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African lake management initiatives: The global connection

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Abstract

There is a global dimension to lake management in Africa and elsewhere that will require a concerted action not only from individual riparian states, but also from regional, continental and global communities. The current global lake threats arise from climate change, regional land degradation and semivolatile contaminants, and share the common feature that the atmosphere is the vector that spreads their impacts over large areas and to many lakes. The Great Lakes of Africa (Malawi, Victoria and Tanganyika) are particularly sensitive to these problems because of their enormous surface areas, slow water flushing rates, and the importance of direct rainfall in their water budgets. Their response times might be slow to yield a detectable change and, unfortunately, their recovery times might also be slow. It is possible for atmospheric effects to act antagonistically to the impacts of catchment change, but antagonistic effects could become synergistic in the future. Improved understanding of the physical dynamics of these lakes, and development of models linking their physical and biogeochemical behaviour to regional, mesoscale climate models, will be necessary to guide lake managers.

Key words

African Great Lakes, climate change, Global Environment Facility, Lake Malawi, Lake Tanganyika, Lake Victoria, mercury, nutrient loading, organochlorines.

INTRODUCTION

All African lakes, large and small, have great significance to their riparian populations, and the nations within which they occur, for providing protein from fisheries, water for agricultural, domestic and drinking use, transportation for commerce, and recreational use. The three largest lakes in Africa: Victoria, Tanganyika and Malawi/Nyasa (the latter hereafter referred to as Malawi), offer similar benefits, and their very size certainly amplifies the numbers of people, and the number of countries, depending on them for beneficial uses. The Lake Victoria catchment is inhabited by ~ 30 million people living in five countries, and the lake also exports critical quantities of water downstream to the Nile River, as well as fish to a global market. The other two lakes are shared by three (Malawi) and five (Tanganyika) countries, being the headwater lakes to the Zambezi and Congo Rivers, respectively, whose outflows sustain downstream benefits to many other users outside their catchments. These three great lakes also have evolved remarkable endemic biodiversity, with nearly 10% of all the planet's freshwater fish species inhabiting these lakes, making them globally significant gene banks. Lakes everywhere, including great lakes, come under stress as human populations and economies in their catchments increase. However, the multinational distribution of ecosystem benefits, and the potential losses of such benefits if the lakes are degraded, places these great African lakes in a class of their own in regard to their management challenges. In recognition of the international scope of the management challenge posed by these great lakes, and the global benefits they provide, the Global Environmental Facility (GEF), and its national and international funding partners, has funded extensive studies and analyses of these lake ecosystems, ranging through the mid- to late-1990s and extending to the present time.

The achievements and shortcomings of these GEF projects are reviewed in case studies presented in the Lake Basin Management Initiative. In aggregate, those studies and other studies around the world have revealed that some challenges to successful management of these great lakes extend beyond their catchments, and that regional or even global action will be necessary to maintain or restore

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many of the lakes' beneficial uses. Smaller lakes are likely also being impacted by these same regional and global scale threats, although other more immediate impacts might be of greater concern at present. The thesis of this paper is that there is a global dimension to lake management in Africa and elsewhere that will require concerted action not only from individual riparian states, but also from regional, continental and global communities. Current lake threats arise from global climate change, land degradation and contaminants, and they share the common feature that the atmosphere is the vector spreading their impacts over large areas and to many lakes.

HYDROLOGICAL SENSITIVITIES

The African Great Lakes occupy a large proportion of their catchments. Their huge surface area allows precipitation (P) directly on their water surface, and evaporation (E) from their surface, to dominate the gains and losses in their water budgets (Table 1). This is true of the deep Rift Valley lakes, as well as the shallower Lake Victoria, which occupies a depression between uplifted highlands bordering the rift valleys. Unlike Lake Victoria, however, the deeper lakes are permanently stratified, resulting in accumulation of high nutrient concentrations in their slightly cooler and anoxic deep waters (Bootsma & Hecky 1993). Direct rainfall accounts for >50% of all water inputs for all three lakes, with Lake Victoria being the most extreme because inflowing rivers (I) account for only 15% of its total water input. In terms of the water budget, E is the greatest water loss, with river outflow (O) accounting for 15% or less of its total water loss in Victoria. Maintenance of the lakes as open drainage basins, however, is dependent on their river inputs, as the P/E balance over the lake surface area is negative for the two deep lakes, and just in balance for Lake Victoria.

Table 1. Morphometric and hydrological data for Africa's three largest lakes (after Bootsma & Hecky 1993)

	Malawi	Tanganyika	Victoria
Catchment area (km^2)	100 500	220 000	195 000
Lake area (km^2)	28 000	32 600	68 800
Maximum depth (m)	700	1 470	70
Mean depth (m)	292	580	40
Volume (km^3)	8 400	18 900	2 760
Outflow (O) (km^3 year^{-1})	11	2.7	20
Inflow (I) (km^3 year^{-1})	29	14	20
Precipitation (P) (km^3 year^{-1})	39	29	100
Evaporation (E) (km^3 year^{-1})	55	44	100
Flushing time (V/O) (year)	750	7 000	140
Residence time (V/(P + I)) (year)	140	440	23

Rainfall in eastern Africa is relatively low over most of the terrestrial catchments of these lakes, although the lakes themselves generate higher rainfall over the lakes than the average rainfall over the catchment (Nicholson & Yin 2002). Evaporation is highly sensitive to still poorly known over-lake wind regimes. The most recent estimates of evaporation over the lake are higher than the published values, largely because of better definition of diurnal and offshore wind regimes (Hamblin *et al.* 2002; Verburg & Hecky 2003). The water-level history of these lakes, as recorded for the past century (Fig. 1) and inferred from historical accounts over the previous century, indicates that the water balance of the lakes can be very dynamic. Lake Malawi was a closed basin from 1915 to 1930 (and nearly again in the late 1990s), Lake Tanganyika was closed when the Lukuga outlet was first observed by Europeans, and Lake Victoria had its highest documented water level at about the same time in the early 1880s (Nicholson 1998). The variability of lake levels is even more dramatic over longer periods, with Lake Victoria desiccating ca 12 000 years ago (Johnson *et al.* 1996). Lake Tanganyika (Haberyan & Hecky 1987) also had much lower levels, and many smaller lakes in eastern Africa had low water stands or were also desiccated. Grove *et al.* (1996) previously commented on two apparent synchronies in the level records of these three large lakes: (i) the very high stands of the early 1960s (a period of record high rainfall in eastern Africa), and (ii) declining levels (and associated river discharges) since the 1980s. Both Lakes Tanganyika and Malawi have returned to their pre-1960s water levels, although Lake Victoria has not. The persistence of Lake Victoria at higher than the 1960 levels is still anomalous, although it has engendered optimism that the lake has found a new long-term water level that can be harvested for increased hydroelectric generation at the Owen Falls generating stations at its outlet. It is hoped that this optimism is well founded.

CLIMATE CHANGE

The water level records of the three lakes over decades, centuries and millennia indicate that the lakes respond sensitively to changes in rainfall and evaporation. Even in their modern condition, they are barely open lakes, with flushing times of >100 years for Lake Victoria, to >7000 years for Lake Tanganyika (Bootsma & Hecky 1993). When they fall below their outlet, they will decrease to a level where evaporative losses are balanced by water inputs, making the lakes very sensitive recorders of P/E over geological time. The lakes can also be affected, however, by changes in their surface heat budget, even when levels are relatively constant. Verburg *et al.* (2003) have recently shown that Lake Tanganyika has been warming through the last century, and at relatively high rates since 1980, in response to globally (and regionally) rising air temperatures. As water density change per degree of warming increases rapidly as temperatures rise, small temperature changes in tropical lakes can result in significant changes in the stability of thermal stratification (Hecky 2000). As Lake Tanganyika does not mix throughout its depths annually, its upper waters have warmed more rapidly than its deep waters, with the result that the density stratification of the lake has been strengthened, with the interchange with the deeper metalimnion and hypolimnion having been slowed. This might have resulted in reduced internal nutrient loadings from the deeper waters and decreasing primary productivity in the lake (Verburg *et al.* 2003). O'Reilly *et al.* (2003) also suggest that this might have resulted in reduced fish production in Lake Tanganyika, although Sarvala *et al.* (2006) disagree that fish production decreased during this period of warming.

Vollmer *et al.* (2005) have also documented the rising temperatures over the last 60 years in Lake Malawi, as well as the measured reduced ventilation of the deep waters since 1980 (Vollmer *et al.* 2002). As the internal nutrient loading is a significant source of silicon and phosphorus, two critical plant nutrients (Bootsma *et al.* 2003), Lake Malawi would have reduced the internal loading of these nutrients for over the past 20 years. Lake Victoria also had warmer deep-water temperatures in its seasonal hypolimnion in the 1990s, relative to those temperatures in the 1960s (Hecky *et al.* 1994). Its more stable stratification at present, compared to 1960 (Hecky 1993), could partly be a consequence of warmer air temperatures and reduced nocturnal cooling. However, changing wind strengths might also affect Lake Victoria, which still mixes throughout its depths in July and August. Lorke *et al.* (2004) found that the recent lava flows in 2002 into Lake Kivu did have a local effect on water temperatures down to 100 m, but had lesser effect on the water column structure than on the climatic warming over the last three decades that increased the water temperature by 0.5°C in the upper 250 m. Across all the African Great Lakes for which historical data are available, there is clear evidence for climate warming over the past few decades and longer.

Meteorological events, especially the periods of high rainfall and river inflows, could affect the deep-water ventilation in Lake Malawi (Vollmer *et al.* 2005) and other deep tropical lakes. Many of the inflowing rivers entering the northern end of Lake Malawi plunge below the warm epilimnion because they are cooler and more turbid than the mixed layer. The cooler river plumes plunge to depths determined by their densities (Bootsma *et al.* 2003), and can potentially plunge below the depth of annual mixing (≈110 m), dispersing into the large volumes of the metalimnion and hypolimnion and cooling the deep waters. These deeper, cooler water layers subsequently slowly exchange with upper warmer water layers, and the incoming nutrient loads might not affect the mixed water layer for decades (Vollmer *et al.* 2002). Thus, the sediment and nutrient loads carried by these rivers might bypass the mixed layer with little effect. In southern Lake Malawi, the plunging is confined by the shallower bottom depths, thereby remaining above the depth of annual mixing, with the fluvially transported loads being available to affect surface waters during annual mixing. Similarly, riverine loads enter into shallow water in shallow Lake Victoria, and the lake mixes throughout its depth annually. Thus, the incoming loads do affect the water quality of the whole lake on an annual basis.

A warming climate, such as the one that occurred over the past century in eastern Africa, will warm rivers more rapidly than the deep waters of Lakes Tanganyika and Malawi, and might have reduced the cooling effect from these plunging rivers, thereby contributing to the warming

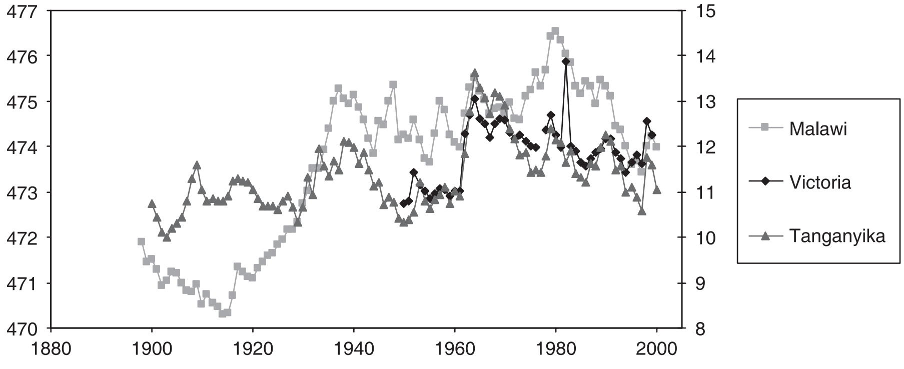

Fig. 1. Annual mean water levels for the African Great Lakes (expressed in m a.s.l.), relative to Lake Malawi elevations (left-hand axis) or Lake Victoria datum (right-hand axis) to allow direct comparison of interannual variation.

trends in the lakes' hypolimnions (Vollmer *et al.* 2005). The potential climatic effects on lake behaviour, including the distribution of incoming nutrient loads, are complex, and cannot be adequately modelled at present because of a lack of data, especially on river temperatures and material loads. The lakes are warming, however, with the full consequences yet undefined. The reduced internal circulation, as measured in Lake Malawi, and inferred for Lake Tanganyika, could reduce the internal nutrient loading, offsetting increases in the external loading from rivers and the atmosphere. Although this would be a positive benefit that ameliorates cultural eutrophication, it could also mask the evolving problems in the catchments if they are adding more nutrients than they did historically (Hecky *et al.* 2003). A future reduction in the warming trend would allow deep-water temperatures to increase, relative to the mixed layer, eventually resulting in rapidly increasing nutrient loadings if cultural eutrophication is neglected. As a result of the slow response rates of these lakes to changes in heat fluxes and nutrient inputs, it is important that the implications of these changes are understood before their impacts are fully manifested, because the lakes' response rates to mitigation also will be slow (Bootsma & Hecky 1993). Managing the nutrient loading of these large systems is only partially controllable through managing their external loads. Global climate change, and dependent changes in internal loading, can certainly delay the response of the lakes to catchment management, as well as potentially overwhelm and reverse positive trends in the external nutrient loading. The challenge is aggravated by the current projections that climate warming over the next century in the tropics will be three to five times greater than that observed over the last century (Hulme *et al.* 2001).

NUTRIENT LOADING

The rapidly growing human populations in eastern Africa require increased agricultural production, with this production increasingly encompassing marginal lands and increased elevations and slopes. It is well known that the transformation of land from forest or natural continuous savanna to grazed grasslands and tilled agriculture increases water and sediment yields from the land surface into waterways (Sundborg & Rapp 1986). Basin-scale estimates of the impacts of land clearance and changing land uses are less common. Hecky *et al.* (2003) compared forested catchments with extensively cultivated catchments, concluding that the nutrient yields increased six to ninefold, and the sediment yields from 10- to 40-fold, depending on catchment slopes over predisturbance yields. Land use, topography, soils and hydrology interact to determine the watershed export, and these aspects can be modelled to predict future changes in land uses, or to guide landscape restoration to reduce the nutrient loading (e.g. Lam *et al.* 2002). The sediment and nutrient yields at the basin scale represent costly depletions of natural soil capital that ultimately reduce farmers' yields. This negative effect at the farm scale can provide the motivation to undertake lake basin management initiatives to improve farming practices and maintain soil fertility and crop productivity, while also reducing losses of soil and nutrients downstream where there are negative impacts on receiving waters.

Tropical Africa has the highest rate of biomass burning in the world, being especially high in savanna areas (Hao & Liu 1994). Agricultural practices in Africa are very dependent on fire to clear the land, regenerate nutrients from agricultural debris and on grazing lands, and to control pests. Fire is also heavily used for domestic heating and cooking. Fire mobilizes fine ash and volatile elements into the atmosphere, where these materials can travel widely. Ash from such fires is rich in phosphorus (Lewis 1981), which is often the limiting nutrient for plant growth in lakes and on land. Fires export nutrients from the burned lands and transport them down-wind, and frequently into lakes. Recent studies suggest the nutrients' possible transport over hundreds and even thousands of miles (Jickells *et al.* 1998), although the highest deposition rates in wild fires and windstorms could be closer to the source fire, as the coarser ash will be removed more rapidly from the atmosphere. In the planting season, the soil surface is exposed to wind erosion after clearing and tilling, with exposed soils being a source of fine soil and ash particles to the atmosphere until a vegetation cover is re-established after the rains commence (Bootsma *et al.* 1996). Measurements in eastern Africa on Lake Malawi and around Lake Victoria indicate that the phosphorus deposition rates in rain and dry fall are among the highest that have been measured (Table 2), but which are not exceptionally high for tropical areas undergoing land clearance. Because of the large lake surface area available to receive dry fall, and the dominance of rain in the water budget of the great lakes, the atmospheric deposition of phosphorus is an important external phosphorus source to Lake Malawi (Fig. 2), and also appears to be the dominant external phosphorus-loading source to Lake Victoria (Table 3). Phosphorus is not the only nutrient mobilized, with others, such as sulphur, nitrogen, iron and potassium (Crutzen & Andreae 1990), also transported through the atmosphere, potentially affecting the lakes that receive these inputs. Atmospherically borne nitrogen and phosphorous have been documented to enrich oligotrophic lakes far from the origins of the atmospheric nutrients (Lewis 1981; Jassby *et al.* 1994; Sickman *et al.* 2003), and to have been transported long distances (Jickells *et al.* 1998; Brunner & Bachofen 1998).

The similarity of atmospheric phosphorus deposition rates between the stations on Lake Malawi and around Lake Victoria (including the stations with dominant winds offshore and dominant winds onshore from the lake), and in the protected area of Serengeti National Park, is consistent with the widespread and relatively uniform atmospheric phosphorous concentrations (Tamatamah *et al.* 2005). Bootsma *et al.* (1999) compared the nutrient deposition rates at three locations on Lake Malawi, finding that the deposition rates of most nutrients were similar at all stations, although particulate carbon, nitrogen and phosphorous deposition was greater at an inland location. Areas of higher rainfall tend to have higher wet deposition rates and lower dry-fall deposition, and the same is true when comparing rainy season deposition rates with dry season rates (Tamatamah *et al.* 2005), the result being that the annual deposition rates are remarkably similar throughout East and southern Africa, despite the quite different climatic conditions and land uses at the monitoring stations.

Table 2. Total phosphorus loading rates by precipitation from selected global sites relevant to tropical lakes (expressed in kg ha^{-1} year^{-1}; data sources in Tamatamah *et al.* 2005)

	Wet	Dry	Wet + dry
Mwanza, Lake Victoria	0.5	2.2	2.7
Bukoba, Lake Victoria	0.6	1.3	1.9
Seronera, Lake Victoria	0.3	1.5	1.8
Duma, Lake Victoria	–	1.8	–
Jinja, Lake Victoria	0.7	–	–
West Coast of Africa	1.2	–	–
Lake-Valencia, Venezuela	–	–	1.68
Lake Malawi, Africa	0.3	2.1	2.5
Ontario Canadian Shield	–	–	0.32
Colorado Mountains, USA	–	–	0.26

Table 3. Provisional total nitrogen (TN) and total phosphorus (TP) nutrient budget for Lake Victoria (precipitation data from Tamatamah (2002); nitrogen fixation from Mugidde *et al.* (2003); river data extrapolated from Linthipe River, Lake Malawi from Hecky *et al.* (2003)

Flux	Water (mm year^{-1})	TN (kt year^{-1})	TP (kt year^{-1})
Rainfall	1790	83	4.8
Dryfall		110	13
Rivers	338	43	9.8
External total		236	27.6
Nitrogen fixation		480	
Total inputs		716	27.6

Despite the apparently similar and high rates of phosphorous deposition around southern Africa, both the number of monitored stations and their geographical distribution are still quite limited. What is needed is a regional monitoring network to define spatial and temporal trends and significant source areas. Furthermore, extrapolation of these rates over large areas, such as the surface area of Lake Victoria, requires confirmation by monitoring on the lake itself before full confidence can be given to estimates such as those presented in Table 3. The atmospheric and ecological consequences of biomass burning in the tropics, and the potential for disrupting nutrient cycles and the productivity of the burned terrestrial systems, have been known for some time (Crutzen & Andreae 1990). Less appreciated is the possible effect of these mobilized nutrients on lakes. In terms of atmospheric transport and deposition, lakes are the receiving systems, functioning as effective sinks for the mobilized nutrients. Except for very conservative ions (e.g. chloride), whatever material enters the Great African Lakes will remain in the lakes. Nutrients such as sulphur, nitrogen, silicon and phosphorous are highly retained in these poorly flushed systems, even when compared to Lake Superior, which has the longest water-flushing time of the Laurentian Great Lakes (Hecky 2000). Such high retention times mean that any pollutant entering these lakes will remain in the water or sediment of the lakes, with potentially prolonged effects on the aquatic systems (Bootsma & Hecky 1993). As the water-flushing times decrease in smaller lakes and reservoirs, the importance of atmospheric deposition in the nutrient budgets should decline, although nutrient management in the great lakes still will require addressing atmospheric deposition which, in turn, will require a regional approach to maintaining or restoring air quality. Biomass burning also produces other atmospheric hazards, such as ground-level ozone, that can reduce plant productivity (Ashmore *et al.* 1994; Maggs *et al.* 1995), and can cause respiratory problems. For farmers to change their current practices, benefits will have to accrue at the farm scale, as well as at the basin scale. Lake managers will have to work closely with their partners in managing land uses and agricultural practices to facilitate such changes.

CONTAMINANTS

The atmosphere can also be a transport medium for volatile contaminants, such as organochlorines (e.g. DDT, PCBs), mercury, and other semivolatile gaseous and dust-borne toxic compounds (e.g. polynuclear aromatic hydrocarbons). The organochlorines have caused serious biotic degradation to the Laurentian Great Lakes, especially affecting fish-eating birds because of bioaccumulation of organoclorines in food webs. Banning the manufacture and use of the most persistent and toxic organochlorines, such as DDT and PCBs, has led to a slow downward trend in the concentrations of these compounds, from high concentrations in the Laurentian Great Lakes biota in the late 1970s. Even after 30 years, however, PCB concentrations in some fish remain above the levels considered acceptable for consumption (Lamon *et al.* 1999). Mercury is also toxic, particularly as its methylated species, methyl mercury (CH_3Hg^+), that can bioaccumulate in food webs and exceed acceptable concentrations in piscivorous fish when the concentrations in water are at sub-nanogram per litre concentrations. The lucrative Lake Erie fishery, for example, was closed in the early 1970s because mercury concentrations in predatory fishes exceeded the market acceptability. Removal of mercury from industrial point sources allowed rapid recovery and reopening of the commercial Lake Erie fishery. However, mercury concentrations still remain sufficiently high in the Laurentian Great Lakes to prompt fish consumption advisory statements urging people to limit the consumption of many predatory fish species. Atmospheric mercury concentrations have risen through the past century and, even in remote lakes, mercury deposition has increased by approximately a factor of two all over the globe. Recognition of this historical contamination of the atmosphere and aquatic ecosystems has led to the international efforts to further reduce or eliminate the use of mercury in industrial processing and in manufactured products. Similarly, organochlorine concentrations have been rising in remote Arctic lakes and coastal marine systems because of their atmospheric transport from lower latitudes where their historical use was high, or remains high. The volatility of these organochlorine compounds leads to a 'grasshopper' effect, moving the compounds from warmer ecosystems to colder ecosystems, and eventually to accumulation in continuously cold lipid-rich aquatic food webs at high latitudes (Wania & Mackay 1993). The transboundary dimension of this problem has led to recent global protocols for reducing

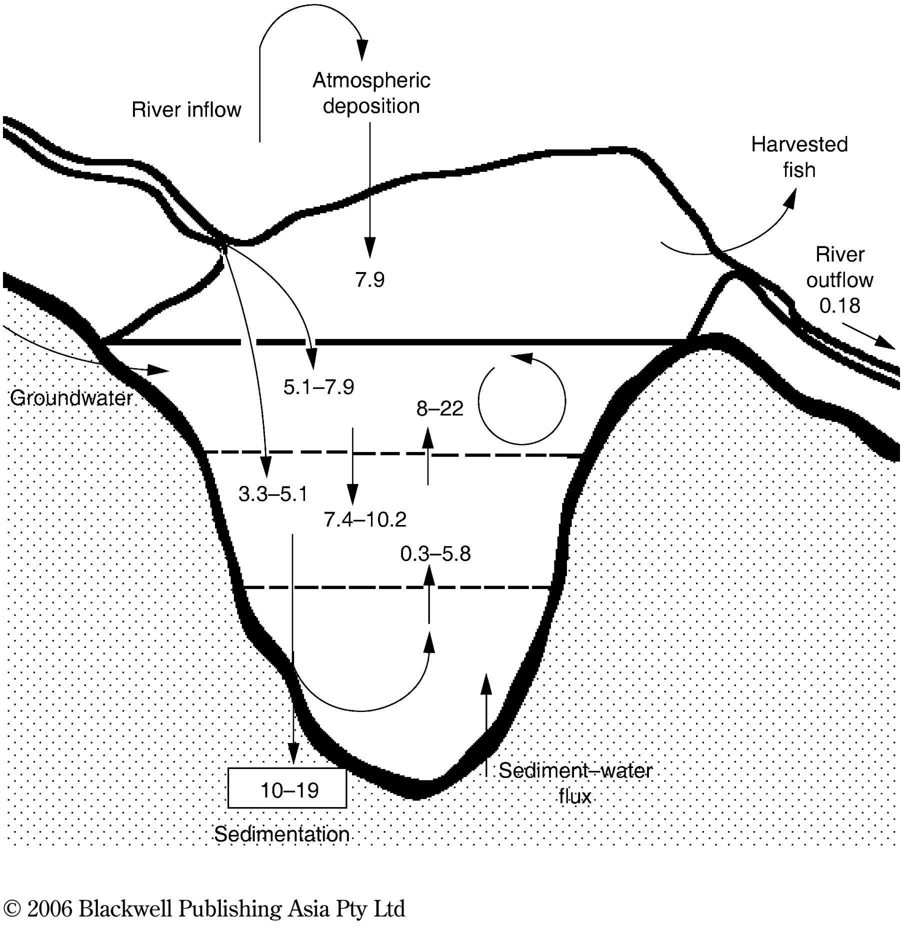

Fig. 2. Total phosphorous fluxes to and from Lake Malawi (numerical units are mmol m^{-2} $year^{-1}$; ranges are given for high and low estimated fluxes for the rivers, based on different approaches to extrapolation to unmonitored terrestrial catchments (Bootsma and Hecky 1999); riverine inputs are split on the basis of the density of the inflowing stream into fluxes to the mixed layer, and likely fluxes to the metalimnion).

and eliminating organochlorines, and should encourage the developed countries in higher latitudes to assist tropical and subtropical developing countries to find alternatives to the use of persistent, toxic organochlorine compounds.

Organochlorines, especially DDT, are still used in tropical countries, being detectable in the air at stations in Uganda (Fig. 3) and in air, water and aquatic biota of Lake Malawi (Karlsson *et al.* 2000; Kidd *et al.* 2001) at concentrations well above those found at higher latitudes. Fortunately, volatilization (and perhaps degradation) of these compounds keeps their concentrations low in tropical waters and biota (Kidd *et al.* 2001), and well below concentrations of concern for fish consumers. Nevertheless, the disturbing trend over time, as recorded in a sediment core from Lake Victoria (Lipiatou *et al.* 1996), is for increasing concentrations in sediment. Thus, careful monitoring, and eventually elimination of the use of these persistent organic pollutants, will be the only way to eliminate the risk of contamination of aquatic organisms while these pollutants are still used. Although pesticide use has been historically limited by the poor economic conditions in Africa, wise use of such pesticides might be necessary to boost the agricultural production, especially the valuable export crops, as well as to control health risks, such as disease-bearing insects. Thus, the future use of pesticides is likely to increase in the developing countries.

Eliminating mercury from the atmosphere of eastern Africa and its lakes will not be possible. Mercury is a naturally occurring element, being found everywhere and in every environmental media. Metallic or inorganic mercury itself can be toxic, but rarely at environmental concentrations. Inorganic mercury compounds can be excreted by the kidneys of higher organisms, thereby not bioaccumulating to any significant degree. The production of methyl mercury by bacteria in the environment, however, can lead to efficient bioaccumulation and biomagnification of methyl mercury in aquatic food webs, often by a factor of >1 million times above water concentrations, and can cause potentially unacceptable concentrations in top predators (Campbell *et al.* 2003a). Surveys of African fisheries have found generally acceptable mercury concentrations in fish for marketing and frequent human consumption, except for very large piscivorous Nile perch in Lake Victoria, or as a result of long food-chains such as found in Lake Albert, Uganda (Fig. 4; Campbell *et al.* 2002). This positive outlook is tempered by the recognition that mercury deposition has increased over time for Lake Victoria (Fig. 5), and that the capacity of bacteria to methylate mercury can be modified both by the addition of more mercury to an ecosystem, and by the enhanced rates of bacterial methylation (Hecky *et al.* 1992). The total mercury concentrations are actually higher in Lake Victoria waters (Campbell *et al.* 2003b) than they are in the Laurentian Great Lakes, although the fishes in the African lakes have lower concentrations of methyl mercury in their flesh than do the temperate Great Lakes fishes, for reasons that are currently unclear. Biomass burning is likely the greatest mercury source to Lake Victoria (Campbell *et al.* 2003a), and its reduction would reduce the mercury loading to the lake. More problematic is determining what controls the rates of bacterial methylation of mercury. Any increase in mercury methylation could cause mercury concentrations in top predatory fish to rise to unacceptable levels for

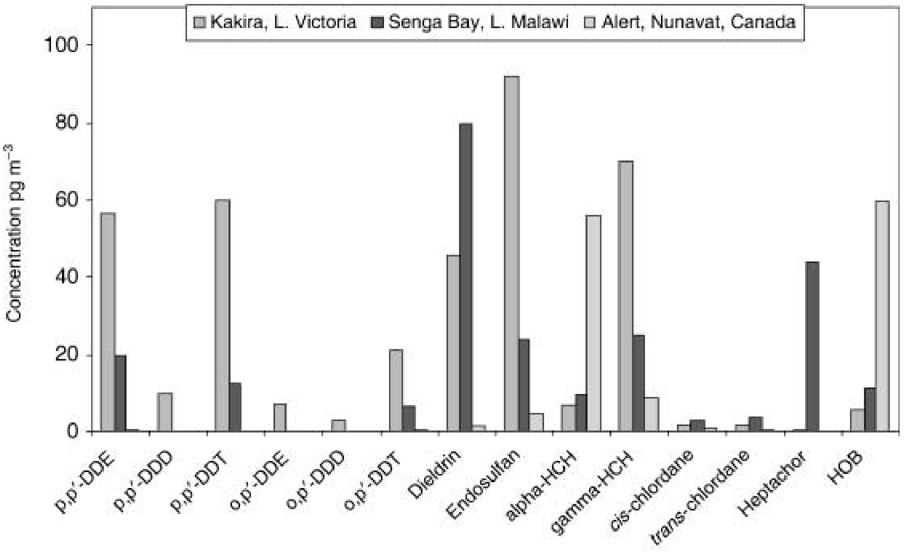

Fig. 3. Atmospheric concentrations of selected pesticides and some degradation products for two monitoring stations in eastern Africa, Kakira, Uganda and Senga Bay, Malawi, compared to a remote monitoring station in the high Arctic, Alert, Canada (data from Wejjuli *et al.* 2002).

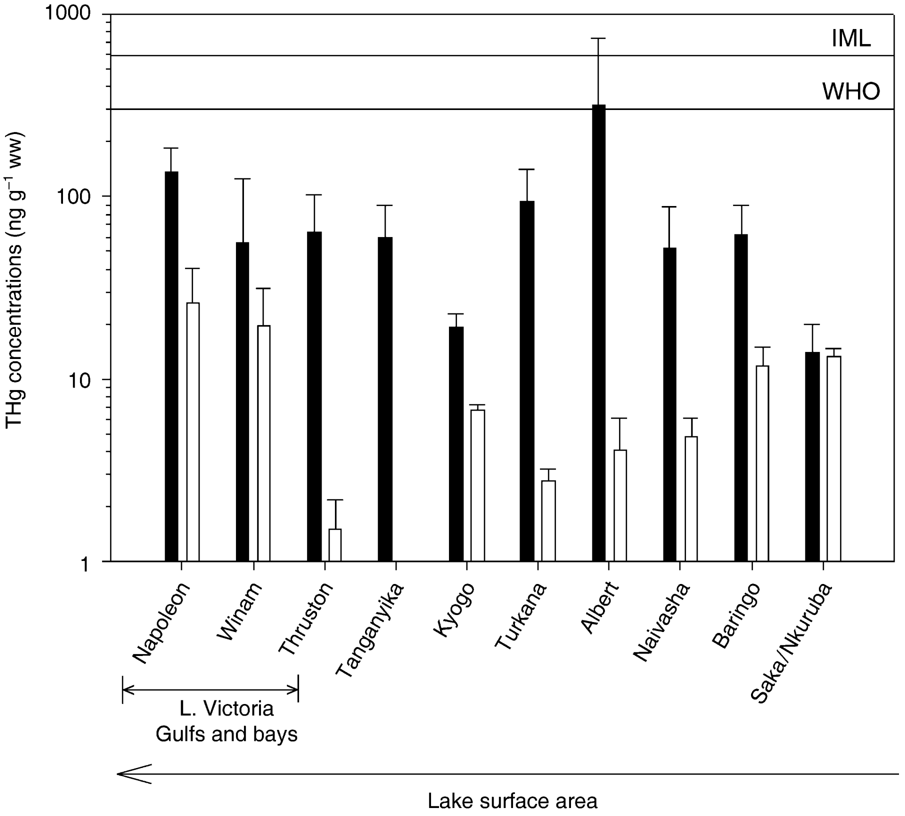

Fig. 4. Mercury (Hg) concentrations in top predator fishes (solid bars) and herbivorous/detritivorous fishes (light bars) in African lakes (note the logarithmic scale; from Campbell *et al.* (2002). IML, acceptable Hg level for marketing fish internationally; WHO, guideline concentration for frequent fish consumption by sensitive groups (e.g. nursing mothers and children).

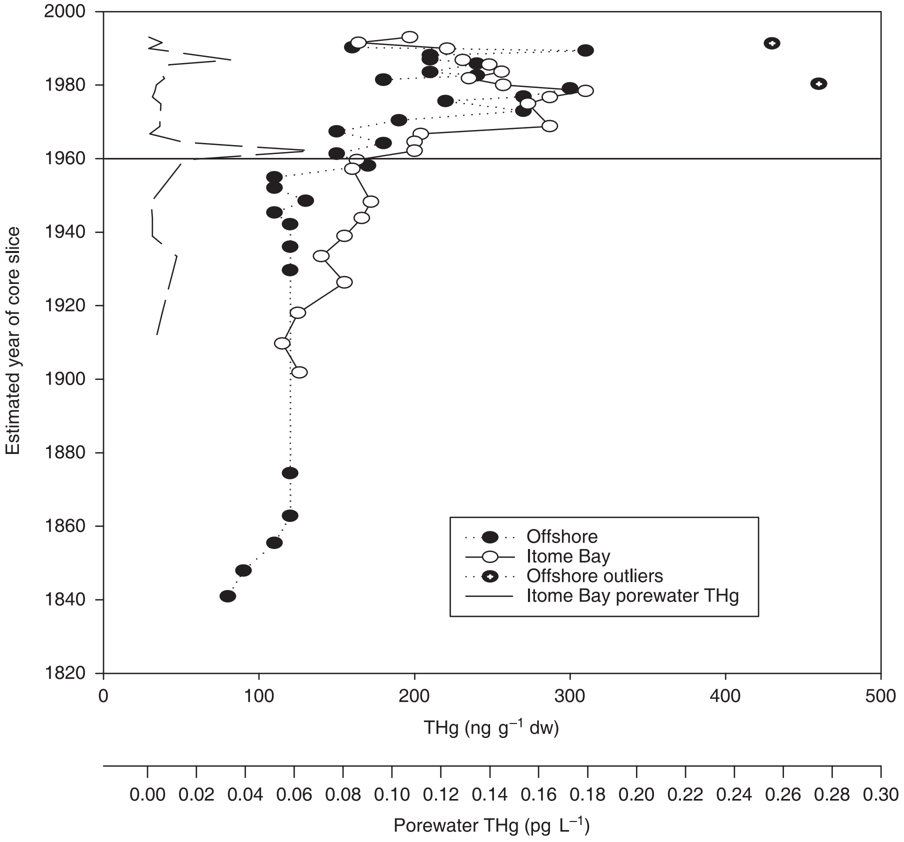

Fig. 5. Total mercury (THg) concentrations in two sediment cores (offshore and inshore) in Lake Victoria (dashed line = porewater THg concentration in inshore core; from Campbell *et al.* 2003b).

frequent consumption or even for export. Research is needed to address this issue for tropical ecosystems. Sulphate-reducing bacteria are often implicated in elevated rates of bacterial methylation, and the low concentrations of dissolved sulphate in the African Great Lakes could be limiting the methylation rates. Biomass burning will also increase the sulphur loading to the lakes (Crutzen & Andreae 1990), and could act synergistically with increased mercury loadings to increase methyl mercury production over time.

Careful monitoring of mercury and organochlorine concentrations in fish can protect fish consumers, as well as the international market place for fish products from the African lakes, and hopefully allow for the detection of any upward trend before mercury concentrations in fishes become unacceptable. If upward trends are detected, regional action to reverse those trends in these great lakes and their fisheries will likely be required.

CONCLUSION

Many environmental risks to African lakes arise within their catchments and can be addressed by riparian states in the catchment through appropriate basin management initiatives, bolstered with adequate funding. However, other risks arising from atmospheric change can affect lakes over broad areas, and will require regional or even global action to address them. Evidence from the Great African Lakes indicates that climate change, intensifying land use (mobilizing nutrients) and toxic substances are increasingly affecting the atmosphere over the African Great Lakes. The Great Lakes are particularly sensitive to these changes because of their enormous surface areas, slow water-flushing rates and the importance of direct rainfall in their water budgets. Their response times might be slow to yield a detectable change and, unfortunately, their recovery times also might be slow. It is possible for atmospheric effects to act antagonistically to impacts of catchment change (e.g. evidence for lower productivity in Lake Tanganyika despite ongoing catchment degradation), but antagonistic effects could become synergistic in the future (e.g. the positive effect that increasing atmospheric sulphur deposition might have on mercury methylation). Improved understanding of the physical dynamics of these lakes, and development of models that link their physical and biogeochemical behaviour to regional, mesoscale climate models, will be necessary to guide lake managers.

The inherent hydrological sensitivity of the African Great Lakes, and the attention they have received from GEF-sponsored studies as international waters requiring cooperative management among riparian states, have now highlighted the risks inherent in atmospheric change. However, the scale of the risks, the rates of change and, most importantly, the regional and global management responses are yet to be defined. The GEF programmatic focal areas are international waters, biodiversity, climate change, ozone depletion, land degradation, and persistent organic pollutants. Clearly, the transboundary issues regarding the African Great Lakes are appropriate for further GEF action. At the same time, however, the states of eastern Africa that enjoy the benefits from these lakes will increasingly have to collaborate to engender a regional, or possibly even continental, approach to resolve many of these issues. In particular, climate change will have to be addressed at a global scale in order to safeguard the African Great Lakes. The challenge to lake management will be to unravel the causation of undesirable changes, in order to determine whether local catchment impacts are the main cause of the changes, or whether atmospherically mediated and/or climatically driven changes are responsible. The scale of response, and the possibility of effective management intervention, requires resolution of that challenge for all the lakes of Africa.

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REFERENCES

Ashmore M. R. (1994) Critical levels and agriculture in Europe. In: *Air Pollution Research Report 46* (eds H. J. M. Jager, L. Unsworth De Temmerman & P. Mathy) pp. 105–29. CEC, Brussels, Belgium.

Bootsma H. A., Bootsma M. J. & Hecky R. E. (1996) The chemical composition of precipitation and its significance to the nutrient budget of Lake Malawi. In: *The limnology, climatology and paleoclimatology of the East African lakes* (eds T. C. Johnson & E. Odada) pp. 251–66. Gordon and Breach, Amsterdam.

Bootsma H. A. & Hecky R. E. (1993) Conservation of the

African Great Lakes: a limnological perspective. *Conserv. Biol.* **7**, 644–56.

Bootsma H. A. & Hecky R. E. (1999) Nutrient cycling in Lake Malawi/Nyasa. In: *Water Quality Report. SADC/GEF Lake Malawi/Nyasa Biodiversity Conservation Project* (eds H. A. Bootsma & R. E. Hecky) pp. 213–41. Washington, D.C.

Bootsma H. A., Hecky R. E., Johnson T. C., Kling H. J. & Mwita J. (2003) Inputs, outputs and silica cycling in a large, tropical lake. *J. Great Lakes Res.* **29**, 121–38.

Bootsma H. A., Mwita J., Mwichande B., Hecky R. E., Kihedu J. & Mwambungu J. (1999) The atmospheric deposition of nutrients on Lake Malawi/Nyasa. In: *Water Quality Report. SADC/GEF Lake Malawi/Nyasa Biodiversity Conservation Project* (eds H. A. Bootsma & R. E. Hecky) pp. 85–110. Washington, D.C.

Brunner U. & Bachofen R. (1998) The biogeochemical cycles of phosphorus: a review of local and global consequences of the atmospheric input. *Tech. Env. Chem.* **67**, 171–88.

Campbell L. M., Hecky R. E. & Dixon D. G. (2003a) Review of mercury in Lake Victoria (East Africa): Implications for human and ecosystem health. *J. Toxicol. Environ. Health, Part B* **6**, 325–56.

Campbell L. M., Hecky R. E., Muggide R., Dixon D. G. & Ramlal P. S. (2003b) Variation and distribution of total mercury in water, sediment and soil from northern Lake Victoria, East Africa. *Biogeochemistry* **65**, 195–211.

Campbell L. M., Hecky R. E., Wandera S. B. *et al.* (2002) Distribution of THg in perciformes (Nile perch and black bass) and tilapiines from across East Africa. In: *Proceedings of the International Workshop on Health and Environmental Effects of Mercury Held at University of Dar Es Salaam 19–20 November.* pp. 187–97. National Institute of Minimata Disease, Minimata, Japan.

Crutzen P. J. & Andreae M. O. (1990) Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* **250**, 1669–77.

Grove A. T. (1996) African river discharges and lake levels in the twentieth century. In: *The limnology, climatology and paleoclimatology of the East African lakes* (eds T. C. Johnson & E. Odada) pp. 95–102. Gordon and Breach, Amsterdam.

Haberyan K. & Hecky R. E. (1987) The late Pleistocene and Holocene stratigraphy and paleolimnology of Lakes Kivu and Tanganyika. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* **61**, 169–97.

Hamblin P. F., Verburg P., Roebber P., Bootsma H. A. & Hecky R. E. (2002) Observations, evaporation and preliminary modeling of over-lake meteorology on large African lakes. In: *The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity* (eds E. Odada & D. O. Olago) pp. 11–52. Kluwer Academic, Dordrecht.

Hao W. M. & Liu M.-H. (1994) Spatial and temporal distribution of tropical biomass burning. *Global Biogeochem. Cycles* **8**, 495–503.

Hecky R. E. (1993) The eutrophication of Lake Victoria. *Verh. Int. Ver. Limnol.* **25**, 39–48.

Hecky R. E. (2000) A biogeochemical comparison of Lakes Superior and Malawi and the limnological consequences of an endless summer. *Aquat. Ecosystem Health Manage.* **3**, 23–33.

Hecky R. E., Bootsma H. A. & Kingdon M. L. (2003) The importance of river basin characteristics and impact of land use change on sediment and nutrient yields to Lake Malawi/Nyasa (Africa). *J. Great Lakes Res.* **29**, 139–58.

Hecky R. E., Bugenyi F. W. B., Ochumba P. *et al.* (1994) Deoxygenation of the deep water of Lake Victoria. *Limnol. Oceanogr.* **39**, 1476–80.

Hecky R. E., Ramsey D. J., Bodaly R. A. & Strange N. E. (1992) Increased methylmercury contamination in fish in newly formed freshwater reservoirs. In: *Advances in Mercury Toxicology* (eds T. Clarkson & T. Suzuki) pp. 33–52. Plenum, New York.

Hulme M., Doherty R., Ngara T., New M. & Lister D. (2001) African climate change: 1900–2100. *Climate Res.* **17**, 145–68.

Jassby A. D., Reuter J. E., Axler R. P., Goldman C. R. & Hackley S. H. (1994) Atmospheric deposition of nitrogen and phosphorus in the annual nutrient load of Lake Tahoe (California Nevada). *Water Resour. Res.* **30**, 2207–16.

Jickells T. E., Dorling S., Deuser W. G., Church T. M., Arimoto R. & Prospero J. M. (1998) Air-borne dust fluxes to a deep water sediment trap in the Sargasso Sea. *Global Biogeochem. Cycles* **12**, 311–20.

Johnson T. C., Scholz C. A., Talbot M. R. *et al.* (1996) Later Pleistocene desiccation of Lake Victoria and rapid evolution of cichlid fishes. *Science* **273**, 1091–3.

Karlsson H., Muir D. C. G., Teixeira C. F. *et al.* (2000) Persistent chlorinated pesticides in air, water, and precipitation from the Lake Malawi area, Southern Africa. *Environ. Sci. Technol.* **34**, 4490–5.

Kidd K. A., Bootsma H. A., Hesslein R. H., Muir D. C. G. & Hecky R. E. (2001) Biomagnification of DDT through the benthic and pelagic food webs of Lake Malawi, East Africa: Importance of trophic level and carbon source. *Environ. Sci. Technol.* **35**, 14–20.

Lam D. C. L., Leon L., Hecky R. E., Bootsma H. & McCrimmon R. C. (2002) A modeling approach for Lake Malawi/Nyasa/Niassa: Integrating hydrological and limnological data. In: *The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity* (eds E. Odada & D. Olago) pp. 189–208. Kluwer Academic, Dordrecht.

Lamon E. C., Carpenter S. R. & Stow C. A. (1999) Rates of decrease of polychlorinated biphenyl concentrations in five species of Lake Michigan salmonids. *Can. J. Fish. Aquat. Sci.* **56**, 53–9.

Lewis W. M. Jr. (1981) Precipitation chemistry and nutrient loading by precipitation in a tropical watershed. *Water Resour. Res.* **17**, 169–81.

Lipiatou E., Hecky R. E., Eisenreich S. J., Lockhart L., Muir D. & Wilkinson P. (1996) Recent ecosystem changes in Lake Victoria reflected in sedimentary natural and anthropogenic compounds. In: *The Limnology, Climatology and Palaeoclimatology of the East African Lakes* (eds T. C. Johnson & E. Odada) pp. 523–42. Gordon and Breach, Amsterdam.

Lorke A., Tietze K., Halbwachs M. & Wuest A. (2004) Response of Lake Kivu stratification to lava inflow and climate warming. *Limnol. Oceanogr.* **49**, 778–83.

Maggs R., Wahid A., Shamsi S. R. A. & Ashmore M. R. (1995) Effects of ambient air pollution on wheat and rice yield in Pakistan. *Water, Air and Soil Pollut.* **85**, 1311–6.

Mugidde R., Hendzel L. & Hecky R. E. (2003) Pelagic nitrogen fixation in Lake Victoria, Uganda. *J. Great Lakes Res.* **29**, 76–88.

Nicholson S. E. (1998) Historical fluctuations of Lake Victoria and other lakes in the northern rift valley of East Africa. In: *Environmental Change and Response in East African Lakes* (ed. J. T. Lehman) pp. 7–36. Kluwer Academic, Dordrecht.

Nicholson S. E. & Yin X. (2002) Mesoscale patterns of rainfall, cloudiness and evaporation over the Great Lakes of East Africa. In: *The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity* (eds E. Odada & D. O. Olago) pp. 92–120. Kluwer Academic, Dordrecht.

O'Reilly C. M., Alin S. R., Plisnier P.-D., Cohen A. S. & McKee B. A. (2003) Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature* **424**, 766–8.

Sarvala J., Langenberg V. T., Salonen K. *et al.* (2006) Fish catches in Lake Tanganyika mainly reflect fishing practices, not climate. *Verh. Int. Ver. Limnol.* **29**, 1182–8.

Sickman J. O., Melack J. M. & Clow D. W. (2003) Evidence for nutrient enrichment of high elevation lakes in the Sierra Nevada California. *Limnol. Oceanogr.* **48**, 1885–992.

Sundborg A. & Rapp A. (1986) Erosion and sedimentation by water: problems and prospects. *Ambio* **15**, 215–25.

Tamatamah R. A. (2002) Nonpoint source loading of phosphorus to Lake Victoria from the atmosphere and rural catchments in Tanzania, East Africa. PhD Thesis, University of Waterloo, Waterloo, Canada. 200 p.

Tamatamah R. A., Duthie H. C. & Hecky R. E. (2005) The importance of atmospheric deposition to the phosphorus loading of Lake Victoria. (East Africa). *Biogeochemistry* **73**, 325–44.

Verburg P. & Hecky R. E. (2003) Diel wind pattern and evaporation at Lake Tanganyika, East Africa. *J. Great Lakes Res.* **29**, 48–61.

Verburg P., Hecky R. E. & Kling H. (2003) Ecological consequences of a century of warming in Lake Tanganyika. *Science* **301**, 505–7.

Vollmer M. K., Bootsma H. A., Hecky R. E. *et al.* (2005) Deep-water warming trend in Lake Malawi, East Africa. *Limnol. Oceanogr.* **50**, 727–32.

Vollmer M. K., Weiss R. F. & Bootsma H. A. (2002) Ventilation of Lake Malawi/Nyasa. In: *The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity* (eds E. Odada & D. O. Olago) pp. 209–34. Kluwer Academic, Dordrecht.

Wania F. & Mackay D. (1993) Global fractionation and cold condensation of low volatility organochlorine compounds in polar regions. *Ambio* **22**, 10–8.

Wejuli M. S., Muir D. C. G., Kiremire B. T. *et al.* (2002) Ambient air concentrations of persistent organochlorine pesticides in the northern Lake Victoria watershed. Poster at SETAC 2002 North American Annual Meeting. Salt Lake City, Utah.