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Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world

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Abstract

In summer 2003 central Europe suffered an unusually severe heat wave, with air temperatures similar to those predicted for an average summer during the late 21st century. We use a unique set of over half a century of lake data from two lakes in Switzerland to determine the effect of the 2003 heat wave on water temperature and oxygen conditions in order to assess how temperate lakes will react when exposed to the increased ambient summer air temperatures that will be encountered in a generally warmer world and to test the predictions of relevant simulation models. In both lakes, surface temperature and thermal stability in summer 2003 were the highest ever recorded, exceeding the long-term mean by more than 2.5 standard deviations. The extremely high degree of thermal stability resulted in extraordinarily strong hypolimnetic oxygen depletion. These results are consistent with the predictions of the simulation models. Additionally, the results indicate that climatic warming will increase the risk of occurrence of deep-water anoxia, thus counteracting long-term efforts that have been undertaken to ameliorate the effects of anthropogenic eutrophication.

Measurements and reconstructions of surface air temperatures indicate the existence of a marked global warming trend during the recent past (Folland et al. 2001) that is predicted to continue in the near future (Cubasch et al. 2001). The heat balance of the vast majority of lakes is governed almost exclusively by meteorological forcing across the air-water interface (Edinger et al. 1968; Sweers 1976), and such meteorological forcing also determines to a large extent the distribution of heat within lakes (Imboden and Wüest 1995). A change in climate conditions manifested in a change in local meteorological forcing will therefore result in changes in heat balance, temperature profiles, and vertical mixing in lakes, which in turn will affect vertical fluxes of nutrients and dissolved oxygen, and hence the productivity and composition of the lake plankton. A knowledge of how lake ecosystems will function in a warmer world is of considerable importance (Arnell et al. 2001). Physical modeling studies of medium-sized lakes in the temperate zone (Hondzo and Stefan 1993; Stefan et al. 1998; Peeters et al. 2002) predict that increasing air temperatures will cause increases in water temperature in the upper regions of the water column than in the lower regions, resulting in generally steeper vertical temperature gradients and enhanced thermal stability, and there is some evidence that this may indeed be gradually taking place globally (Livingstone 2003; Coats et al. in press).

During the summer of 2003, central Europe suffered an extraordinarily severe heat wave (Schär et al. 2004; Meehl and Tebaldi 2004). In the part of Switzerland lying north of the Alps, the mean air temperature in summer (June–August) exceeded the long-term mean (1864–2000) by more than 5 standard deviations (σ), making summer 2003 by far the warmest in this region since instrumental records began in 1864 (Schär et al. 2004). The occurrence of this heat wave—regardless of whether it is related to global warming or not

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Table 1. Characteristics of Lake Zurich and Greifensee. $P_{tot,w}$, mean total phosphorus concentration in winter (1975–2003); asl, above sea level.

	Lake Zurich	Greifensee
Altitude (m asl)	406	435
Area (km^2)	67	8
Maximum depth (m)	136	32
Mean depth (m)	51	18
Volume (km^3)	2.87	0.15
$P_{tot,w}$ (μg L^{-1})	69	191

(Schär and Jendritzky 2004; Stott et al. 2004)—provided an excellent opportunity to test empirically some general model predictions about how lakes in the temperate zone are likely to function in a warmer world. Here we compare mean summer water temperatures and oxygen concentrations in 2003 with corresponding long-term means and with the predictions of relevant physical simulation models.

Study sites and data

For our comparison we chose two lakes—Lake Zurich and Greifensee—that are only 10 km apart, and therefore subject to essentially the same climatic forcing, but which differ markedly with respect to size and trophic status (Table 1). Lake Zurich is medium-sized, deep, and mesotrophic to weakly eutrophic (Peeters et al. 2002), whereas Greifensee is comparatively small, much shallower, and highly eutrophic (Thomas and Örn 1982). These two lakes are among the few globally in which temperature and oxygen profiles have been recorded reliably and regularly for approximately half a century. The trophic status of each of the lakes is reflected in the oxygen concentrations in the deep water: whereas summer anoxia in Lake Zurich is generally confined to the bottom-water region close to the sediment/water interface (Örn 1980), in Greifensee the entire water column below 5 m often becomes almost completely anoxic by the end of the summer (Thomas and Örn 1982).

Historical water temperature and oxygen profiles have been recorded at approximately monthly intervals in Lake Zurich since 1936 (Kutschke 1966; Örn 1980; Livingstone 1993) and in Greifensee since 1956 (Thomas and Örn 1982). Usable data (i.e., with no gaps) extended from 1945 to 2003 for Lake Zurich, yielding 716 profiles of each variable, and from 1956 to 2003 for Greifensee, yielding 576 profiles of each variable. For Lake Zurich, which has a maximum depth of 136 m, the number of depths per profile varied between 17 and 43, but was typically about 19 (Kutschke 1966; Örn 1980; Livingstone 2003). For Greifensee, with a maximum depth of 32 m, the number of depths per profile varied between 9 and 14 (Thomas and Örn 1982).

Early measurements were carried out in both lakes using a high-quality reversing thermometer for temperature (Thomas 1949, 1955; Kutschke 1966) and the Winkler method for oxygen (Thomas and Örn 1982, 1984). From the 1960s onward in Lake Zurich, and from the 1970s onward in Greifensee, temperatures were measured by thermistor, either manually using a Wheatstone Bridge or automatically using a digital thermistor meter (H. Ambühl pers. com.; Livingstone 2003); in both cases, regular calibration was carried out against a calibrated mercury thermometer. Since 2001 in Lake Zurich and since 2000 in Greifensee, oxygen concentrations have been measured using oxygen electrodes that are calibrated regularly using the Winkler method. All measurements are considered to be accurate to within $\pm$0.1 K (temperature) and $\pm$0.25 mg L^{-1} (oxygen).

Because of irregularities in sampling depths and sampling intervals, historical limnological data are normally standardized by interpolating and averaging prior to analysis (Livingstone 2003). Here each measured profile was first standardized by converting it to a finer set of standard depths by cubic spline interpolation at intervals of 1 m. The temperature and oxygen values at each standard depth were then spline-interpolated over the entire period of the data at intervals of 1 d. For the temperatures, mean summer values were calculated as the arithmetic mean of the daily values from 01 June to 31 August.

For the purposes of the present study, and to conform with previous studies of the effects of climate change on Lake Zurich (Peeters et al. 2002; Livingstone 2003), the lake water column is divided into two regions, defined for simplicity in terms of depth rather than temperature gradient. The hypolimnion is defined here as the lowermost region within which temperature gradients did not exceed 0.5 K m^{-1} at any time in summer (JJA) during the period 1956–2003. The remaining region is denoted here as the epi/metalimnion. Defined thus, the boundary between the epi/metalimnion and hypolimnion lay at 20 m in Lake Zurich and 17 m in Greifensee. From each standardized summer temperature profile, the volume-weighted mean temperatures of the epi/metalimnion (T_{em}) and the hypolimnion (T_h) were calculated, as was the Schmidt stability (S), a measure of the thermal stability of the water column, which is defined as the work that would hypothetically be necessary to transform the observed density distribution into a vertically homogeneous density distribution by mixing with no net gain or loss of heat (Schmidt 1928; Idso 1973). From each standardized monthly oxygen profile, the volume-weighted mean hypolimnetic oxygen concentration (C_h) was calculated. The hypolimnetic oxygen depletion (HOD) in summer was defined as the difference of the June and September values of C_h. In the following, mean summer water temperatures are defined as the mean from 01 June to 31 August, and long-term means are defined with respect to the period 1956–2002 inclusive. Here, we compare mean summer water temperatures and oxygen concentrations in 2003 with the corresponding long-term means and with the predictions of relevant simulation models.

Daily minimum and daily maximum air temperatures measured at the Zurich meteorological station (located approximately 10 km from the deepest points of both Lake Zurich and Greifensee) were available uninterruptedly over the entire period covered by the present study. For the purposes of this study, the daily mean air temperature was defined as the mean of the daily minimum and daily maximum air temperatures. Mean summer air temperatures were calculated as the arithmetic mean of the daily values from 01 June to 31 August.

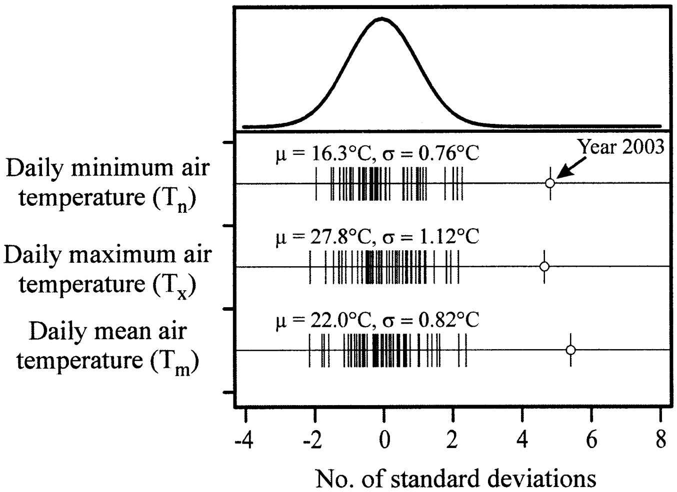

Fig. 1. Standardized summer means (01 June–31 August) of the daily minimum (T_n), daily maximum (T_x), and daily mean (T_m) air temperatures measured at the Zurich meteorological station. The variables were standardized by removing the long-term summer mean (μ, 1956–2002) and dividing by the long-term standard deviation (σ, 1956–2002). Data from the year 2003 are shown as open circles. The Gaussian distribution is depicted. In 2003, all variables illustrated exceeded their respective long-term means by at least 2σ.

The relevant simulation models taken from the literature are deterministic, one-dimensional topographic lake models that use subdaily weather data to simulate profiles of temperature (Hondzo and Stefan 1993; Stefan et al. 1998; Peeters et al. 2002) and oxygen (Stefan et al. 1996; Fang and Stefan 1997) in lakes of the temperate zone. The model predictions chosen are for average winter conditions followed by the 2003 extreme summer heat wave.

Results and discussion

As would be expected from Schär et al. (2004), the mean summer air temperature at the local meteorological station in 2003 considerably exceeded that in all other years from 1956 to 2002, both during the day (mean daily maximum) and during the night (mean daily minimum), with the overall mean summer air temperature being 5.4σ (+4.4°C) higher than the long-term mean (Fig. 1). In the nearby lakes, the mean water temperature of the epi/metalimnion (T_{em}) reflected this situation. Mean summer values of T_{em} in 2003 were the highest ever recorded, exceeding the long-term mean by 2.7σ (+2°C) in Lake Zurich and 2.8σ (+1.5°C) in Greifensee (Fig. 2). These values agree very well with the results of model simulations, which predict that a 4°C increase in ambient air temperature will result in an increase of 1–3°C in T_{em} (Hondzo and Stefan 1993; Stefan et al. 1998; Peeters et al. 2002).

Mean hypolimnetic temperatures (T_h) of both lakes in

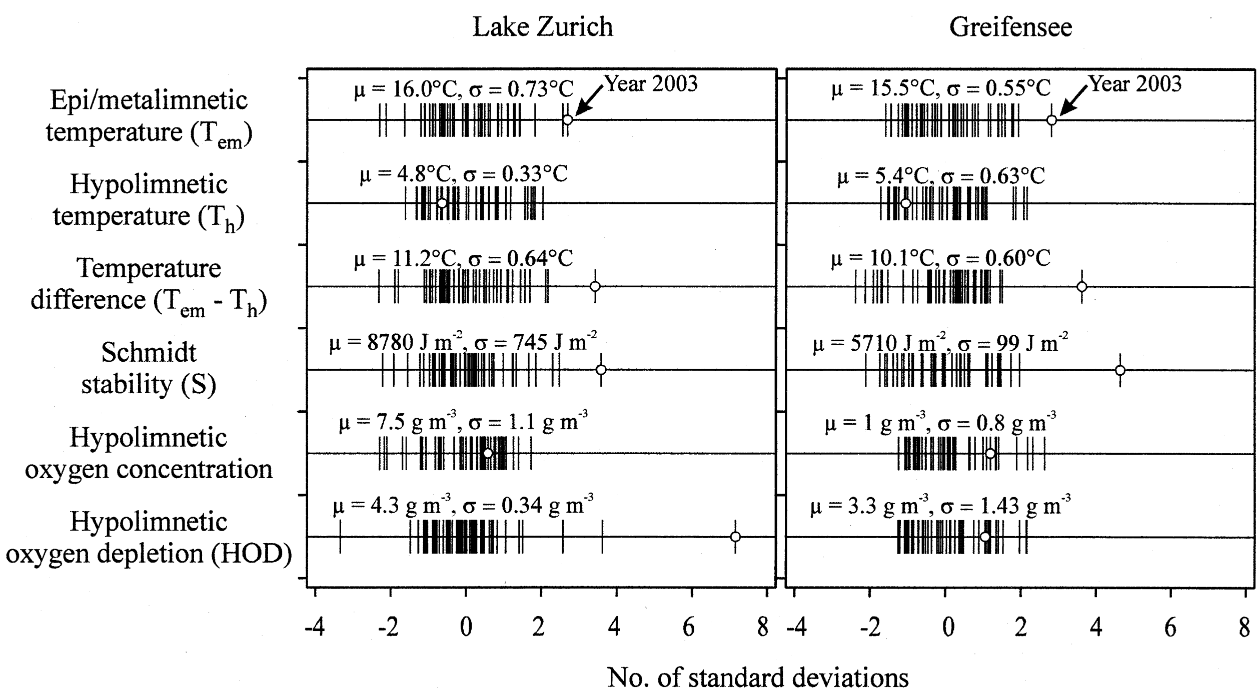

Fig. 2. Impact of the extremely hot summer of 2003 on selected physical characteristics of Lake Zurich and Greifensee. Shown are standardized values of the summer mean epi/metalimnetic temperature (T_{em}), the summer mean hypolimnetic temperature (T_h), their difference ($T_{em} - T_h$), the summer mean Schmidt stability (S), the summer mean hypolimnetic oxygen concentration, and the hypolimnetic oxygen depletion from June to September (HOD) in the two lakes. The variables (all means from 01 June–31 August except HOD) were standardized by removing the long-term summer mean (μ, 1956–2002) and dividing by the long-term standard deviation (σ, 1956–2002). Data from the year 2003 are shown as open circles. In 2003, all variables illustrated exceeded their respective long-term means by at least 2σ, except T_h (in both lakes) and HOD (in eutrophic Greifensee).

summer 2003, however, were lower than the equivalent long-term means (Fig. 2). The high temperatures in the epi/metalimnion, coupled with the relatively low hypolimnetic temperatures, resulted in extreme vertical temperature gradients, and consequently in an unusually high thermal stability in the water column, suppressing the downward turbulent mixing of warmer epi/metalimnetic water into the deep water. In summer 2003 in Lake Zurich, the mean temperature difference between epi/metalimnion and hypolimnion ($T_{em} - T_h$) exceeded its long-term mean by 3.4σ (+2.2°C), and the mean Schmidt stability S exceeded its long-term mean by 3.6σ (Fig. 2). In Greifensee the situation was similar, the equivalent figures being 3.6σ (+2.1°C) for ($T_{em} - T_h$) and 4.7σ for S. Relevant simulation models do indeed predict that an increase in air temperature will result in stronger stratification (e.g., De Stasio et al. 1994; Stefan et al. 1998; Peeters et al. 2002), with an increase in ($T_{em} - T_h$) of 1.5–3°C being predicted for situations like the one that occurred in 2003 (Stefan et al. 1998; Peeters et al. 2002).

The extreme thermal stability of the water column in summer 2003 had considerable consequences for the oxygen conditions in the hypolimnion. Although the mean hypolimnetic oxygen concentration in summer 2003 did not differ significantly from the long-term summer mean in either lake (Fig. 2), this was not true of the HOD, defined here as the decrease in the monthly mean hypolimnetic oxygen concentration from June to September. In Lake Zurich, the mean HOD in 2003 exceeded the long-term mean by 7.2σ (Fig. 2), and oxygen depletion at almost all depths within the hypolimnion was much greater than at any time since the beginning of the record (Fig. 3). Remarkably, this includes even the period of maximum eutrophication of the lake at the end of the 1970s and beginning of the 1980s. In contrast to this, no significant difference in summer HOD was found in eutrophic Greifensee, because a large proportion of the hypolimnion was already anoxic in most summers anyway. This pattern corresponds exactly to the predictions of relevant lake oxygen models. Oxygen consumption in summer is forecast to increase in deep, stratified lakes (Stefan et al. 1996; Fang and Stefan 1997). In mesotrophic and weakly eutrophic lakes with only slight anoxic tendencies (such as Lake Zurich now), HOD is predicted to increase more strongly in response to climate change than in highly eutrophic lakes (such as Greifensee), in which the hypolimnion is already largely anoxic (Stefan et al. 1996). The increase in HOD, which will be exacerbated by a longer period of stratification during summer, may result in extensive anoxia in the hypolimnion (Stefan et al. 1996; Fang and Stefan 1997), a situation more commonly associated with anthropogenic eutrophication (Wetzel 2001). This emphasizes the importance of deeply penetrative ventilative mixing during the cold season for hypolimnetic oxygen conditions. However, climate models indicate that air temperatures will also increase in winter and spring. This is likely to cause a reduction in the frequency and intensity of deep-water mixing (Peeters et al. 2002), resulting in uninterrupted deep-water oxygen depletion throughout the entire seasonal cycle (Livingstone 1997), the negative ecological consequences of which are well known (e.g., phosphorus dissolution from the sediments leading to internal loading, algal blooms, and fish kills; Carpenter et al. 1998). However, on a time scale of several years, winter warming may also result in a gradual increase in hypolimnetic temperature (Livingstone 1993, 1997) because of heat carry-over in the hypolimnion from one year to the next (Peeters et al. 2002). Nevertheless, even in this model scenario, climate warming is predicted to result in increased thermal stability (Peeters et al. 2002).

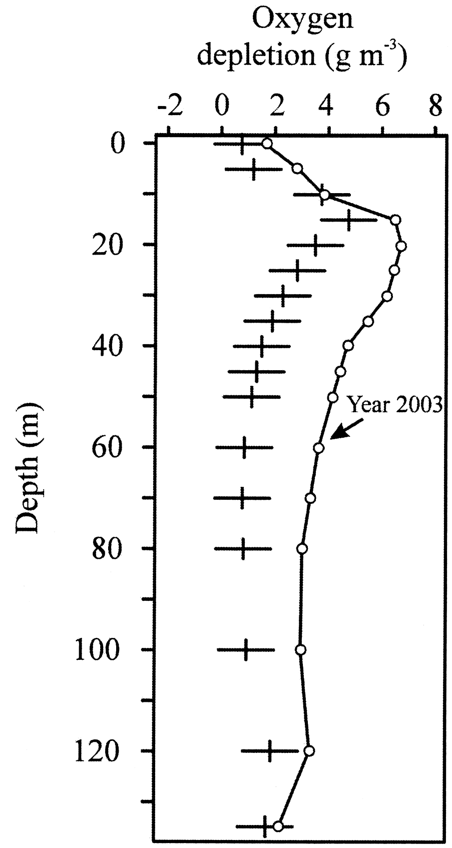

Fig. 3. Profile of oxygen depletion in Lake Zurich from June to September 2003 (open circles) compared with the mean June–September oxygen depletion profile from 1956 to 2002 (mean $\pm 1\sigma$). Calculation of the volume-weighted hypolimnetic oxygen depletion (HOD) in summer was based on the illustrated values below 20 m.

The results described above are based on a comparison of summer 2003 with the 47-yr baseline period 1956–2002, for which temperature and oxygen data are available from both Lake Zurich and Greifensee. However, the temperature and oxygen data sets from Lake Zurich alone actually extend back uninterruptedly to 1945 (extended 58-yr baseline period). The analysis described above was repeated for Lake Zurich using the extended baseline period and yielded the same results: in 2003, the thermal stability and the HOD were still the highest ever recorded.

The ''natural experiment'' described here has shown that summer climate conditions equivalent to those expected to prevail near the end of the present century have an extreme physical impact on temperate lakes, resulting in an unprecedented intensification of thermal stratification with a concomitant increase in HOD. It provides quantitative confirmation of the predictions made by relevant physical simulation models for a range of temperate Northern Hemisphere lakes covering a wide variety of morphometry and trophic status and provides a strong indication that the physical effect of climate warming on such lakes poses a potential threat to the largely successful long-term management efforts that have been undertaken to ameliorate the effects of anthropogenic eutrophication.

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