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.
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. 1991). 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 1993a). 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 1993a, 1997b).

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; Hendriks 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).

Methods

Study lakes—The lakes chosen for this study—Lower Lake Zurich, Greifensee, 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 1993a). 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 1993a, 1997b).

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Lower Lake Zurich</th>
<th>Greifensee</th>
<th>Lake of Walenstadt</th>
<th>Upper Lake Zurich</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude a.s.l. (m)</td>
<td>406</td>
<td>435</td>
<td>419</td>
<td>406</td>
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<tr>
<td>Surface area (km²)</td>
<td>65</td>
<td>8</td>
<td>24</td>
<td>20</td>
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<tr>
<td>Volume (km³)</td>
<td>3.3</td>
<td>0.15</td>
<td>2.42</td>
<td>0.47</td>
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<tr>
<td>Mean depth (m)</td>
<td>51</td>
<td>18</td>
<td>103</td>
<td>23</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
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<td>33</td>
<td>145</td>
<td>48</td>
</tr>
<tr>
<td>zₜ (m)</td>
<td>20</td>
<td>17</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Mean retention time (yr)</td>
<td>1.2</td>
<td>1.5</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Trophic status</td>
<td>Mesotrophic</td>
<td>Hypertrophic</td>
<td>Oligotrophic</td>
<td>Mesotrophic</td>
</tr>
</tbody>
</table>
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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 (Poeters 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_b) 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 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_b) for the four lakes are listed in Table 1.

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**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 ([O₂]) for the entire lake volume (T_\text{tot}), the epimetalimnion (T_\text{em}, [O₂]_\text{em}), and the hypolimnion (T_h, [O₂]_h) as described by Bührrer (1979). The temperature difference between epimetalimnion and hypolimnion (T_d = T_h - T_\text{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 ([O₂]_d = [O₂]_h - [O₂]_\text{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 uninterrupted 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, [O₂]_\text{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
Effect of a mild winter on Swiss lakes

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 ([O2]em,2006-7 = 9.9 g O2 m⁻³) was the second highest of the entire study period. The mean hypolimnetic oxygen concentration ([O2]h,2006-7 = 7.2 g O2 m⁻³), however, lay well within its usual historical range. This combination resulted in the highest value of [O2]tot during the entire study period ([O2]tot,2006-7 = 2.7 g O2 m⁻³), providing further evidence for the abnormal lack of vertical mixing in Lower Lake Zurich during this winter. The highest values of both [O2]em and [O2]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 [O2]em, [O2]h, nor [O2]tot showed an abnormally large deviation from the long-term mean in the winter of 2006–2007, although [O2]tot did substantially exceed its long-term mean ([O2]tot,2006-7 = 2.2 g O2 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
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
increasingly maintaining some degree of thermal strati-
ification 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 1993a, 1997b, 2003). Thus, during mild
winters mixing may be weak and confined to the upper-
most 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 mor-
phometry. 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 thermo-
cline 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. 3. As Fig. 2, but for Greifensee.](image-url)
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. 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 epilimnion ([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$_2$]$_{dl}$ = [O$_2$]$_{em}$ - [O$_2$]$_h$). For further information see the caption to Fig. 1.

Fig. 5. As Fig. 4, but for Greifensee.
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 [O₂]_{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
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 $[O_2]_h$, 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 $\sim 20$ m in Lower Lake Zurich and $\sim 10$ m in Greifensee. By January 2007 the mixed layer had deepened to over 30 m in both lakes, encompassing only $\sim 45\%$ of the volume of Lower Lake Zurich, but essentially the entire volume of Greifensee. By January 2007 the mixed layer had deepened to over 30 m in both lakes, encompassing only $\sim 45\%$ 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 $\sim 50$ 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 $\sim 60$-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 1997b). 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.

Acknowledgments

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