Global warming is reducing thermal stability and mitigating the effects of eutrophication in Lake Victoria (East Africa)

Global warming is reducing thermal stability and mitigating the effects of eutrophication in Lake Victoria (East Africa)

Brian E. Marshall[1], Charles N. Ezekiel[2], John Gichuki[3], Oliva C. Mkumbo[1], Lewis Sitoki[3] & Fred Wanda[4]

[1]*Lake Victoria Fisheries Organization, P.O. Box 1625, Jinja, Uganda*
[2]*Tanzanian Fisheries Research Institute, P.O. Box 475, Mwanza, Tanzania*
[3]*Kenya Marine and Fisheries Research Institute, P.O. Box 1881, Kisumu, Kenya*
[4]*National Fisheries Resources Research Institute, P.O. Box 243, Jinja, Uganda.*

The impacts of global warming have been reported from several deep lakes in the African Rift Valley and in each thermal gradients within the water column have increased thus strengthening already existing oxyclines, below which the water is permanently anoxic.[1,2,3,4] The temperature of Lake Victoria rose by 0.9°C between 1960 and 1990 raising fears that thermal stability would increase resulting in more extensive and severe anoxia in the deeper waters.[5] This is of concern because of the eutrophication of the lake, which began in the 1960s,[6,7] and led to dense blooms of sometimes toxic cyanobacteria, increased deoxygenation of the bottom waters, and fish kills in some parts of the lake.[8,9,10] Here we show that thermal gradients in the water column have weakened over the last decade and that deoxygenation of deeper waters is less pronounced than expected. Since 1927 the temperature of the deeper waters has risen by 1.3°C compared to only 1.0°C in the surface layers, thereby decreasing thermal and density differentials in the water column. This contradicts the view that eutrophication would increase deoxygenation of the water column perhaps to the point where fish production could not be sustained.[11] Our results suggest that the impacts of global warming on tropical lakes are likely to highly variable and may not, in the short term at least, be uniformly detrimental.

Lake Victoria supports one of the world's largest inland fisheries, producing around 1 million tonnes per annum and providing a livelihood for 200,000 fishermen and their families, as well as being an important source of export revenue for the surrounding countries (Kenya, Tanzania and Uganda). Concerns about the possible impacts of any decline in the catch are reinforced by the knowledge that the lake has undergone extensive ecosystem disruption over the last 30 years as a result of eutrophication and the Nile perch, *Lates niloticus*, a predatory fish introduced in the 1960s. Eutrophication is a consequence of the rapid growth of the human population around the lake, still increasing at double the global rate[12], and the Lake Victoria drainage basin is now one of the most densely-populated areas in Africa. Most of the population lives directly off the land, leading to severe deforestation and soil erosion with the result that nutrient loading to the lake has increased and there is evidence that it started to become eutrophic in the 1960s.[6,7] The effects of eutrophication did not, however, become obvious until the mid-1980s after the Nile perch population exploded, having until then grown very slowly since it its introduction 20 years earlier. This predator quickly brought about the apparent destruction of the 500+ endemic haplochromine species flock that made up the bulk of the fish biomass in the lake[13]. Food chains in the lake were greatly simplified and the cascading effects of these changes enabled the consequences of eutrophication to become apparent.[14,15] These included algal blooms, the replacement of the dominant diatom species by cyanobacteria, deoxygenation, and fish kills as well as a rapidly-growing infestation of water hyacinth *Eichhornia crassipes.*[16]

An added concern is the question of global warming because evidence of climate-induced changes to the thermal structure of African lakes is beginning to emerge. In Lake Kivu, for example, the temperature of the upper layers of the water column apparently increased by 0.5°C over thirty years[3] while in Lake Malawi the temperature increased by ~0.7°C over 60 years[4]. The most noticeable impact was reported from Lake Tanganyika where the temperature at 100-150 m depth increased at a rate of ~0.01°C per annum. The rate of increase in deeper water was much lower and this led to a trebling of the density gradients, thus increasing thermal stability and hindering mixing. As a result, productivity has declined because the circulation of nutrients trapped in the deeper waters has been reduced, partly by increased thermal stability and partly by a weakening of the trade winds that drove the upwelling of deep water.[1,2]

Lake Victoria was reported to have warmed by ~0.3°C from 1960-61 to 1990-91 with an apparent increase in thermal stability[5] but the data came from only two sampling stations. Given the size of the lake (68,800 km^2) a clearer picture might be obtained from lake-wide surveys involving a much larger number of stations. Data are available from three such surveys, the first of which was a six-month fishery investigation carried out in 1927 that obtained temperature records from 55 sites around the lake[17]. The other two are more recent, coming from (a) the Lake Victoria Fisheries Research Project (LVFRP) which ran from 1999-2001 and (b) the Implementation of a Fisheries Management Plan project (IFMP) which began in 2005. In both cases samples were collected in February-March and August-September from around 45 stations across the lake, the objective being to cover both the stratified and isothermal periods.

Considerable warming appears to have taken place with both surface and bottom waters having increased by about 1.0°C and 1.3°C respectively over a period of 81 years (Table 1). This gives an average rate of change of around 0.012° yr^{-1} in surface waters and 0.017° yr^{-1} in deep waters, which is comparable to the rate of ~0.01° yr^{-1} obtained earlier.[5] The rate of warming appears to have accelerated over the last decade; in the 73 years from 1927 to 2000 the surface and bottom temperatures increased by 0.36° and 0.59° respectively, while they increased by 0.63° and 0.75° in the eight years from 2000 to 2008 (Table 2). The annual rate of warming from 2000-2008 was thus an order of magnitude greater than it had been in the 1927-2000 period. A striking feature in both periods was that the temperature in the bottom waters increased more rapidly than it did at the surface. This has important implications because although the density of both surface and deeper waters will decrease as they warm, the density of the latter was decreasing about 30% faster (Table 2). The reasons why surface water did not warm as rapidly are unclear but evaporation may play a part. An enormous quantity of water (> 100 km^3) evaporates from the lake's surface each year[18] and this must have some cooling effect.

The principal impact of global warming in the Rift Valley lakes so far investigated has been to strengthen stratification and deoxygenation[1,2,3,4] and it was feared that warming would do the same in Lake Victoria[5]. However, the Rift Valley lakes are very deep and characterised by the presence of permanent oxyclines below which the water is permanently anoxic while Lake Victoria is relatively shallow (maximum depth = 79 m, mean depth = 35 m) with a very large surface area. It has a seasonal pattern of stratification such that it is isothermal for part of the year and complete mixing throughout the water column is possible[19]. The deeper waters of the lake regularly became anoxic during the period of stratification even before the ecological changes that began in the 1980s and reports of "poor oxygen conditions and a strong smell of hydrogen sulphide" suggest that deoxygenation might have been quite severe at times.[20]

Recent data indicate that stratification weakened between 2000 and 2008, with deoxygenation becoming much less pronounced and extensive. In February 2000, for instance, distinct temperature stratification occurred at various depths between about 25 m and 50 m and the water temperature at the bottom was around 24°C (Figure 1). Deoxygenation was pronounced, in some cases beginning at about 20 m depth, while some stations were anoxic from about 40 m, and all were anoxic from 50 m downwards. In some cases, the rate at which deoxygenation occurred was relatively gradual but in others very pronounced oxyclines were present, with oxygen concentrations decreasing rapidly from about 6-7 mg l^{-1} to almost nothing in the space of a few metres. In February 2007, by contrast, thermal stratification was much weaker and the temperature of water deeper than 40 m had risen to around 25°C, a degree higher than in 2000. Although some deoxygenation occurred it was not as severe as in 2000, with no stations being anoxic and there was only one with an oxygen concentration lower than 2 mg l^{-1}. The oxygen concentrations below 40 m at most stations was around 3-4 mg l^{-1} which represents a marked improvement in the situation a few years earlier.

There is no evidence to suggest that Lake Victoria is becoming less eutrophic and the concentrations of plant nutrients remain well above historical levels (Table 3) yet the impacts of eutrophication seem less severe than they were a decade ago. Fish kills are rarely reported now and this reflects the decrease in the intensity of deoxygenation, which has lowered the risk of anoxic water upwelling to the surface after strong winds. Increased mixing within the water column means that nutrients cannot accumulate in the deeper waters thereby reducing the seasonal algal blooms that were sometimes sometimes dominated by toxic species that have also been implicated in fish kills.[8] The improved environmental situation in Lake Victoria is an unexpected consequence of the rapid warming that it has experienced over the last decade which, rather than strengthening thermal stability, seems to have weakened it through the more rapid warming of the bottom waters. The impact of global warming on the relatively shallow Lake Victoria is therefore quite different from the impact in the deep Rift valley lakes, which suggests that warming will have various, and possibly unpredictable, impacts on tropical lakes. Some of them, as in Lake Victoria, may not be universally detrimental over the short term at least. Over the long term, global warming may bring adverse changes in rainfall patterns and river flows which are likely to have a major impact on the lake.

Finally, very few tropical lakes have long time series of data and this has hampered investigations into the effects of global warming. The finding that warming has accelerated in lake Victoria over the last decade suggests that short data sets may give useful results. This should help to increase our understanding of the potential impacts of climate change.

Methods

In 1927 temperatures were measured at the surface with surface thermometers and in deeper waters with reversing thermometers that were calibrated in the United Kingdom before and after the survey.[17] A submersible Conductivity-Temperature-Depth profiling system (CTD, Sea-bird Electronics®, Sea Cat SBE 19) was used during the later surveys to determine temperature dissolved oxygen concentrations. Before each survey, the CTD was checked for accuracy in the laboratory, and at the start and end of each cruise it was calibrated against the Winkler titration method for determining dissolved oxygen concentrations.

References

1. Verburg, P., Hecky, R.E. & Kling, H. Ecological consequences of a century of warming in Lake Tanganyika. *Science* **301**: 505-507 (2003).
2. O'Reilly, C.M., Alin, S.R., Plisnier, P-D., Cohen, A.S. & McKee, B.A. Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature* **424**: 766-768 (2003).
3. Lorke, A., Tietze, K., Halbwachs M. & Wüest, A. Response of Lake Kivu stratification to lava inflow and climate warming. *Limnol. Oceanogr.* **49**: 778-783 (2004).
4. Vollmer, M.K., Bootsma, H.A., Hecky, R.E., Patterson, G., Halfman, J.D., Edmond, J.M., Eccles, D.H. & Weiss, R.F. Deep-water warming trend in Lake Malawi, East Africa. *Limnol. Oceanogr.* **50**: 727-732 (2005).
5. Hecky, R.E., Bugenyi, F.W.B., Ochumba, P., Talling, J.F., Mugidde, R., Gophen, M. & Kaufman, L. Deoxygenation of the deep water of Lake Victoria, East Africa. *Limnol. Oceanogr.* **39**: 1476-1481 (1994).
6. Hecky, R.E. The eutrophication of Lake Victoria. *Verh. Internat. Verein. Limnol.* **25**: 39-48 (1993).
7. Verschuren, D., Johnson, T.C., Kling, H.J., Edgington, D.N., Leavitt, P.R., Brown, E.T., Talbot, M.R. & Hecky, R.E. History and timing of human impact on Lake Victoria, East Africa. *Proc. Roy. Soc. London* B **269**: 289-294 (2002).
8. Ochumba, P.B.O. & Kibaara. 1989. Observations on blue-green algal blooms in the open waters of Lake Victoria, Kenya. *Afr. J. Ecol.* **27**: 23-34 (1989).
9. Ochumba, P.B.O. Massive fish kills within the Nyanza Gulf of Lake Victoria, Kenya. *Hydrobiologia* **208**: 93-99 (1990).
10. Sekadende, B.C., Lyimo, T.J. & Kurmayer, R. Microcystin production by cyanobacteria in the Mwanza Gulf (Lake Victoria, Tanzania). *Hydrobiologia* **543**: 299-304 (2005).
11. Kolding, J., van Zweiten, P., Mkumbo, O., Silsbe, G. & Hecky, R. in *The Ecosystem Approach to Fisheries* (eds Bianchi, G. & Skjoldal, H.R.) 309-354 (CAB International, London, 2008).
12. Data from 2007 Population data Sheet, Population Reference Bureau, New York (http://www.prb.org).

13. Witte, F., Goldschmidt, T., Wanink, J., van Oijen, M., Goudswaard, K., Witte-Maas, E. & Bouton, N. The destruction of an endemic species flock: quantitative data on the decline of the haplochromine cichlids of Lake Victoria. *Environmental Biology of Fishes* **34**: 1-28 (1992).
14. Goldschmidt, T., Witte, F. & Wanink, J. Cascading effects of the introduced Nile perch on the detritivorous/phytoplanktivorous haplochromine species (Pisces: Cichlidae) from Lake Victoria. *Oikos* **58**: 343-355 (1993).
15. Wanink, J.H. & Witte, F. 2000. The use of perturbation as a natural experiment: effects of predator introduction on the community structure of zooplanktivorous fish in Lake Victoria. *Advances in Ecological Research* **31**: 553-570.
16. Albright, T.P., Moorhouse, T.G. & McNabb, T.J. 2004. The rise and fall of water hyacinth in Lake Victoria and the Kagera River basin. *Journal of Aquatic Plant Management* **42**: 73-84.
17. Graham, M. 1929. *The Victoria Nyanza and its Fisheries. A Report of the Fisheries Survey of Lake Victoria 1927-1929*. Crown Agents, London.
18. Tate, E, Sutcliffe, J., Conway, D. & Farquharson, F. Water balance of Lake Victoria; update to 2000 and climate change modelling to 2100. *Journal of Hydrological Sciences* **49**: 563- (2004).
19. Talling, J.F. The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). *Internationale Revue der Gesamten Hydrobiologie* **51**: 545-621 (1966).
20. Kitaka, G.E.B. Limnology. East African Freshwater Fisheries Research Organisation, Annual report (1970): pp 15-16 (1971).
21. Talling, J.F. & Talling, I.B. The chemical composition of African lake waters. *Internationale Revue der Gesamten Hydrobiologie* 50: 421-463 (1965).
22. Gophen, M., Ochumba, P.B.O. & Kaufman, L.S. Some aspects of perturbation in the structure and biodiversity of the ecosystem of Lake Victoria (East Africa). *Aquatic Living Resources* **8**: 27-41 (1995).
23. Lung'ayai, H., Sitoki, L. & Kenyanya, M. The nutrient enrichment of Lake Victoria (Kenyan waters). *Hydrobiologia* **458**: 75-82 (2001).
24. Lewis Sitoki, unpublished data.

Acknowledgments We thank the master and crew of the RV *Victoria Explorer* for their assistance throughout these surveys and the technical staff at the three research institutes for their assistance. Dr J.F. Talling is thanked for his helpful comments. These investigations were funded by the European Union through the support given to the Lake Victoria Fisheries Organisation.

Author Contributions C.N.E., J.G., L.S. and F.W. were involved with data collection at various times during the surveys; B.E.M. and O.C.M. assisted with data analysis and preparation of the paper. All authors discussed the results and commented on the manuscript.

Author information Correspondence should be addressed to B.E.M (bmarshall@lvfo.org) or O.C.M. (ocmkumbo@lvfo.org).

Table 1. Mean temperature (°C) in Lake Victoria at the surface and at depths > 50 m. Data from Graham[17] and LVFRP and IFMP surveys (unpublished). N = number of stations sampled.

	Surface		> 50 m deep	
Year	N	Mean ± SD	N	Mean ± SD
1927	55	24.69 ± 0.71	27	23.32 ± 0.29
2000	98	25.05 ± 0.71	35	23.91 ± 0.15
2008	89	25.68 ± 0.83	20	24.66 ± 0.23

Table 2. Changes in temperature in Lake Victoria from 1927 to 2000, and from 2000 to 2008. The values for density change are indicative only, as they are based on pure water and take no account of dissolved compounds.

	1927-2000 (73 years)		2000-2008 (8 years)	
	Surface	>50 m	Surface	>50 m
Difference (°C)	0.36	0.59	0.63	0.75
Rate of change (°C yr^{-1})	0.005	0.008	0.079	0.094
Decrease in density (g m^{-3})	0.112	0.146	0.156	0.200

Table 3. Concentrations of nitrate-nitrogen and soluble reactive phosphorus (µg l^{-1}) in the Nyanza Gulf, Lake Victoria. Data are means ± standard deviation.

Period	NO_3-N	PO_4-P	Source
1960-61	15-29	4	21
1989	21.9 ± 21.9	41.8 ± 76.9	22
1998	70.9 ± 49.1	57.1 ± 36.6	23
2008	98.7 ± 36.4	57.0 ± 74.0	24

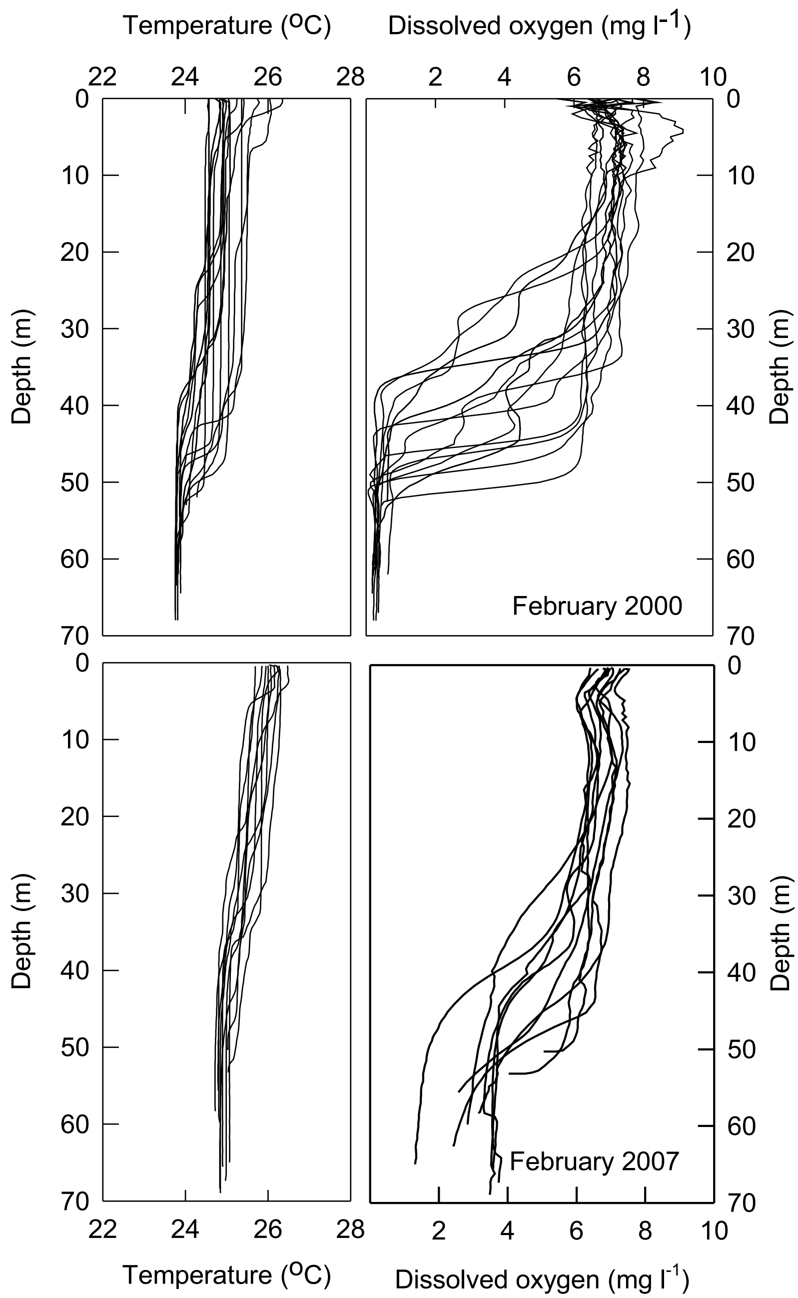

Figure 1. Temperature and oxygen profiles at stations > 50 m deep in Lake Victoria during periods of stratification, February 2000 and February 2007. From LVFRP and IFMP survey data.