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The effect of the exceptionally mild European winter of 2006–2007 on temperature and oxygen profiles in lakes in Switzerland: A foretaste of the future?

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Abstract

The European winter of 2006–2007 was unusually mild, with record high mean winter air temperatures comparable with those predicted to become the norm by the end of the current century as a result of climate warming. In Lake Zurich and Greifensee, two neighboring Swiss perialpine lakes with several decades of data, mean lake temperatures for this winter were the highest ever recorded, as was thermal stability. Associated with the high thermal stability, mean winter oxygen concentrations in Lake Zurich were unusually high in the epilimnion and metalimnion, but normal in the hypolimnion. In Greifensee, however, which is much shallower, mean winter oxygen concentrations did not deviate substantially from the norm anywhere in the water column. From 17–19 January 2007, an unusually severe cyclonic storm, "Kyrill," traversed Europe. Monthly oxygen profiles suggest that the stabilizing effect of the mild winter on the two lakes was greatest before the occurrence of the storm, and that wind mixing resulted in a deepening of the mixed layer in both lakes. The mixing was able to encompass the entire water column of Greifensee, but not of Lake Zurich. These results, supported by more limited data from two other neighboring lakes, suggest that climate warming will likely inhibit complete mixing of some deep, temperate, normally monomictic lakes in winter even when extremely intense cyclonic storms occur. In shallower lakes, however, complete mixing is unlikely to be inhibited.

During the past century global mean surface temperatures have risen by about 0.74°C ± 0.18°C from 1906 to 2005 (Trenberth et al. 2007). Compared with the period 1980–1999, mean global air temperatures are predicted to increase by about 1.8–4.0°C (depending on the emissions scenario) by the end of the 21st century (Meehl et al. 2007). Regional climate projections show that the air temperature increase in Europe during the 21st century is likely to exceed the global mean increase (Christensen et al. 2007).

According to numerical model predictions, increases in air temperature of the magnitude expected are likely to have a substantial effect on water temperatures in temperate lakes (Hondzo and Stefan 1993; Stefan et al. 1998; Peeters et al. 2002) and on oxygen concentrations (Stefan et al. 1996; Fang and Stefan 1997). Despite the successes of such modeling efforts, predicting the potential effects of climate change on lakes remains a challenging task involving much uncertainty (Hondzo and Stefan 1992). However, the general results of model predictions are now supported by a growing body of observational evidence confirming that long-term changes in physical lake variables are occurring that correspond to model expectations. Observed phenomena include shifts toward later ice-on and earlier ice-off, with a corresponding reduction in the duration of ice cover (Livingstone 1997*a*; Magnuson et al. 2000); a reduction in the frequency of occurrence of ice cover (Hendricks Franssen and Scherrer 2008); increases in water temperature (Livingstone 2003; Arhonditsis et al. 2004; Coats et al. 2006); increases in thermal stability (Livingstone 2003; Coats et al. 2006); and increases in the duration of the period of stratification (Livingstone 2003). Because these long-term changes in physical lake properties are affecting the distribution of nutrients and oxygen within lakes (Straile et al. 2003), they are likely to have a substantial ecological influence, with likely effects manifesting themselves throughout the food web. Effects can also be expected on lake water quality and thus, potentially, on the quality of raw drinking water obtained from lakes.

For the majority of lakes, external meteorological forcing is the main determinant not only of the amount of heat stored within the lake, but also of the vertical distribution of this heat (Imboden and Wüest 1995). A long-term change in any of the important meteorological forcing factors—such as air temperature—is therefore likely to result in corresponding changes in mean lake temperature and in lake temperature profiles. Deep, temperate, open-water lakes typically exhibit a strong annual cycle, with thermal stratification being strong in summer but much weaker or absent in winter. The lack of stratification in winter can allow intense, penetrative

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Table 1. Characteristics of the four study lakes (z_h = depth of the upper boundary of the hypolimnion). Data from Zimmermann et al. (1991).

	Lower Lake Zurich	Greifensee	Lake of Walenstadt	Upper Lake Zurich
Altitude a.s.l. (m)	406	435	419	406
Surface area (km^2)	65	8	24	20
Volume (km^3)	3.3	0.15	2.42	0.47
Mean depth (m)	51	18	103	23
Maximum depth (m)	136	33	145	48
z_h (m)	20	17	20	30
Mean retention time (yr)	1.2	1.5	1.4	1.4
Trophic status	Mesotrophic	Hypertrophic	Oligotrophic	Mesotrophic

mixing to occur during periods of high wind speed. The sensitivity of lake variables to external forcing factors is therefore not constant throughout the year (Güss et al. 2000): deep-water oxygen concentrations, for instance, are affected much more by external factors such as wind speed in winter than in summer.

Oxygen is an important indicator of water quality and has been described as the most important lake variable aside from water itself (Wetzel 2001). As the sensitivity of deep-water oxygen concentrations to fluctuations in external forcing is highest during the period of lowest thermal stability, a long-term climate-related increase in the thermal stability of deep lakes during this period may be a potential threat to mixing intensity, and hence also to the replenishment of the deep water with oxygen. Furthermore, deep-water oxygen concentrations at the onset of stratification in spring are at their maximum, representing an initial oxygen pool that is available for consumption during the subsequent stratification period (Livingstone and Imboden 1996). Thus the meteorological forcing to which a lake is subjected during winter and spring leaves its signature in deep-water oxygen concentrations during the entire following seasonal cycle.

In addition to being affected by gradual changes in the mean values of important meteorological forcing variables, lake ecosystems can also be affected by extreme meteorological events. One example of this is the heat wave that occurred in large parts of Europe during the summer of 2003. The mean summer air temperature during this heat wave was equivalent to that predicted by regional climate models to occur in a normal summer during the period 2071–2100 (Schär et al. 2004). By comparing summer temperature and oxygen profiles measured in two Swiss lakes (Lake Zurich and Greifensee) in 2003 statistically with those measured in the same lakes during several previous decades, Jankowski et al. (2006) were able to assess the potential future response of these lakes to climate warming. During 2006–2007, Europe experienced an extremely mild winter with mean air temperatures that are likely to become the norm in the second half of this century (Maignan et al. 2008). Analogously to Jankowski et al. (2006), we attempt here to assess the potential effects of future warm winters on temperature and oxygen profiles in the same lakes and in two other neighboring lakes by comparing the profiles measured during the winter of 2006–2007 with long-term historical records.

Methods

Study lakes—The lakes chosen for this study—Lower Lake Zurich (often referred to simply as Lake Zurich), Greifensee, the Lake of Walenstadt, and Upper Lake Zurich—are all perialpine lakes located within 60 km of one another on the Swiss Plateau, and their altitudes differ by less than 30 m (Table 1). They can therefore be assumed to be subject to similar meteorological forcing (Anneville et al. 2004). Air temperature in particular is known to fluctuate coherently over the entire Swiss Plateau, and the surface water temperatures of lakes on the Swiss Plateau fluctuate coherently with each other and with regional air temperature (Livingstone and Lotter 1998). However, the study lakes differ markedly with regard to morphometry and trophic status (Table 1), both of which are known to affect the influence of climate on the deep water of Swiss perialpine lakes (Livingstone 1993*a*). Three of the four lakes are linked hydrologically: the Lake of Walenstadt is connected via the River Linth to Upper Lake Zurich, which is separated from Lower Lake Zurich by a natural sill that rises up to 3 m below the lake surface.

Depending on the weather conditions prevailing during winter, Lower Lake Zurich can behave either as a dimictic, a warm monomictic, or an oligomictic lake. The lake turns over twice during very cold winters, when the lake either freezes over or is inversely stratified, but ice cover is rare: since 1944 the lake has been completely ice-covered only once; viz. in the winter of 1962–1963 (Örn 1980; Peeters et al. 2002). Otherwise, the lake turns over once or, during very mild winters, only incompletely (Livingstone 1993*a*, 1997*b*).

Greifensee freezes over during cold winters, but not during mild winters, so the type of mixing regime depends critically on the severity of the winter. During the 51-yr Greifensee data record (1956–2007), the lake was frozen over in 21 winters (Thomas and Örn 1982; Hendricks Franssen and Scherrer 2008).

The Lake of Walenstadt is exposed to strong, locally amplified westerly winds (Anneville et al. 2004) that ensure the lake is always well mixed in winter, usually at a temperature slightly above the temperature of maximum density (Zimmermann et al. 1991). The lake has never frozen over within living memory (Zimmermann et al. 1991).

Upper Lake Zurich freezes over occasionally, but not as frequently as Greifensee (Hendricks Franssen and Scherrer

2008). Thus, depending on the severity of the winter, which determines whether the lake freezes over or not, the lake can turn over twice or only once. During the 35-yr Upper Lake Zurich data record (1972–2007), the lake was ice-covered in only four winters (Hendricks Franssen and Scherrer 2008).

During the past century, the trophic status of Swiss perialpine lakes, including the four study lakes, underwent substantial changes. A phase of anthropogenic eutrophication was followed by an oligotrophication phase that resulted from the successful implementation of remedial measures in the 1970s and 1980s (Zimmermann et al. 1991; Anneville et al. 2005). These changes in trophic status can be assumed to have affected oxygen concentrations (Zimmermann et al. 1991).

For simplicity, in previous studies of the effects of climate change on Lower Lake Zurich (Peeters et al. 2002; Livingstone 2003; Jankowski et al. 2006) the water column was divided into two static compartments: an epimetalimnion (i.e., the epilimnion and metalimnion taken together) and a hypolimnion. The hypolimnion was defined as the lower region within which temperature gradients did not exceed 0.5°C m^{-1} at any time during the period of data availability. For consistency with the previous studies, the distinction between epimetalimnion and hypolimnion is retained in the present study although the water column is typically not stratified in winter. The calculated depths of the boundary between epimetalimnion and hypolimnion (z_h) for the four lakes are listed in Table 1.

Because ice cover inhibits gas exchange across the air–water interface almost entirely, the presence or absence of ice cover on lakes is an extremely important determining factor for the reaeration of the deep water (Livingstone 1993*b*). In the present study, winters during which the presence of ice cover was reported in the literature (Hendricks Franssen and Scherrer 2008) were therefore excluded from the analysis.

Data—The data examined in the present study comprise air temperatures measured at the Zurich meteorological station (556 m above sea level [a.s.l.]) and profiles of water temperature and oxygen concentration measured in the four study lakes.

Daily mean air temperatures were calculated as the arithmetic mean of the daily minimum and daily maximum values, a standard meteorological method that performs well (Bilbao et al. 2002). Mean winter air temperatures were calculated as the arithmetic mean of the daily means from 01 December to 28 February.

Temperature and oxygen profiles were measured in each of the lakes at approximately monthly intervals. The profiles were measured at the deepest point of each lake except Upper Lake Zurich, where sampling was conducted in the second-deepest basin (Zimmermann et al. 1991). Irregularities in sampling depths and sampling intervals made it necessary to standardize the temperature and oxygen profiles spatially and temporally before conducting comparisons with the more regularly sampled meteorological data. This was done by interpolating the data in space and time. Each measured profile was first linearly interpolated at intervals of 0.25 m. The values obtained were then interpolated temporally at intervals of 1 d using a cubic spline function, and monthly arithmetic means calculated from these daily values. The monthly means were used to obtain volume-weighted winter (December–February) mean values of water temperature (T) and oxygen concentration ($[O_2]$) for the entire lake volume (T_{tot}), the epimetalimnion (T_{em}, $[O_2]_{em}$), and the hypolimnion (T_h, $[O_2]_h$) as described by Bührer (1979). The temperature difference between epimetalimnion and hypolimnion ($T_d = T_h - T_{em}$) was used as a measure of the thermal stability of the water column, as was the Schmidt stability (S), calculated according to Schmidt (1928) and Idso (1973). The difference of the mean oxygen concentration in the epimetalimnion and the hypolimnion ($[O_2]_d = [O_2]_h - [O_2]_{em}$) was used as a simple indicator of mixing intensity.

The duration of the period of available data differs among the lakes. Lower Lake Zurich and Greifensee are among the few lakes globally for which monthly profiles of water temperature and oxygen concentration have been measured regularly for over half a century: measurements are available almost uninterruptedly from Lower Lake Zurich since 1944, and from Greifensee since 1956. To assess the effect of the extremely mild winter of 2006–2007 on temperatures and oxygen concentrations in these two lakes, we compared mean water temperatures and oxygen concentrations in this winter with those in the previous 34 winters (1972–1973 to 2005–2006).

Monthly sampling in the Lake of Walenstadt and Upper Lake Zurich began in February 1972. Unfortunately, for financial reasons the sampling interval was reduced from monthly to quarterly in 2001 for the Lake of Walenstadt and in 2006 for Upper Lake Zurich, thus substantially reducing the value of these two time-series for climate effect studies. Luckily, however, both lakes were sampled in February 2007. To assess the effect of the extremely mild winter of 2006–2007 on temperature and oxygen in these two lakes, we therefore confined our analysis to the February values alone, and restricted the length of the comparison time-series to 1973–2000.

Statistical analysis—Using the Matlab® statistics toolbox we fitted a generalized extreme value distribution (GEV) to each of the time-series of winter means to be analyzed (except one, $[O_2]_{em}$ in Greifensee, that had an empirical probability distribution that was not amenable to fitting with the GEV). This yielded estimates of the probability density function and cumulative distribution function (cdf) of the winter mean of each variable in analytical form. The winter mean of 2006–2007 was then compared with the corresponding cdf to obtain an estimate of its probability of occurrence. The Kolmogorov–Smirnov goodness-of-fit test revealed no significant deviation between the empirical probability distribution and the fitted GEV distribution for any of the data sets analyzed. To ensure that the interpolation process did not introduce bias into the parameters of the GEV, a bootstrapping technique (Efron 1979) was applied that allows the magnitude of such an effect to be determined. The fitted

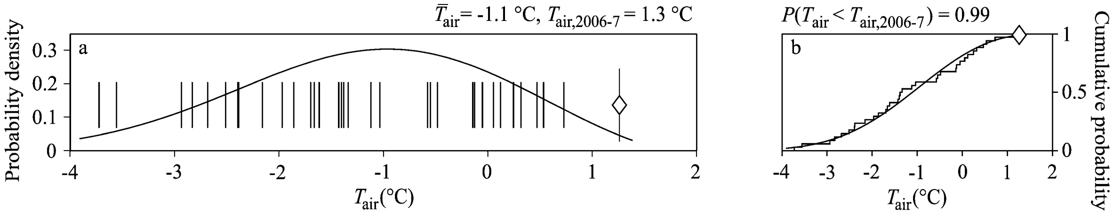

Fig. 1. (a) Mean winter (December–February) air temperatures (T_{air}) at Zurich meteorological station for the winters of 1972–1973 to 2006–2007. Each vertical line represents one mean winter value; the value for the winter of 2006–2007 ($T_{air,2006\text{-}7}$) is represented by an open diamond and an elongated line. The curve represents the generalized extreme value (GEV) probability density function fitted to the data. The mean value over the entire study period ($\overline{T}_{air}$) is also given. (b) Comparison of empirical and fitted cumulative distribution functions of T_{air}. $T_{air,2006\text{-}7}$ is shown as an open diamond and the probability of occurrence of values smaller than $T_{air,2006\text{-}7}$, calculated from the fitted GEV distribution, is indicated.

GEV was found to be robust in all cases, implying that the interpolation process does not bias the results. This is particularly true of the tail of the GEV, where the extremes are located.

Results

Air temperature—A comparison of mean winter air temperatures at Zurich from 1891–1892 to 2006–2007 revealed that the winter of 2006–2007 was the mildest in the entire 116-yr period. Considering solely the study period 1972–1973 to 2006–2007, the mean air temperature in the winter of 2006–2007 ($T_{air,2006\text{-}7} = 1.3°C$) exceeded the long-term mean ($\overline{T}_{air} = -1.1°C$) by 2.4°C. On the basis of the fitted GEV distribution, the probability of this occurring is $P(T_{air} \geq T_{air,2006\text{-}7}) = 0.01$ (Fig. 1); i.e., once per century.

Water temperatures—In both Lower Lake Zurich and Greifensee, the highest value of T_{tot} within the period 1972–1973 to 2006–2007 occurred during the extremely mild winter of 2006–2007 (Figs. 2a, 3a). The same was true of T_{em} in both lakes, but the deviation from the long-term mean was even more extreme, with $T_{em,2006\text{-}7}$ exceeding the long-term mean by 1.5°C in Lower Lake Zurich, giving $P(T_{em} \geq T_{em,2006\text{-}7}) = 0.01$ (Fig. 2b), and by 2.0°C in Greifensee, giving $P(T_{em} \geq T_{em,2006\text{-}7}) = 0.03$ (Fig. 3b). However, the two lakes differed with regard to T_h. In Greifensee, $T_{h,2006\text{-}7}$ was also the highest recorded during the study period ($T_{h,2006\text{-}7} = 5.7°C$; Fig. 3c), but in Lower Lake Zurich, T_h did not deviate notably from its long-term mean ($T_{h,2006\text{-}7} = 5.2°C$; Fig. 2c). For both lakes, the temperature difference $T_d = T_{em} - T_h$ in the winter of 2006–2007 was the highest observed during the study period, with $T_{d,2006\text{-}7} = 1.8°C$ for Lower Lake Zurich (Fig. 2d) and 0.8°C for Greifensee (Fig. 3d). As the temperature gradient within the water column can be regarded as a simple indicator of thermal stability, it is not surprising that the highest mean winter Schmidt stability (S) in both lakes also occurred in 2006–2007 ($S_{2006\text{-}7}$ = 528.2 J m^{-2} and 22.2 J m^{-2}; Figs. 2e, 3e). This implies that vertical mixing was strongly hampered during the winter of 2006–2007. Temperature profiles are available from Lower Lake Zurich back to 1944 and from Greifensee back to 1956, which allowed the comparisons to be repeated on the basis of longer study periods. For both lakes, the results obtained were similar to those obtained on the basis of the shorter study period: the highest values of T_{em}, T_d, and S occurred in the winter of 2006–2007.

Oxygen concentrations—In contrast to the anomalous behavior of some of the physical limnological variables in the winter of 2006–2007, and despite the abnormally high thermal stability that prevailed then, anomalies in oxygen concentration are much less striking (Figs. 4, 5). In the winter of 2006–2007, the mean oxygen concentration in the epimetalimnion of Lower Lake Zurich ($[O_2]_{em,2006\text{-}7}$ = 9.9 g O_2 m^{-3}) was the second highest of the entire study period. The mean hypolimnetic oxygen concentration ($[O_2]_{h,2006\text{-}7}$ = 7.2 g O_2 m^{-3}), however, lay well within its usual historical range. This combination resulted in the highest value of $[O_2]_d$ during the entire study period ($[O_2]_{d,2006\text{-}7}$ = 2.7 g O_2 m^{-3}), providing further evidence for the abnormal lack of vertical mixing in Lower Lake Zurich during this winter. The highest values of both $[O_2]_{em}$ and $[O_2]_h$ shown in Fig. 4a and 4b, respectively, occurred in the winter of 1981–1982. This was a result of the abnormally long duration of homothermy in this winter (Rempfer et al. 2009). In Greifensee, neither $[O_2]_{em}$, $[O_2]_h$, nor $[O_2]_d$ showed an abnormally large deviation from the long-term mean in the winter of 2006–2007, although $[O_2]_d$ did substantially exceed its long-term mean ($[O_2]_{d,2006\text{-}7}$ = 2.2 g O_2 m^{-3}; Fig 5c).

The deviations between the oxygen concentrations measured during the winter of 2006–2007 and the long-term historical data are illustrated in more detail in Figs. 6, 7, and 8. In Lower Lake Zurich (Fig. 6a–c), negative oxygen concentration anomalies of more than one standard deviation (1σ, calculated from the GEV distribution) were rare during the winter of 2006–2007. Positive anomalies, however, occurred above 15 m in December 2006, above 30 m in January 2007, and above 40 m in February 2007. In Greifensee (Fig. 7a–c) the situation was different: in December 2006 oxygen concentrations below 15 m were below average, and around 15 m substantially (i.e., more than 1σ) below average. Simultaneously, oxygen concentrations closer to the surface (0–5 m) were abnormally high (more than 1σ above the long-term mean). In January and February 2007, oxygen concentrations at all depths were within 1σ of the long-term mean, and the oxygen profiles were almost orthograde.

Because monthly sampling was replaced by quarterly sampling in the Lake of Walenstadt in 2001 and in Upper

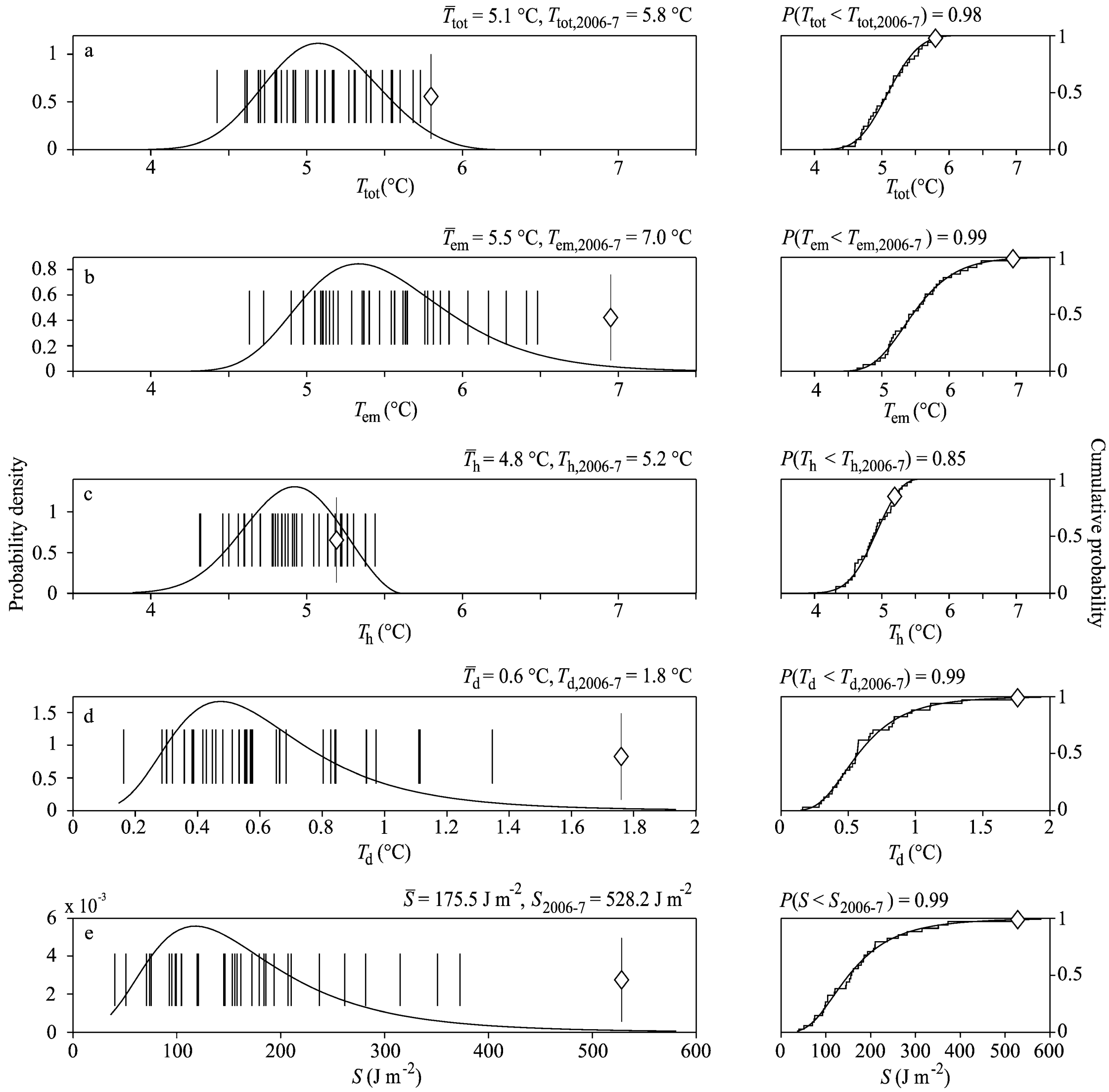

Fig. 2. Mean winter (December–February) values of various thermal lake variables in Lower Lake Zurich for the winters of 1972–1973 to 2006–2007. (a) Mean winter temperature of the entire lake (T_{tot}); (b) mean winter temperature of the epimetalimnion (T_{em}); (c) mean winter temperature of the hypolimnion (T_h); (d) the difference of T_{em} and T_h ($T_d = T_{em} - T_h$); (e) Schmidt stability (S). For further information *see* the caption to Fig. 1.

Lake Zurich in 2006, monthly comparisons are not possible for these lakes. Instead, we compared the oxygen concentrations measured in February 2007 with the February means and standard deviations calculated from the GEV distribution for the 28-yr period 1972–1973 to 1999–2000 (Fig. 8). In these two lakes, oxygen concentrations in February 2007 exceeded their long-term mean value by more than 1σ at several depths. In the Lake of Walenstadt (Fig. 8a), deep-water oxygen concentrations below about 60 m were substantially lower than in other years. Oxygen concentrations in the upper water layers also tended to lie below their long-term mean, but the anomalies did not exceed 1σ. Upper Lake Zurich (Fig. 8b) behaved differently: between the surface and 20-m depth, oxygen concentrations were substantially (more than 1σ) lower than long-term mean values, but deeper in the water column (30 and 36 m) the oxygen concentrations were within 1σ of the long-term mean.

Discussion

During the extremely mild European winter of 2006–2007, mean winter water temperatures in the epimetalimnion of both Lower Lake Zurich and Greifensee were the highest ever recorded (Figs. 2b, 3b). We attribute this finding to two factors. First, air temperature is an extremely important forcing variable that is involved in many of the processes that determine a lake's heat balance (Edinger et al. 1968; Sweers 1976), so milder winters will automatically be reflected in higher mean lake temperatures. More importantly, however, an increase in the frequency of occurrence of mild winters during the past few decades, related to climate warming and, in Europe, to the long-term behavior of the North Atlantic Oscillation, has resulted in the increased suppression of deeply penetrative mixing in temperate lakes that are usually perceived as being holomictic. Such lakes are

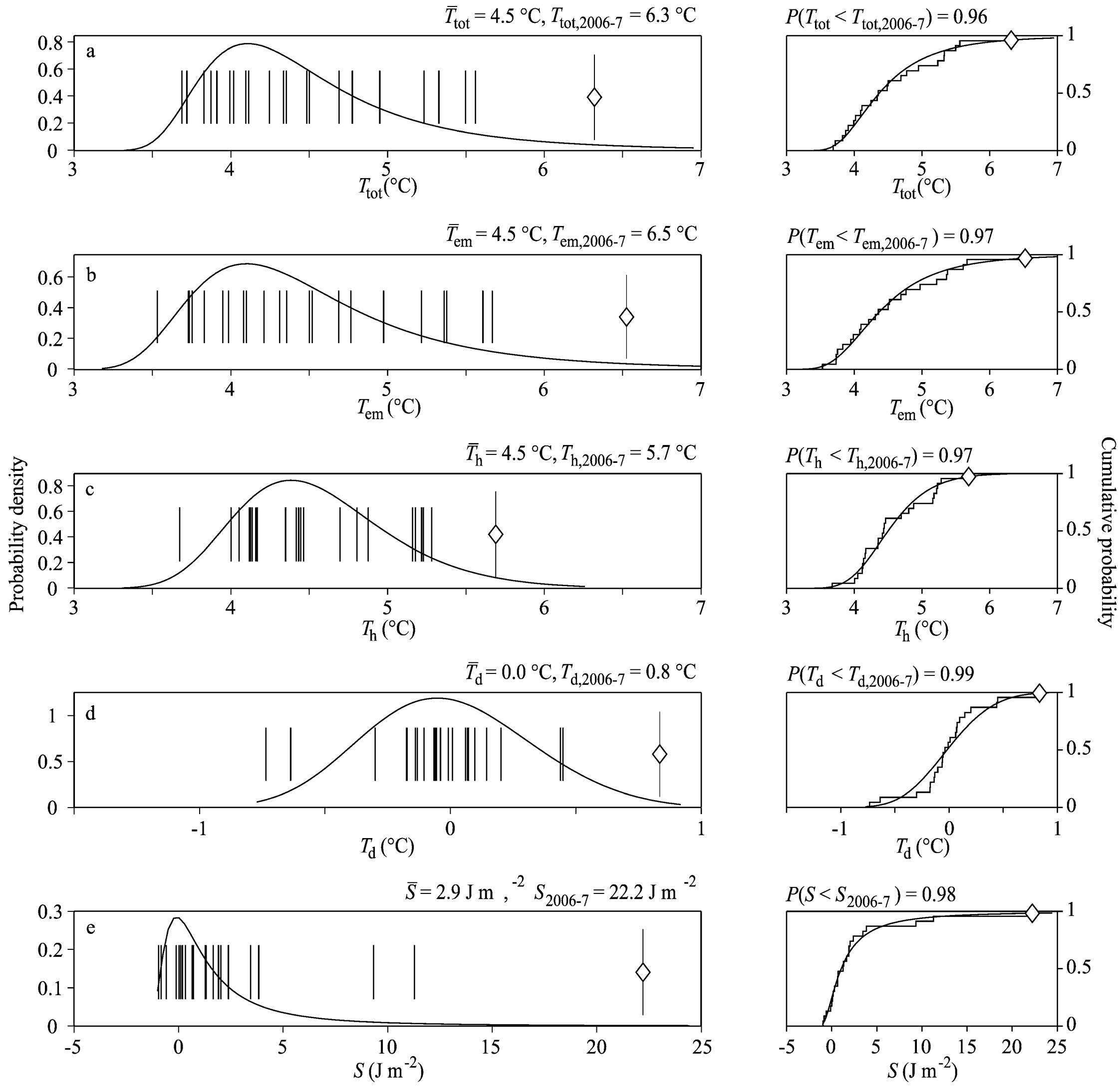

Fig. 3. As Fig. 2, but for Greifensee.

increasingly maintaining some degree of thermal stratification throughout the entire winter and are effectively undergoing a change in their physical character from monomictic to oligomictic (Livingstone 2008). Specifically, this has been shown to be the case for Lower Lake Zurich (Livingstone 1993*a*, 1997*b*, 2003). Thus, during mild winters mixing may be weak and confined to the uppermost part of the water column. The resulting suppression of the upward transport of cool water from the deep hypolimnion amplifies the effect of mild winters on the surface layers.

The occurrence of an extremely mild winter like that of 2006–2007 also has an effect on the deep water, but the magnitude of this effect depends strongly on lake morphometry. In deep Lower Lake Zurich (maximum depth z_m = 136 m), the mean value of T_h during the winter of 2006–2007 was normal; mixing was too weak to affect the deep-water temperature appreciably. There was essentially no deep-water renewal, and T_h was determined largely by the duration and intensity of mixing during the previous spring and earlier. In Greifensee, which is much shallower (z_m = 33 m), the mixing was strong enough to result in unusually high temperatures throughout the water column.

In both lakes, however, thermal stability, expressed either in terms of the temperature difference $T_d = T_{em} - T_h$ or in terms of the Schmidt stability S, was the highest ever recorded. Normally, Greifensee mixes completely at a temperature between 4.0°C and 5.0°C, making it essentially neutrally stable (Fig. 3b–e). Although mixing did take place to a certain extent during the winter of 2006–2007, it was apparently not vigorous enough to erode the thermocline completely. Modeling studies predict that climate warming will result not only in higher lake water temperatures, but also in an increase in the temperature gradient within the water column, and hence will lead to an increase in thermal stability (Fang and Stefan 1999; Peeters et al. 2002). In Lower Lake Zurich from the 1950s to the 1990s, a long-term increase in winter thermal stability occurred that corresponds to a 68% increase in Schmidt stability (Livingstone 2003). On the basis of the abnormally high positive deviations of S in both Lower Lake Zurich and Greifensee from their respective long-term means, an

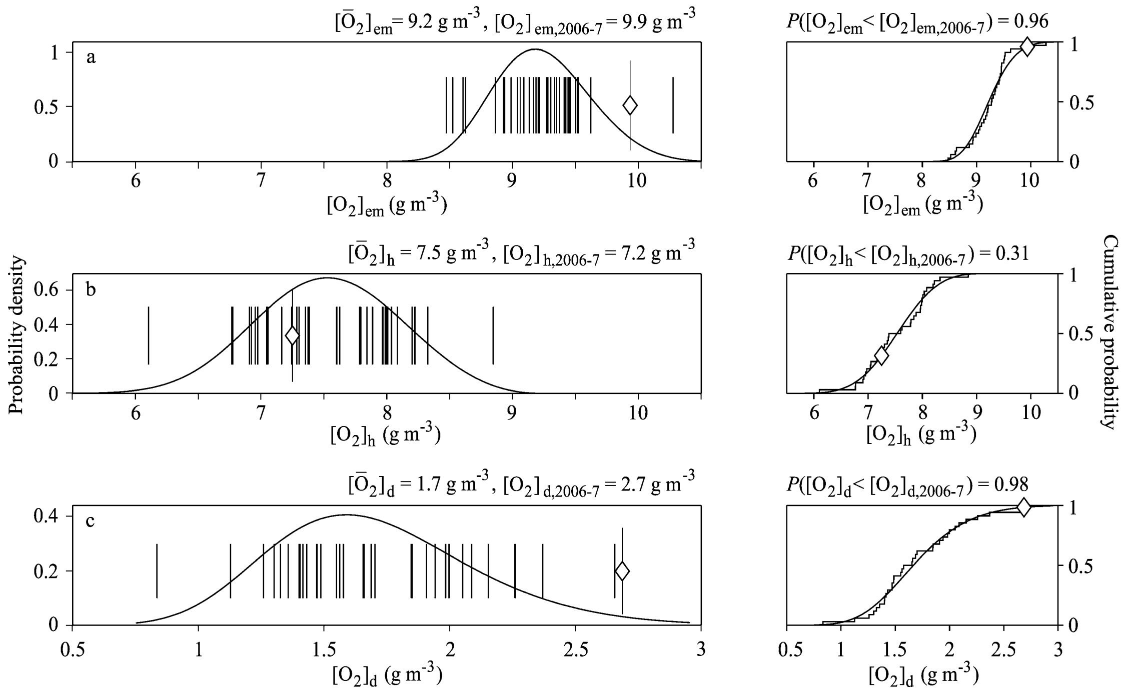

Fig. 4. Mean winter (December–February) oxygen concentrations in Lower Lake Zurich for the winters of 1972–1973 to 2006–2007. (a) Mean winter oxygen concentrations in the epimetalimnion ($[O_2]_{em}$); (b) mean winter oxygen concentrations in the hypolimnion ($[O_2]_h$); (c) the difference of $[O_2]_{em}$ and $[O_2]_h$ ($[O_2]_d = [O_2]_{em} - [O_2]_h$). For further information *see* the caption to Fig. 1.

adverse effect on the replenishment of the deep water with oxygen in both lakes seems likely. For Lower Lake Zurich the probable negative consequences of an increase in winter thermal stability on deep-water oxygen concentrations was specifically pointed out by Peeters et al. (2002).

Oxygen profiles provide a useful natural tracer of mixing intensity. In deep, temperate Lake Constance, for instance, weak mixing during mild winters is known to result in only partial erosion of vertical oxygen concentration gradients (Straile et al. 2003). Stabilization of the water column during a mild winter might be expected to result in higher-than-normal oxygen concentrations in the uppermost part of the water column, because oxygen taken up from the atmosphere or produced biologically will not be lost to the

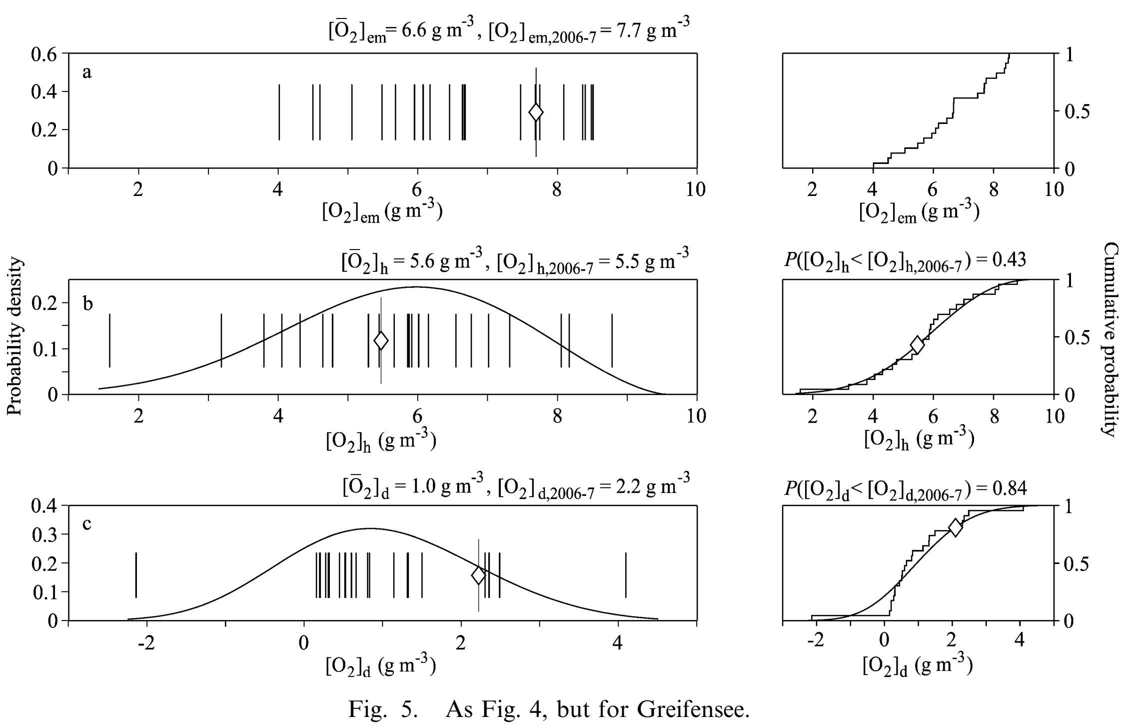

Fig. 5. As Fig. 4, but for Greifensee.

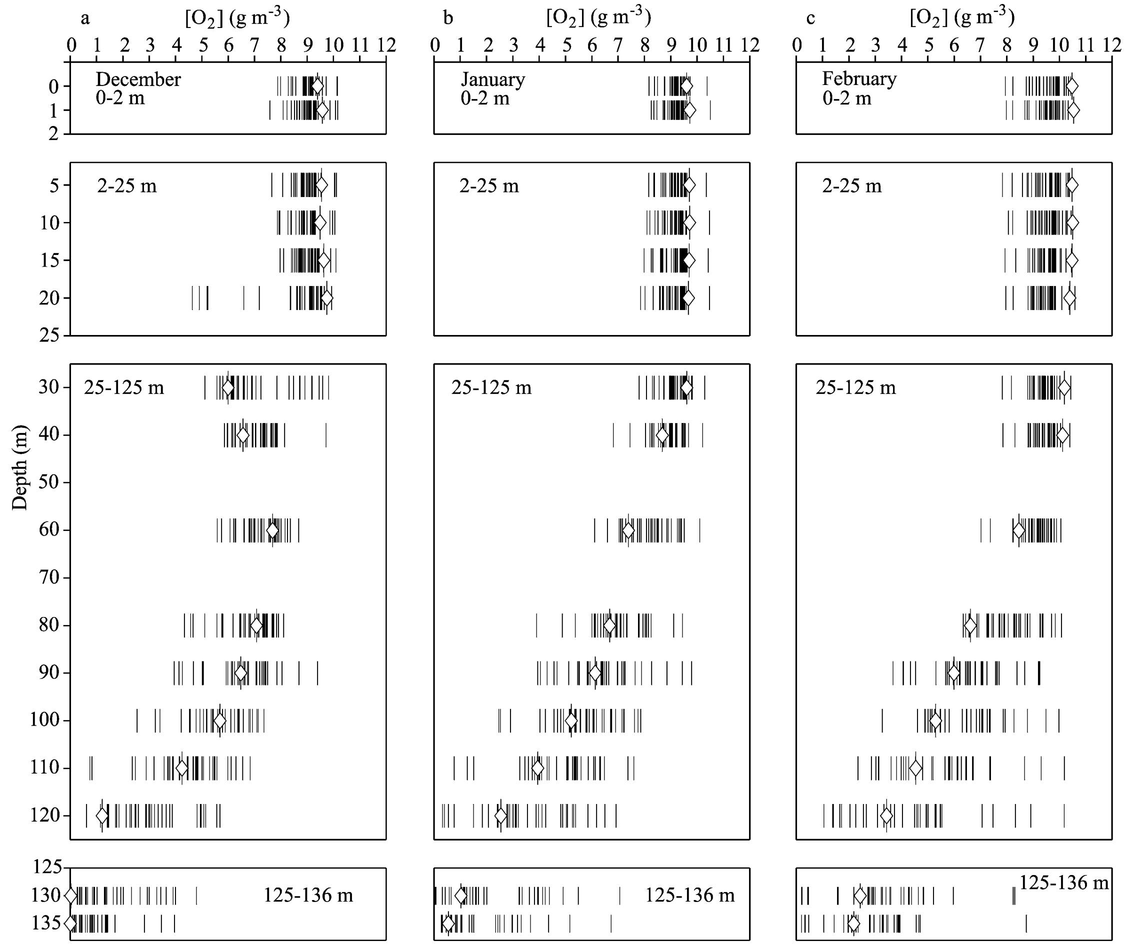

Fig. 6. Comparison of profiles of monthly mean oxygen concentration $[O_2]$ in Lower Lake Zurich for (a) December, (b) January, and (c) February from the winter of 1972–1973 to the winter of 2006–2007. Each vertical line represents one monthly mean value; the value for the winter of 2006–2007 ($T_{air,2006\text{-}7}$) is represented by an open diamond and an elongated line. The water column was split up into different depth ranges for clarity; note that the depth scales differ among panels. The mean values and standard deviations mentioned in the text were calculated from the GEV distribution fitted to the illustrated data.

relatively oxygen-poor hypolimnion by mixing, and because stratification will tend to stabilize the phytoplankton and, assuming sufficient nutrient availability, will therefore tend to enhance biological oxygen production. In the winter of 2006–2007 both temperature and oxygen profiles indicate that Lower Lake Zurich was stably stratified, and the mean value of $[O_2]_{em}$ was indeed extremely high, being exceeded only by its value in the winter of 1981–1982, when the duration of homothermy—and hence presumably also mixing—was unusually long (Rempfer et al. 2009). Thus at

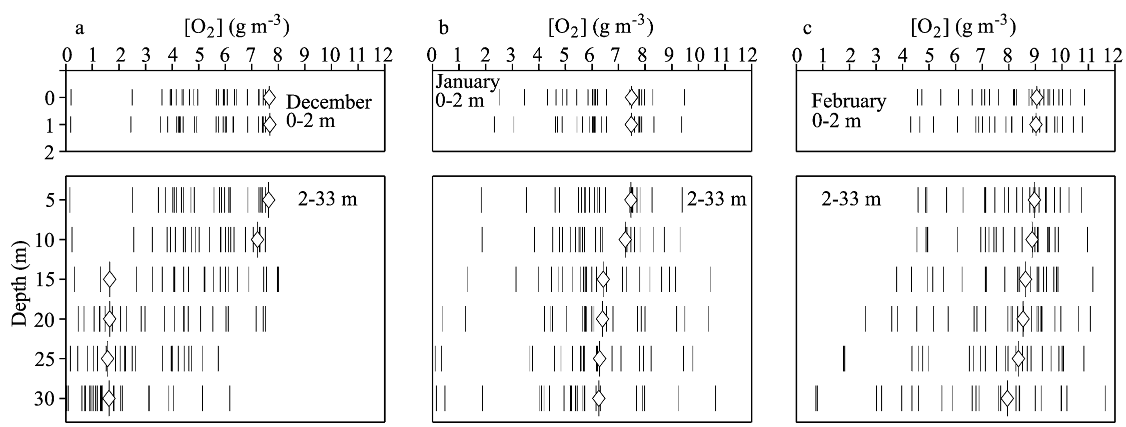

Fig. 7. As Fig. 6, but for Greifensee.

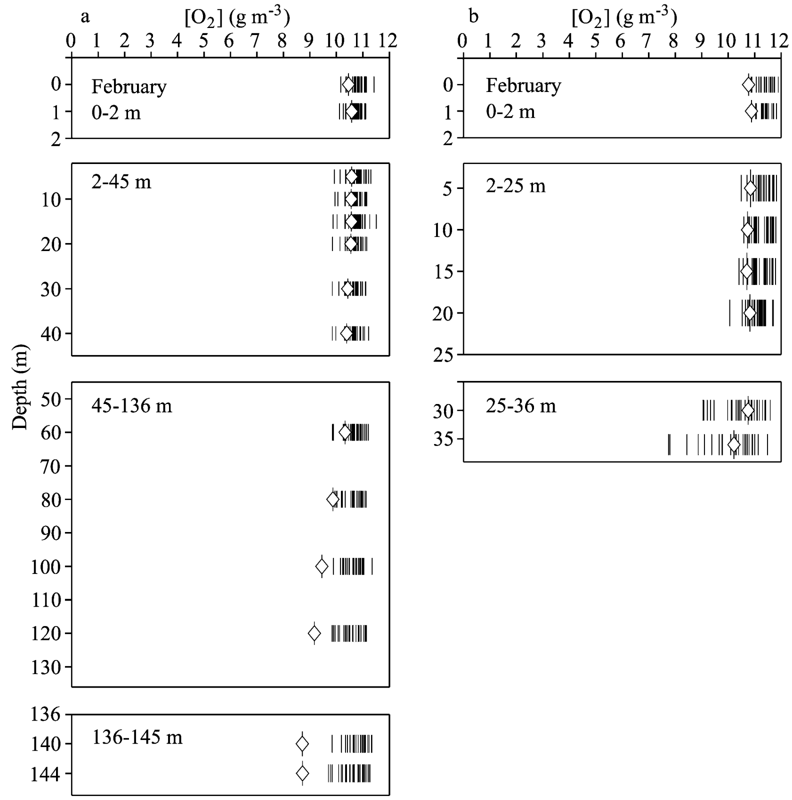

Fig. 8. As Fig. 6, but for (a) the Lake of Walenstadt and (b) Upper Lake Zurich. The oxygen profiles measured in Lake of Walenstadt on 19 February 2007 and in Upper Lake Zurich on 05 February 2007 are compared with the February monthly means in these lakes from 1973 to 2000.

least two mechanisms can result in high values of $[O_2]_{em}$ in winter: long-lasting thermal stratification (as in 2006–2007), or the opposite case, long-lasting homothermy, which is favorable to mixing (as in 1981–1982). This suggests that the effect on $[O_2]_{em}$ of the uptake of atmospheric oxygen during long, vigorous mixing (as in 1981–1982) can sometimes outweigh the effect of oxygen loss to the lower water column by downward mixing (Rempfer et al. 2009).

In both Lower Lake Zurich and Greifensee, $[O_2]_h$ in 2006–2007 differed little from its respective long-term mean (Figs. 4b, 5b). However, unlike Lower Lake Zurich, in Greifensee $[O_2]_{em}$, and hence $[O_2]_d$, were only slightly higher than normal. The reason for the difference, which is primarily morphometric, is apparent from the monthly mean oxygen profiles illustrated in Figs. 6 and 7. In December 2006, mixing extended down to ~ 20 m in Lower Lake Zurich and ~ 10 m in Greifensee. By January 2007 the mixed layer had deepened to over 30 m in both lakes, encompassing only ~ 45% of the volume of Lower Lake Zurich, but essentially the entire volume of Greifensee. In December, $[O_2]_{em}$ in Greifensee was much higher than usual for this month and $[O_2]_h$ much lower, but the subsequent deepening of the mixed layer resulted in both $[O_2]_{em}$ and $[O_2]_h$ approaching much more closely their long-term mean values. The temporal resolution of the available limnological measurements is not sufficient to allow the deepening of the mixed layer to be analyzed in detail. However, it is likely that the severe cyclonic storm Kyrill, which traversed Europe from 17 to 19 January 2007, causing major damage and loss of life (Fink et al. 2009), was the major factor resulting in this deepening. On 22 January, just after the passage of Kyrill, profiles of temperature, electrical conductivity, and oxygen were measured in Greifensee. These profiles show that the lake was very well mixed on that date: the water temperature and electrical conductivity profiles were homogeneous, with values of 6.0°C and 484 μS cm^{-1}, respectively, and the oxygen profile was nearly so, with values decreasing by only 0.4 g O_2 m^{-3} from the surface (7.5 g O_2 m^{-3}) to 30 m depth (7.1 g O_2 m^{-3}) in this hypertrophic lake. In February 2007, deep-water oxygen concentrations attained normal values not only in Greifensee (Fig. 7c) but also in Upper Lake Zurich (Fig. 8b). This suggests that any negative influence the extremely mild winter may have had on deep-water oxygen concentrations in these two shallow lakes was confined to December, and was subsequently effectively neutralized by deeply penetrative wind-driven mixing, likely associated with Kyrill. In deep Lower Lake Zurich, however, despite the occurrence of Kyrill, wind-induced mixing did not penetrate below ~ 50 m depth. Data from another deep lake, the Lake of Walenstadt, corroborate this observation. Deep-water oxygen concentrations in the Lake of Walenstadt in February 2007 were still substantially below their long-term mean values (Fig. 8a), suggesting that in this lake also, wind-induced mixing during Kyrill was insufficient to counter the negative effects of the mild winter on oxygen concentrations below ~ 60-m depth.

The results of this study suggest that future mild winters associated with climate change (Christensen et al. 2007) are likely to result in enhanced thermal stability in lakes, and that this will affect lake oxygen concentrations. However, the effects of episodic wind mixing in winter differ substantially between shallow lakes such as Greifensee and Upper Lake Zurich, and deep lakes such as Lower Lake Zurich and the Lake of Walenstadt. In shallow lakes, wind mixing is potentially able to neutralize the stabilizing effect of increasingly mild winters to such an extent that even an extremely mild winter might have almost no effect on oxygen concentrations at the end of winter. In deeper lakes such as Lower Lake Zurich, enhanced thermal stability in future mild winters is much more likely to result in oxygen concentrations that are above normal in the epimetalimnion and below normal in the hypolimnion. This is highlighted by the fact that even the occurrence of an unusually severe winter storm like Kyrill in January 2007 was unable to counter the effect of the mild winter of 2006–2007 on oxygen concentrations in Lower Lake Zurich and the Lake of Walenstadt. Current model projections of future wind conditions under Intergovernmental Panel on Climate Change climate scenarios indicate that, although extratropical cyclonic storms may occur less frequently, they will increase in intensity (Christensen et al. 2007). In particular, by the end of the current century central Europe will probably experience higher surface wind speeds than it does at present, suggesting that intense storms such as Kyrill might serve as good case studies to assess the likely effects of future storms (Fink et al. 2009). Thus, although severe winter storms may be able to neutralize the effect of mild winters on oxygen profiles in shallow lakes in the future, this may not be the case for deep lakes, on which future winter warming is likely to have a disproportionately large effect. One consequence of climate-related decreasing hypolimnetic oxygen concentrations in deep lakes is the upward expansion of the anoxic zone (Livingstone and Imboden 1996). The associated dissolution and remobilization of phosphorus from the sediments could potentially result in increased eutrophication, the mitigation of which would pose a difficult lake management problem. The reduction in the duration and intensity of mixing that will occur in a warmer climate might reduce the severity of this problem in individual years by hindering upward transport of the dissolved phosphorus, but mixing will not be totally suppressed. During occasional cold winters vigorous mixing events will still occur, transporting accumulated dissolved phosphorus from the hypolimnion into the photolytic zone and stimulating phytoplankton growth.

The extremely mild winter of 2006–2007 is predicted to be similar to a normal winter at the end of the current century. Despite this, it should be noted that a degree of uncertainty is involved in projecting the results of this study into the future. This is because, although the probability distributions illustrated in Figs. 1–5 are based on 35 yr of data, the historical record includes only one winter mild enough to be considered comparable with future normal winters. The cumulative effect of many consecutive mild winters and warm summers—the likely consequence of climate change—will differ from the effect of only one mild winter. Although this might exacerbate the effects described here, it should also be noted that as deep-water temperatures increase, lakes will tend to mix completely again, but at higher temperatures, thus allowing deep-water ventilation to occur (Livingstone 1997*b*). In addition, it should be noted that global and regional change are both far broader than just climate change: future changes in factors such as land use and water management practice that are highly relevant to lake trophic status, and hence to oxygen concentrations, are almost impossible to estimate. Nevertheless, this study does provide strong indications of the likely future response of temperature and oxygen conditions in lakes to increasingly mild winters.

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