over the period 19–23 June 2008 are clearly illustrated in Figure 3, including departure (Figure 3a), offshore activity (Figure 3b and c), and return (Figure 3d). During pole-and-line fishing, the vessel is almost stationary, except for minimal current drift. Fishing activity is characterized by a cluster of points associated with slow speed, and non-fishing activity (i.e. steaming), by straight paths with corresponding high speeds. The histogram of vessel speeds (Figure 4a) reveals clearly a bimodal distribution, representing fishing (slow speed, first mode) and non-fishing activity (steaming) at higher speeds of 4.5–20 knots. The fact that a fishing vessel travels slower during fishing, gear deployment, and retrieval allows simple data partitioning (Witt and Godley, 2007). However, a fishing vessel may slow down because of a number of factors other than fishing, including approaching or leaving port, setting gear, being in the proximity of other boats, and during adverse weather (Mills *et al.*, 2007). In the case of skipjack tuna, false identification of fishing activity can transpire when tuna schools are identified and chummed, but do not respond to the bait, i.e. the vessel is stopped, but not fishing. A good understanding of the fishery in question can improve VMS data filters and the characterization of fishing activity.

SST, Chl *a*, and SSHA at VMS-derived fishing locations (Figure 4b–d) ranged from 17 to 29°C; 0.07 to 0.7 mg m^{-3}, and −30 to 50 cm, respectively (Figure 4d). These are similar to optimum ranges for the species (20.4–24.4°C, 0.07–0.26 mg m^{-3}, and −8 to 12 cm, respectively) obtained in previous work (Mugo *et al.*, 2010), supporting the accuracy of the VMS-derived fishing locations and associated environmental data.

SST strongly influences skipjack tuna distribution in the western North Pacific (Mugo *et al.*, 2010) and the Southwest Atlantic (de Oliveira *et al.*, 2010), where the fish are found mainly at >15°C (Wild and Hampton, 1993). SRS Chl *a* gradients and SSHA are instrumental in identifying ocean features associated with aggregations of forage species (Zainuddin *et al.*, 2008). The possible mechanisms resulting in these aggregations are beyond the scope of this paper and have been discussed elsewhere (Olson, 1991; Lehodey *et al.*, 1998; Bakun, 2006; Fonteneau *et al.*, 2009; Mugo *et al.*, 2010). This case study illustrates how, at an operational level, VMS information can be used at near real

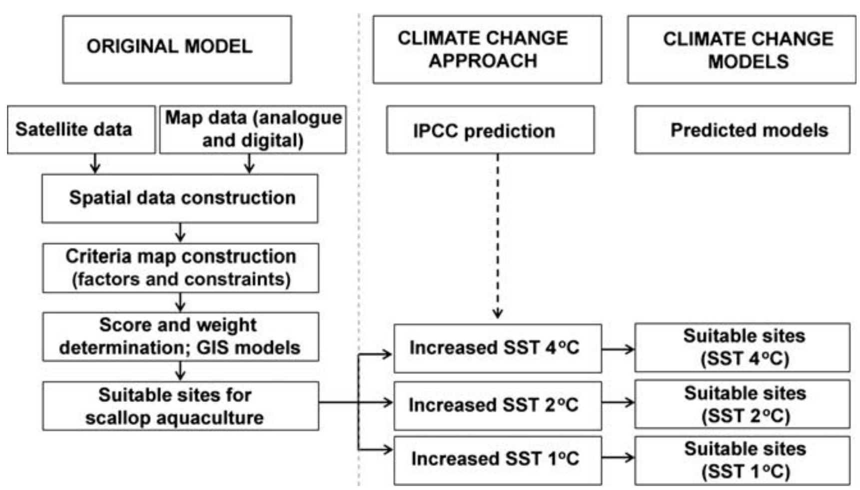

Figure 2. Schematic model of climate change prediction models for Japanese scallop aquaculture development in Funka Bay, southwestern Hokkaido, Japan.

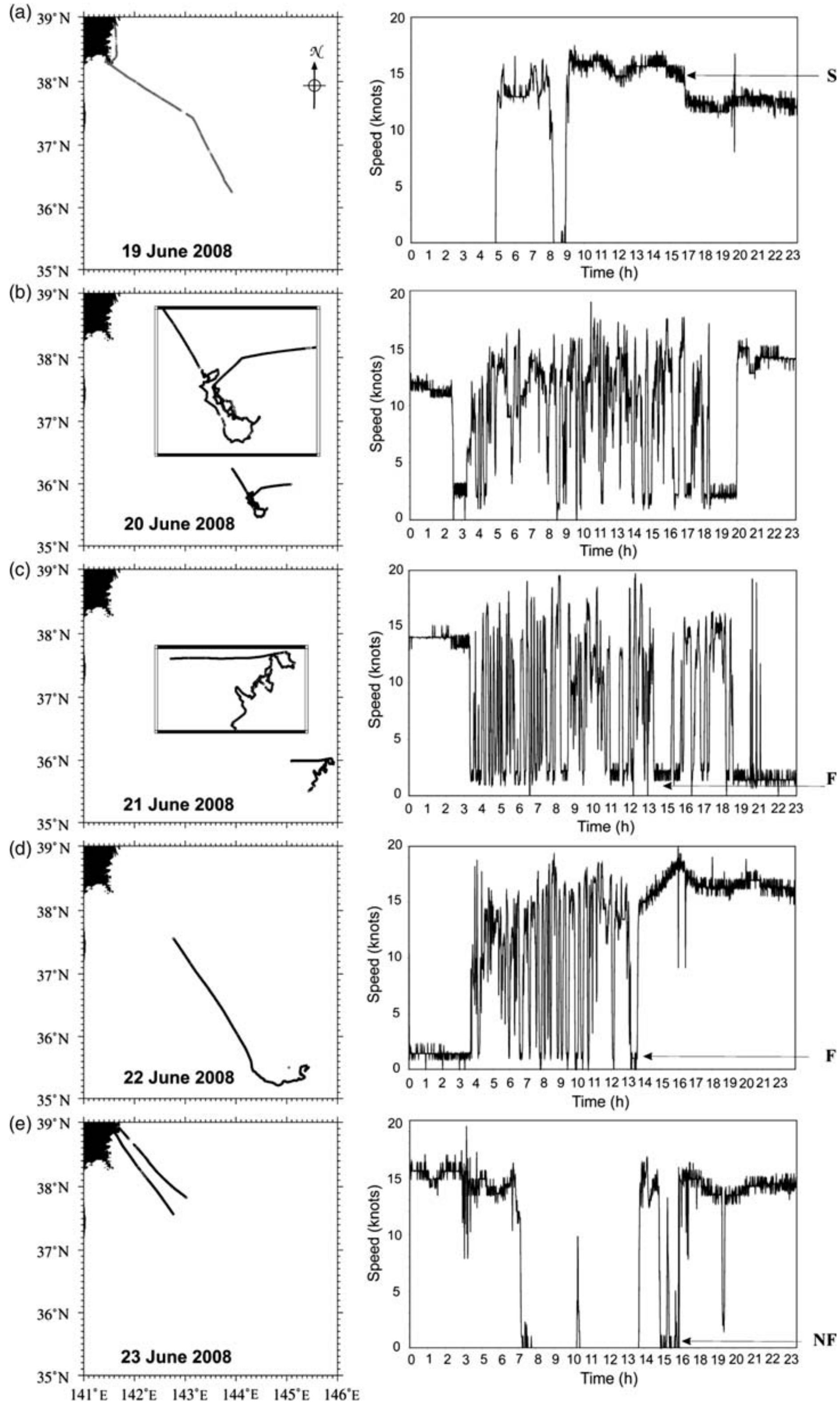

Figure 3. Daily trajectories (left) and associated speed graphs (right) for a complete pole-and-line skipjack fishing trip over the period 19–23 June 2008. The spatial pattern and speed activity are useful in distinguishing fishing (F) from non-fishing (NF) activity. Panels (b) and (c) contain magnified inset maps to illustrate the course clearly.

time to improve fishery forecasts. The data can be used in various ways to augment information normally not available in fishing logbooks. For example, VMS data can be used to identify areas that were traversed, but not fished, accordingly allowing investigations to determine how these differ from selected fishing grounds.

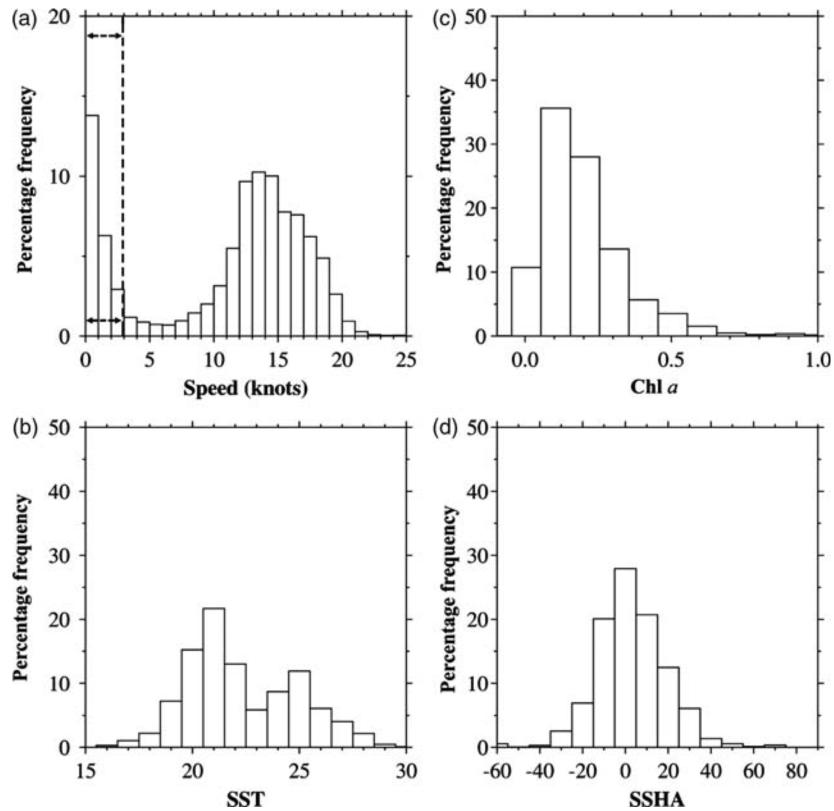

Figure 4. Histograms of (a) vessel speed (b) SST, (c) Chl *a*, and (d) SSHA determined from VMS-derived fishing locations. The range of speeds used in the speed filter to determine fishing activity is illustrated in (a).

Independent and automated feedback from fishing vessels is vital to monitoring fishing effort or improving fishing efficiency. We conclude that the simultaneous use of VMS and SRS information can provide a detailed account of the activities of a vessel fishing skipjack tuna. VMS can also aid in fine-tuning pelagic fishery forecasting models by including information on how fishing vessel skippers select fishing grounds relative to remotely sensed oceanographic data. Another potential application is as an educational tool for transferring fishing skills and knowledge from experienced to new captains.

Climate change and scallop aquaculture

The Japanese scallop is the most successful marine shellfish farming venture in Japan (Bourne, 2000). Currently, >40% of Japanese scallop production is from aquaculture (FAO, 2007). Changes in water temperature will affect the timing and levels of productivity across coastal and marine systems (Walther *et al.*, 2002; Beukema and Dekker, 2005; Harley *et al.*, 2006). The sustainability of scallop aquaculture can be influenced by environmental change associated with climate warming, threatening optimum grow-out temperatures, and the weather.

Suitable sites for scallop aquaculture changed considerably relative to the original model of site suitability after application of the IPCC scenarios (Figure 5). An SST increase of 1°C resulted in relatively little change to suitability scores (Table 1), but increases of 2 and 4°C decreased the most suitable area (score 8) by 52 and 100%, respectively. There were concurrent increases in less suitable areas; for example, areas scoring 7 increased from 28 to 35 and to 41% of the total area with 2 and 4°C increases, respectively. Changes were distributed more or less evenly over the region (Figure 5). These results suggest that climate change could influence the development of scallop aquaculture through changes in site suitability, so should be considered in planning, for example, shellfish breeding programmes designed to increase the temperature tolerance of cultured species.

Handisyde *et al.* (2006) analysed the effects of climate change on world aquaculture from a global perspective and suggested that additional specific case studies (such as presented here) will contribute greatly towards understanding how climate change could influence aquaculture resources. Another example was provided by Baba *et al.* (2009), who described the effect of climate variability, especially the direct influence of *El Niño* and *La Niña*, on scallop aquaculture. GIS-based models on the impact of climate change on Japanese scallop aquaculture demonstrate that climate change is likely to have varying impacts on scallop aquaculture. Clearly, the potential impacts of climate change on shellfish aquaculture need more investigation to help ensure the sustainability of marine aquaculture development.

New challenges of fisheries information systems and future perspectives

SRS imagery for parameters such as SST, Chl *a*, and SSHA reveal oceanic phenomena at synoptic scales. GIS applications have also been instrumental in integrating and analysing SRS information in fisheries science (Meaden, 2009). However, GIS was initially

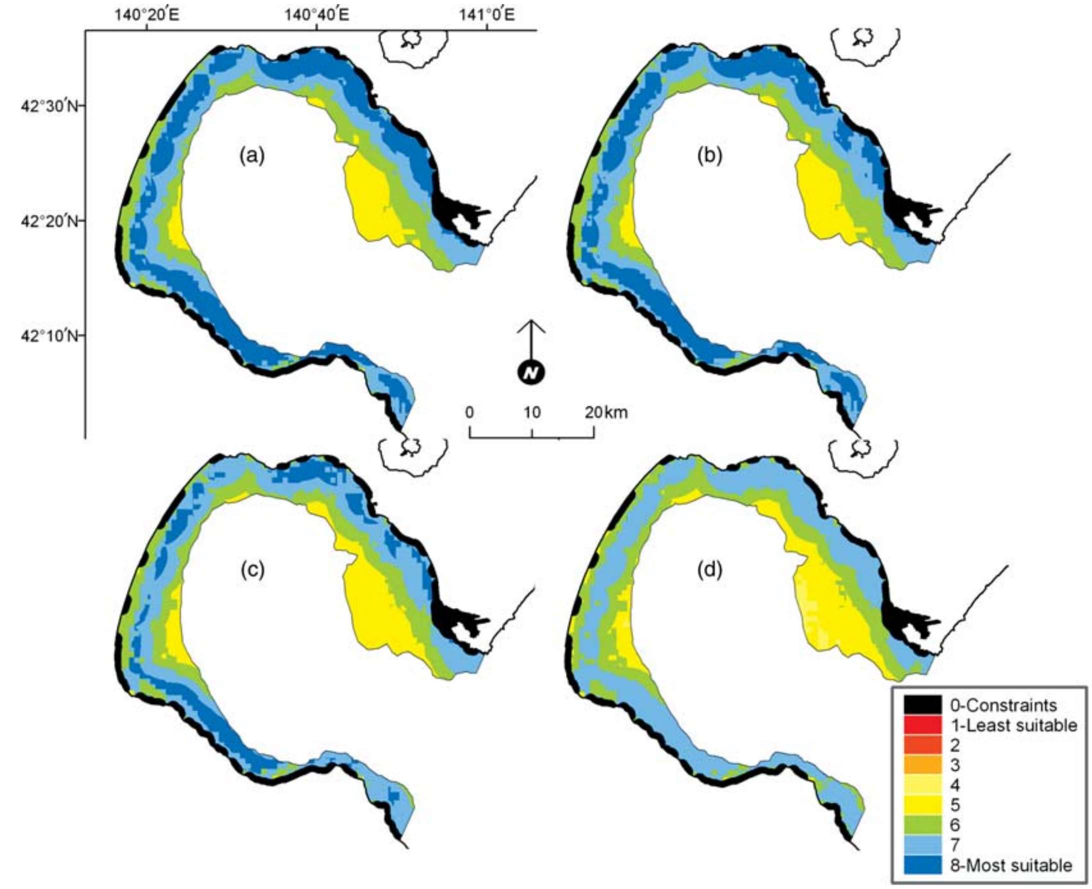

Figure 5. Overall site-selection maps for (a) the original model, and SST increases of (b) 1°C, (c) 2°C, and (d) 4°C. All maps are masked to depths <60 m, which are optimum for Japanese scallop aquaculture in Funka Bay. Constraints mean the restrictions limiting the alternative under consideration, e.g. harbours, towns/industrial areas, and river mouths.

Table 1. Modelled changes in suitability scores (percentage of the total potential area), resulting from three scenarios of SST increase, for Japanese scallop aquaculture potential in Funka Bay.

	Suitability score								
Model	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Original	12.00	0.00	0.00	0.00	0.01	10.89	20.10	28.00	29.00
+1°C	12.00	0.00	0.00	0.00	0.01	11.00	20.60	30.00	26.39
+2°C	12.00	0.00	0.00	0.00	0.01	16.09	23.00	34.90	14.00
+4°C	12.00	0.00	0.00	0.00	2.40	17.90	26.69	41.00	0.01

The total potential area (<60 m deep) is 1038 km^2.

developed for terrestrial data where two-dimensional representations are adequate. Consequently, they are limited in representing the dynamic boundaries and three-dimensional structure of ocean features and marine habitats (Carette *et al.*, 2008). Assimilation of observational data into ocean general circulation models will play a critical role in moving towards three-dimensional representations (Awaji *et al.*, 2003). Our future research directions include the development of an integrated coastal fisheries information system (Figure 6), making use of an array of oceanographic datasets from satellites and *in situ* measurements. In addition, it is intended to further a four-dimensional, variational (4D-VAR) data-assimilation model (Broquet *et al.*, 2009; Ishikawa *et al.*, 2009) capable of generating the integrated products required by fisheries and aquaculture using an optimal synthesis of observational data, an ocean circulation model, and the NEMURO ecological model (Kishi *et al.*, 2007). The system is also expected to include a forecasting and information dissemination component (http://innova01.fish.hokudai.ac.jp/marinegis/).

Dissemination of information to users in real or near real time will be an area of innovation in the next few years (Aguilar-Manjarrez *et al.*, 2010). The continuing miniaturization of communication devices and the low cost of transmitting large quantities of information make it increasingly practical to deliver oceanographic information as value-added, custom-made products. Web-based platforms such as Google Earth/Ocean could be instrumental in advancing this process (Carocci *et al.*, 2009; Aguilar-Manjarrez *et al.*, 2010). In fisheries science, products such as fishing ground updates, site suitability for aquaculture facilities, and safety information will form part of the product package. Improved prediction and validation of oceanographic SRS parameters (SST, chlorophyll) for specific applications will also form a key research area (Saitoh *et al.*, 2009, 2010). Clearly, SRS data have made notable contributions to operational fisheries oceanography. The wealth of information that is continuing to accumulate from satellites is vital for research, monitoring, and management of marine fisheries, as well as supporting the sustainability of aquaculture systems.

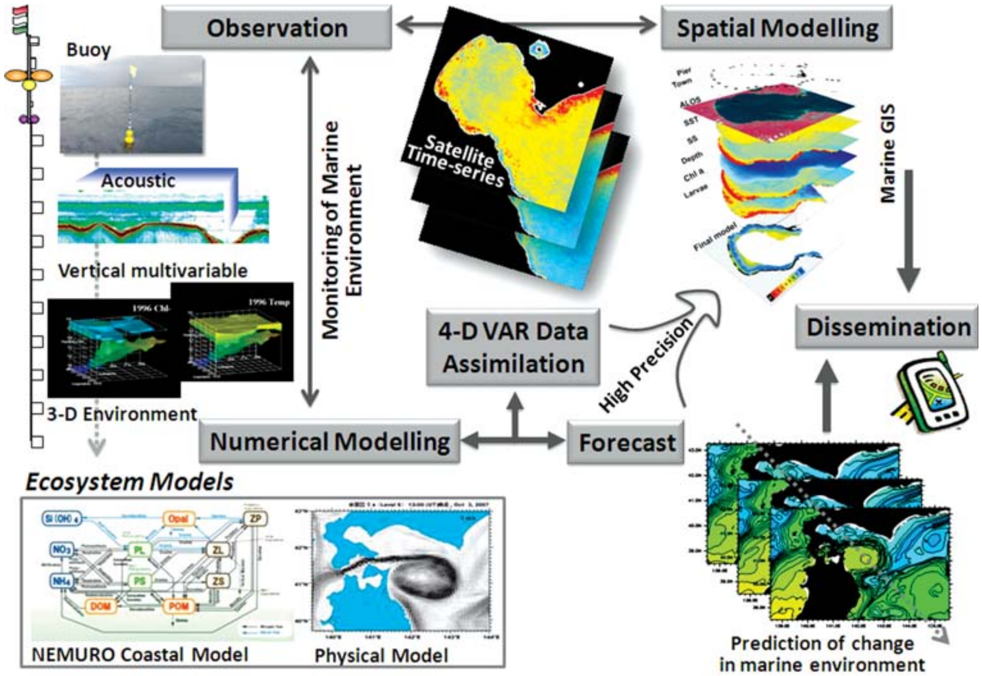

Figure 6. Conceptual framework for an integrated coastal fisheries information system. The key components of the system are (i) observation or data acquisition (*in situ* and satellite data), (ii) utilization of data in numerical/spatial models, and (iii) forecasting and dissemination of operational products responsive to societal needs.

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References

Aguilar-Manjarrez, J., Kapetsky, J. M., and Soto, D. 2010. The potential of spatial planning tools to support the ecosystem approach to aquaculture. Expert Workshop, 19–21 November 2008, Rome, Italy. FAO Fisheries and Aquaculture Proceedings, 17. 176 pp.

Awaji, T., Msuda, S., Ishikawa, Y., Sugiura, N., Toyoda, T., and Nakamura, T. 2003. State estimation of the North Pacific Ocean by a four-dimensional variational data assimilation experiment. Journal of Oceanography, 59: 931–943.

Baba, K., Sugawara, R., Nitta, H., Endou, K., and Miyazono, A. 2009. Relationship between spat density, food availability, and growth of spawners in cultured *Mizuhopecten yessoensis* in Funka Bay: concurrence with ENSO. Canadian Journal of Fisheries and Aquatic Sciences, 66: 6–17.

Bakun, A. 2006. Fronts and eddies as key structures in the habitat of marine fish larvae: opportunity, adaptive response and competitive advantage. Scientia Marina, 70: 105–122.

Barale, V., Gower, J. F. R., and Alberotanza, L. (eds). 2010. Oceanography from Space Revisited. Springer, New York. 361 pp.

Beukema, J. J., and Dekker, R. 2005. Decline of recruitment success in cockles and other bivalves in the Wadden Sea: possible role of climate change, predation on postlarvae and fisheries. Marine Ecology Progress Series, 287: 149–167.

Bourne, N. F. 2000. The potential for scallop culture—the next millennium. Aquaculture International, 8: 113–122.

Brody, M., and Hlohowskyj, I. 1998. Fisheries. *In* Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies, pp. 1–37. Ed. by J. F. Feenstra, I. Burton, J. B. Smith, and R. S. J. Tol. UNEP, Nairobi. 464 pp.

Broquet, G., Edwards, C. A., Moore, A. M., Powell, B. S., Veneziani, M., and Doyle, J. D. 2009. Application of 4D-Variational data assimilation to the California Current System. Dynamics of Atmospheres and Oceans, 48: 69–92.

Carette, V., Mostafavi, M. A., and Devillers, R. 2008. Towards marine geographic information systems: multidimensional representation of fish aggregations and their spatiotemporal evolutions. Oceans, 8: 1–10.

Carocci, F., Bianchi, G., Eastwood, P., and Meaden, G. J. 2009. Geographic information systems to support the ecosystem approach to fisheries. FAO Fisheries and Aquaculture Technical Paper, 532. 120 pp.

de Oliveira, F. S. C., Gherardi, D. F. M., and Stech, J. L. 2010. The relationship between multi-sensor satellite data and Bayesian estimates for skipjack tuna catches in the South Brazil Bight. International Journal of Remote Sensing, 31: 4049–4067.

Deng, R., Dichmont, C., Milton, D., Haywood, M., Vance, D., Hall, N., and Die, D. 2005. Can vessel monitoring system data also be used to study trawling intensity and population depletion? The example of Australia's northern prawn fishery. Canadian Journal of Fisheries and Aquatic Sciences, 62: 611–622.

Dewar, H., Thys, T., Teo, S. L. H., Farwell, C., O'Sullivan, J., Tobayama, T., Soichi, M., *et al.* 2010. Satellite tracking the world's largest jelly predator, the ocean sunfish, *Mola mola*, in the western Pacific. Journal of Experimental Marine Biology and Ecology, 393: 32–42.

FAO. 1988. Fishing operations: vessel monitoring systems. FAO Technical Guidelines for Responsible Fisheries, 1(Suppl. 1). FAO, Rome. 58 pp.

FAO. 2007. Global aquaculture and capture fisheries production. http://www.fao.org/fi/website/FIRetrieveAction.do?dom=topic&fid=16140 (last accessed 12 December 2007).

FAO. 2009. The State of World Fisheries and Aquaculture, 2008. FAO, Rome. 196 pp.

Fonteneau, A., Lucas, V., Tewkai, E., Delgado, A., and Demarcq, H. 2009. Mesoscale exploitation of a major tuna concentration in the Indian Ocean. Aquatic Living Resources, 21: 109–121.

Handisyde, N. T., Ross, L. G., Badjeck, M-C., and Allison, E. H. 2006. The effects of climate change on world aquaculture: a global perspective. www.aquacultur.stir.ac.uk/GISAP/gis-group/climate.php.

Harley, C. D. G., Hughes, A. R., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thornber, C. S., Rodriguez, L. F., *et al.* 2006. The impact of climate change in coastal marine systems. Ecology Letters, 9: 228–241.

Hartog, J. R., Hobday, A. J., Matear, R., and Feng, M. 2010. Habitat overlap between southern bluefin tuna and yellowfin tuna in the east coast longline fishery – implications for present and future spatial management. Deep Sea Research II, doi:10.1016/j.dsr2.2010.06.005.

Hobday, A. J., and Hartmann, K. 2006. Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Management and Ecology, 13: 365–380.

Howell, A. E., Kobayashi, D. R., Parker, D. M., Balazs, G. H., and Polovina, J. J. 2008. TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. Endangered Species Research, 5: 267–278.

IOCCG. 2009. Remote sensing in fisheries and aquaculture. Reports and Monographs of the International Ocean-Colour Coordinating Group, 8. Ed. by M-H. Forget, V. Stuart, and T. Platt. IOCCG, Dartmouth, Canada. 120 pp.

IPCC. 2007. Summary for policymakers. *In* Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change, pp. 1–18. Ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, *et al.* Cambridge University Press, Cambridge, UK. 1008 pp.

Ishikawa, Y., Awaji, T., Toyoda, T., In, T., Nishina, K., Nakayama, T., Shima, S., *et al.* 2009. High-resolution synthetic monitoring by a 4-dimensional variational data assimilation system in the northwestern North Pacific. Journal of Marine Systems, 78: 237–248.

Kishi, M. J., Kashiwai, M., Ware, D. M., Megrey, B. A., Eslingerf, D. L., Werner, F. E., Noguchi-Aitab, M., *et al.* 2007. NEMURO—a lower trophic level model for the North Pacific marine ecosystem. Ecological Modelling, 202: 12–25.

Kiyofuji, H., Takahashi, F., Tachikawa, D., Abe, M., Tateyama, K., Hiraki, M., and Saitoh, S-I. 2007. A ubiquitous information system for the offshore fisheries activities around Japan. *In* GIS/Spatial Analysis in Fishery and Aquatic Sciences, 3, pp. 313–324. Ed. by T. Nishida, P. J. Kailola, and A. Caton. Fishery-Aquatic GIS Research Group, Saitama, Japan. 488 pp.

Kobayashi, D. R., Cheng, I-J., Parker, D. M., Polovina, J. J., Kamezaki, N., and Balazs, G. H. 2011. Loggerhead turtle (*Caretta caretta*) movement off the coast of Taiwan: characterization of a hotspot in the East China Sea and investigation of mesoscale eddies. ICES Journal of Marine Science, 68: 707–718.

Lee, J., South, A. B., and Jennings, S. 2010. Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. ICES Journal of Marine Science, 67: 1260–1271.

Lehodey, P., Adre, J. M., Bertignac, M., Hampton, J., Stoens, A., Menkes, C., Memery, L., *et al.* 1998. Predicting skipjack tuna forage distributions in the equatorial Pacific using a coupled dynamical bio-geochemical model. Fisheries Oceanography, 7: 317–325.

Majkowski, J. 2010. Fishing techniques: tuna pole and line fishing. FAO Fisheries and Aquaculture Department, Rome. http://www.fao.org/fishery/fishtech/30/en (updated 19 September 2003 and last accessed 15 April 2010).

Meaden, G. 2009. Geographic information systems (GIS) in fisheries management and research. *In* Computers in Fisheries Research, 2nd edn, pp. 93–120. Ed. by B. A. Megrey, and E. Moksness. Springer, Heidelberg. 421 pp.

Mills, C., Rogers, S. I., Tasker, M. L., Eastwood, P. D., and Piet, G. J. 2004. Developing the use of satellite fishing vessel monitoring system data in spatial management. ICES Document CM 2004/Y: 05. 13 pp.

Mills, C. M., Townsend, S. E., Jennings, S., Eastwood, P. D., and Houghton, C. A. 2007. Estimating high resolution trawl fishing effort from satellite-based vessel monitoring system data. ICES Journal of Marine Science, 64: 248–255.

Miyake, M. P., Miyabe, N., and Nakano, H. 2004. Historical trends of tuna catches in the world. FAO Fisheries Technical Paper, 467. 74 pp.

Mugo, R., Saitoh, S., Nihira, A., and Kuroyama, T. 2010. Habitat characteristics of skipjack tuna (*Katsuwonus pelamis*) in the western North Pacific: a remote sensing perspective. Fisheries Oceanography, 19: 382–396.

Mullowney, D. R., and Dawe, E. G. 2009. Development of performance indices for the Newfoundland and Labrador snow crab (*Chionoecetes opilio*) fishery using data from a vessel monitoring system. Fisheries Research, 100: 248–254.

Olson, D. B. 1991. Rings in the ocean. Annual Review of Earth and Planetary Sciences, 19: 283–311.

Palmer, M. C., and Wigley, S. E. 2009. Using positional data from vessel monitoring systems to validate the logbook reported area fished and the stock allocation of commercial fisheries landings. North American Journal of Fisheries Management, 29: 928–942.

Perry, A. L., Low, P. J., Ellis, J. R., and Reynolds, J. D. 2005. Climate change and distribution shift in marine fishes. Science, 308: 1912–1915.

Petit, M., Dagorn, L., Lena, P., Slepoukha, M., Ramos, A. G., and Stretta, J. M. 1994. Oceanic landscape concept and operational fisheries oceanography. Mémoires de l'Institut Océanographique, 18: 85–97.

Pinardi, N., and Coppini, G. 2010. Operational oceanography in the Mediterranean Sea: the second stage of development. Ocean Science, 6: 263–267.

Radiarta, I. N., Saitoh, S-I., and Miyazono, A. 2008. GIS-based multicriteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan. Aquaculture, 284: 127–135.

Saitoh, S-I., Chassot, E., Dwivedi, R., Fonteneau, A., Kiyofuji, H., Kumari, B., Kuno, M., *et al.* 2009. Remote sensing applications to fish harvesting. *In* Remote Sensing in Fisheries and Aquaculture, pp. 57–76. Ed. by M-H. Forget, V. Stuart, and T. Platt. IOCCG Report 8. IOCCG, Dartmouth, Canada.

Saitoh, S-I., Hirawake, T., Radiarta, I. N., Isada, T., Mugo, R., Takahashi, F., Imai, I., *et al.* 2010. New challenge of integrated coastal fisheries information system in southern Hokkaido, Japan. *In* North Pacific Ecosystems Today, and Challenges in Understanding and Forecasting Change, p. 164. North Pacific Marine Science Organization, PICES–2010, Program and Abstracts, 22–31 October 2010, Portland, OR, USA. 313 pp.

Santos, A. M. P. 2000. Fisheries oceanography using satellite and airborne remote sensing methods: a review. Fisheries Research, 49: 1–20.

Simpson, J. J. 1992. Remote sensing and geographical information systems: their past, present and future use in global marine fisheries. Fisheries Oceanography, 1: 238–280.

Simpson, J. J. 1993. A conceptual framework for the operational fisheries oceanography community. CalCOFI Reports, 34: 51–57.

Solanki, H. U., Prakash, P., Dwivedi, R. M., Nayak, S., Kulkarni, A., and Somvamshi, V. S. 2010. Synergistic application of oceanographic variables from multi-satellite sensors for forecasting potential fishing zones: methodology and validation results. International Journal of Remote Sensing, 31: 775–789.

Teo, S. L. H., and Block, B. A. 2010. Comparative influence of ocean conditions on yellowfin and Atlantic bluefin tuna catch from longlines in the Gulf of Mexico. PLoS One, 5: e10756. doi:10.1371/journal.pone.0010756

Teo, S. L. H., Boustany, A., Dewar, H., Stokesbury, M. J. W., Weng, K. C., Beemer, S., Seitz, A. C., *et al.* 2007. Annual migrations, diving behavior, and thermal biology of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Marine Biology, 151: 1–18.

Valavanis, D. V., Pierce, G. J., Zuur, A. F., Palialexis, A., Saveliev, A., Katara, I., and Wang, J. 2008. Modelling of essential fish habitat based on remote sensing, spatial analysis and GIS. Hydrobiologia, 612: 5–20.

Walther, G-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J-M., *et al.* 2002. Ecological responses to recent climate change. Nature, 416: 389–395.

Weng, K. C., Stokesbury, M. J. W., Boustany, A. M., Seitz, A. C., Teo, S. L. H., Miller, S. K., and Block, B. A. 2009. Habitat and behaviour of yellowfin tuna *Thunnus albacares* in the Gulf of Mexico determined using pop-up satellite archival tags. Journal of Fish Biology, 74: 1434–1449.

Wild, A., and Hampton, J. 1993. A review of the biology and fisheries for skipjack tuna, *Katsuwonus pelamis*, in the Pacific Ocean. *In* Interactions of Pacific Tuna Fisheries. Proceedings of the first FAO Expert Consultation on Interactions of Pacific Tuna Fisheries, Noumea, New Caledonia, pp. 1–51. Ed. by R. S. Shomura, J. Majkowski, and S. Langi. FAO Fisheries Technical Paper, 336.

Witt, J. M., and Godley, B. J. 2007. A step towards seascape scale conservation: using vessel monitoring systems (VMS) to map fishing activity. PLoS One, 2: e1111. doi: 10.1371/journal.pone.0001111

Zagaglia, C. R., Lorenzzetti, J. A., and Stech, J. L. 2004. Remote sensing data and longline catches of yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic. Remote Sensing of Environment, 93: 267–281.

Zainuddin, M., Saitoh, K., and Saitoh, S. I. 2008. Albacore (*Thunnus alalunga*) fishing ground in relation to oceanographic conditions in the western North Pacific Ocean using remotely sensed satellite data. Fisheries Oceanography, 17: 61–63.