*Water Resources Systems—Water Availability and Global Change* (Proceedings of symposium HS02a held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 280, 2003.


# Impacts of global warming on large lakes

**MICHIO KUMAGAI**
*Lake Biwa Research Institute, 1-10 Uchidehama, Otsu 520-0806, Japan*
kumagai@lbri.go.jp

**KANAKO ISHIKAWA**
*Division of Applied Biosciences, Graduate School of Agriculture, Kyoto University, Kyoto, Japan*

**NAOKO ISHIGURO**
*Department of Geography, Limoges University, F-87038 Limoges, France*

**Abstract** Global warming is now having serious impacts on large lakes (100–1000 km$^2$ in area). Large lakes are not as sensitive as small lakes (<100 km$^2$), however, they are more reactive than lakes with surface areas >1000 km$^2$. We have been studying large lakes of the world and found that some of these are facing a very serious situation. Lake Geneva, between Switzerland and France, has lost almost all oxygen from the hypolimnion over the last two decades. Lake Fuxian in Yunnan Province, China, is also suffering from deoxygenation. Lake Biwa, the largest lake in Japan, appears unaffected to the casual observer, but actually the benthic ecosystem and water quality are deteriorating due to oxygen depletion year by year. We found that the oxygen depletion and benthic ecosystem changes of these lakes are due to insufficient overturning, a result of global warming rather than increases of organic matter related to eutrophication.

**Key words** ecosystem; global warming; hypolimnion; Lake Biwa; Lake Fuxian; Lake Geneva; organic matter; overturning; oxygen depletion

## INTRODUCTION

Protecting our limited supplies of freshwater is a critical world issue at the start of the 21st century. The reliability of drinking water supply, decreasing water supplies for agriculture and the loss of freshwater habitats for aquatic wildlife in many places, are some of the major concerns (Dudgeon, 2000; Robarts *et al.*, 2003). Most of the causes have been considered as mainly derived from anthropogenic activities such as poor sanitation, over-irrigation, toxic organic pollutants and eutrophication. Recently, however, we are seeing signs that global warming can have serious impacts that accelerate the deterioration of large and deep lakes that are 100–1000 km$^2$ in area and over 100 m in depth (Kumagai *et al.*, 2003).

Livingstone (1993) compared the water temperature of four deep Swiss lakes and pointed out the 12- to 16-year periodicities in the hypolimnion of Lake Geneva. These long-term periodicities may be caused by global climate change rather than daily weather change. Insufficient turnover in early spring might reduce oxygen supply with the result that the oxygen concentration in the hypolimnion continues to decrease until an extremely cold winter occurs (Livingston, 1997).

In this study, we compare three different large lakes and discuss the influence of global warming through oxygen change in the hypolimnion. Lake Geneva (46°12′–

46°31′N, 6°10′–6°56′E) is located between France and Switzerland, and is well known as the birthplace of limnology (maximum depth = 309.7 m, area = 584.2 $km^2$ and volume = 88.9 $km^3$; Forel, 1901). Lake Fuxian (24°21′–24°38′N, 102°49′–102°57′E), the second deepest lake in China (maximum depth = 155 m, area = 211 $km^2$ and volume = 18.9 $km^3$; NIGLAS, 1990), has recently experienced increased air temperatures and decreased oxygen in the hypolimnion. Lake Biwa (34°58′–35°31′N, 135°52′–136°17′E) is Japan's largest freshwater lake and its limnological properties, water quality management and environmental protection have therefore received much attention (maximum depth = 104 m, area = 670 $km^2$ and volume = 27.5 $km^3$; Kira, 1984).

Global climate change may exacerbate the water quality effects of local pollution. Changes in the water balance can lead to prolonged hydraulic residence times, in turn favouring higher total phosphorus, pollutant concentrations and algal biomass. Increased temperatures could lead to stronger cycles of diurnal stratification, in turn encouraging cyanobacterial blooms. Such effects may also influence the seasonal stratification regime leading to problems that are especially severe in deep lakes. Small increases in air temperature can result in a reduced extent of convective and wind-induced mixing with the result that deep lakes fail to mix completely in winter, have less recharge of oxygen and a longer period of isolation, ultimately leading to bottom water anoxia.

## LAKE GENEVA

Oxygen depletion in Lake Geneva is alarming (Ishiguro, 2002). As seen in Fig. 1, the dissolved oxygen at 309 m in Lake Geneva started to decrease in the 1960s, and has gradually reached <2 mg $l^{-1}$, with some rapid, short recoveries in 1963, 1970, 1981, 1985 and 1999. The increases in dissolved oxygen between the recoveries became smaller each time while the duration of low oxygen periods became longer. We do not know why the oxygen levels recover suddenly, but it might be related to global warming/cooling (Livingston, 1997). The continuous decrease of dissolved oxygen obviously indicates a lack of sufficient turnover in early spring. Consequently, phosphate accumulates in the hypolimnion after being released from the sediment under anoxic conditions. This sort of accumulation process due to low oxygen is caused by insufficient mixing during winter, and may have a serious influence on water quality in the future (Kumagai *et al.*, 2003).

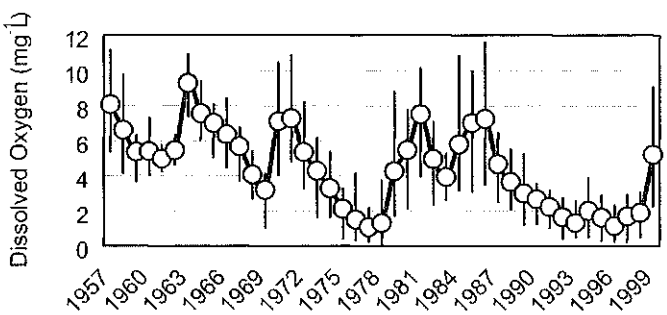


**Fig. 1** Annual average dissolved oxygen concentration at 309 m depth in Lake Geneva. The vertical bar shows the maximum and minimum.

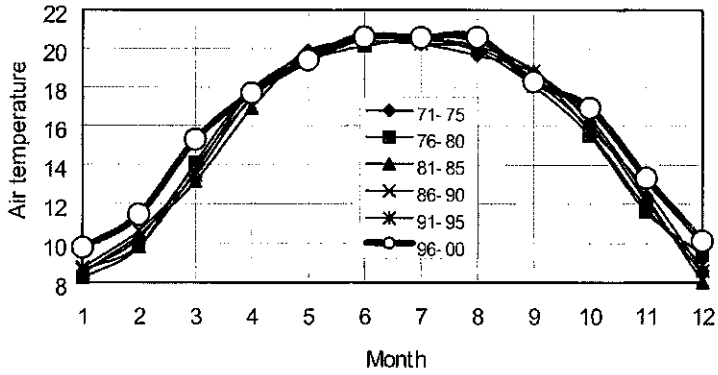


**Fig. 2** Comparison of average air temperature over five years at Lake Fuxian from 1971 to 2000.

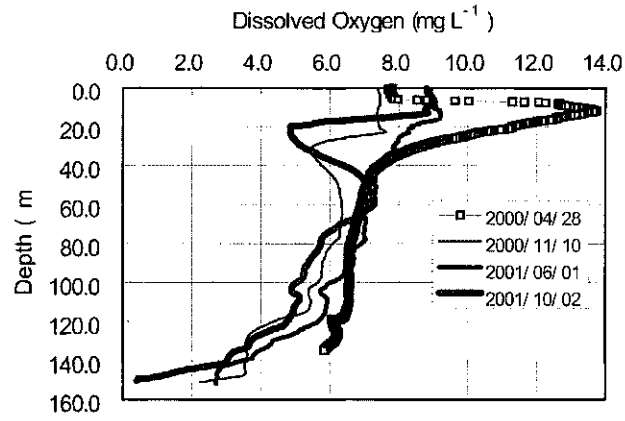


**Fig. 3** Vertical profiles of nearly the deepest area of Lake Fuxian.

## LAKE FUXIAN

Eutrophication is also a serious issue for Yunnan Province located in the south of China on the highland plateau (1000–3000 m altitude) facing Vietnam, Laos and Myanmar. Most of the lakes in this province have suffered from nutrient enrichment and other pollutants due to heavy industrial nonpoint waste sources, including agriculture. Urban wastewater quality research and management is needed to restore and protect these waters. At Lake Fuxian specifically, average air temperature during the period of winter mixing between 1996 and 2000 was nearly 1°C higher than for the preceding five years (Fig. 2). A reduced extent of winter mixing was observed concomitant with an increased deep-water depletion of oxygen.

Actually, dissolved oxygen near the bottom of Lake Fuxian has been decreasing as seen in Fig. 3, which means that the turnover of water in early spring has not occurred sufficiently since 2000. Cooled surface waters bring oxygen to the hypolimnion in deep lakes through vertical convection and/or turbulent diffusion processes (Hosoda &

Hosomi, 2002), while cold, dense river water such as snowmelt can intrude directly along the lake bottom as a density current rich in oxygen (Kumagai & Fushimi, 1995). The latter recharge of bottom water oxygen by inflowing density currents in winter may be an important factor in reducing the effects of eutrophication in many deep lakes, for example Lake Rotoiti, New Zealand (Vincent *et al.*, 1991).

## LAKE BIWA

The reduced input of cold density currents may have a particularly strong influence on hypolimnetic oxygen, which has been steadily declining (Kumagai & Fushimi, 1995). As seen in Fig. 4, the total precipitation measured at Hikone from January to March has a positive relationship with the mean concentration of dissolved oxygen near the bottom of Lake Biwa during February and March before 1996 ($r$ = 0.64, $n$ = 13, $p < 0.001$). This is one piece of the evidence suggesting cold water brings oxygen to the lake bottom as a density current. In 1997 and 1998 we had a warm winter and the discrepancy between precipitation and dissolved oxygen might be due to insufficient oxygen supply of warm river water.

Lake Biwa has a rich biodiversity, with 500 plant species (including algae), 600 animal species, including 9% endemic taxa that reflect the long history of the lake (Mori & Miura, 1990). One of the endemic fish species of Lake Biwa, *Chaenogobius isaza* Tanaka (common name = Isaza), resides in waters deeper than 30 m for most of the year, coming to the surface waters from April to June for spawning in the shallow inshore area. As seen in Fig. 5, the Isaza catch suddenly dropped after 1987 at the same time that the chemical oxygen demand (COD) below 80 m started to increase. There was a significant inverse relationship between the two variables: Isaza catch per unit boat = $-847.43 \times (\mathrm{COD}) + 1623.6$, $r$ = 0.91, $n$ = 22, $p < 0.001$). Although cause and effect relationships for the precipitous decline of Isaza have yet to be clarified, the deterioration of the deep waters under low oxygen is likely to have had a serious influence on this species.

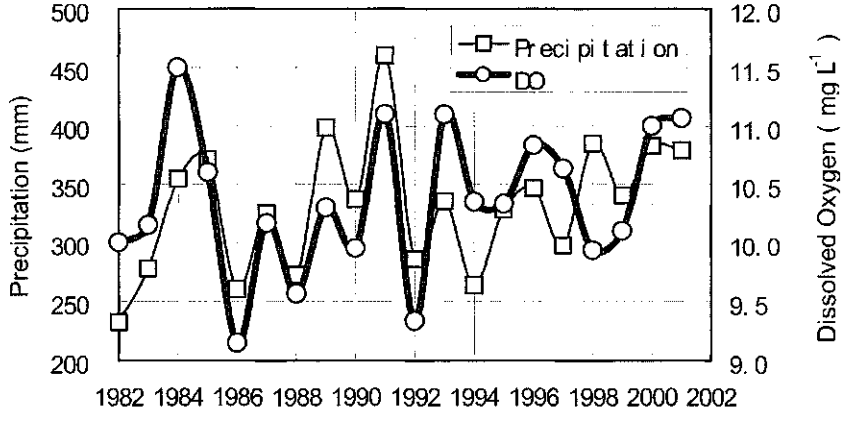


**Fig. 4** Temporal changes of total precipitation at Hikone during January and March and the mean dissolved oxygen at 90 m depth of Lake Biwa during February and March.

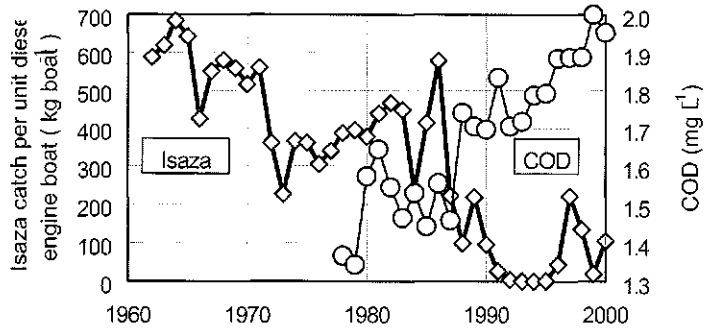


**Fig. 5** Temporal changes of Isaza (*Chaenogobius isaza* Tanaka) measured by Shiga Prefectural Fisheries Experimental Station (◇) and COD measured by Shiga Prefectural Institute of Public Health and Environmental Science (•) in Lake Biwa.

## CONCLUSION

We have compared three temperate lakes (>100 m depth), and shown some possible influences of global warming on dissolved oxygen concentrations in the hypolimnion. The increase of winter air temperature has especially reduced the turnover of water and/or density currents that supply dissolved oxygen to deeper layers. These large lakes provide us with sensitive indicators of global warming. The depletion of dissolved oxygen due to global warming influences signals a very real warning, because it can lead to the accumulation of nutrients and other toxic matter in the hypolimnia of lakes with catastrophic consequences. This may also cause serious impacts on benthic ecosystem communities such as the Isaza.

## REFERENCES

Dudgeon, D. (2000) Conservation of freshwater biodiversity in Oriental Asia: constraints, conflicts, and challenges to science and sustainability. *Limnology* 1, 237–243.

Forel, F. A. (1901) Handbuch der Seenkunde: allegemeine Limnologie. Bibbiothek geographische Handbbücher, Stuttgart, Germany.

Hosoda, T. & Hosomi, T. (2002) A simplified model to predict seasonal variations of vertical water quality distributions in Lake Biwa and its applications. *Advances in River Engineering, JSCE* **8**, 495–500 (in Japanese).

Ishiguro, N. (2002) Some hypothesis concerning the oxygen supply at the bottom of Lake Geneva. *Annals of Ochanomizu Geographical Society* (Ochanomizu Chiri) **43**, 33–40 (in Japanese).

Kira, T. (ed.) (1984) *Data Book of World Lakes*. Shiga Conference '84. Japan.

Kumagai, M., Vincent, W. F., Ishikwa, K. & Aota, Y. (2003) What we have learnt in Lake Biwa. In: *Freshwater Management Global versus Local Perspectives* (ed. by M. Kumagai & W. F. Vincent), 4–33. Springer-Verlag, Tokyo, Japan (in press).

Kumagai, M. & Fushimi, H. (1995) Inflows due to snowmelt. In: *Physical Processes in a Large Lake: Lake Biwa, Japan. Coastal and Estuarine Studies* (ed. by S. Okuda, J. Imberger & M. Kumagai), 129–139. AGU Washington DC, USA.

Livingstone, D. M. (1993) Temporal structure in the deep-water temperature of four Swiss lakes: a short-term climatic change indicator? *Verh. Internat. Verein. Limnol.* **25**, 75–81.

Livingstone, D. M. (1997) An example of the simultaneous occurrence of climate-driven "sawtooth" deep-water warming/cooling episodes in several Swiss lakes. *Verh. Internat. Verein. Limnol.* **26**, 822–828.

NIGLAS (1990) *Fuxian Lake*. Ocean Press, Beijing, China.

Robarts, R. D., Fraser, A. S., Hodgson, K. M. & Paquette G. M. (2002) Monitoring and assessing global water quality—the GEMS/water experience. *Ecohydrol. Hydrobiol.* **2**.

Vincent, W. F., Gibbs, M. M. & Spiegel, R. H. (1991) Eutrophication processes regulated by a plunging river inflow. *Hydrobiologia* **226**, 51–63.