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Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)
Report on effects of climate on water temperature and ice cover

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Deliverable No. 149

Euro-limpacs Workpackage 1, Task 3(i)

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1 INTRODUCTION

This report provides an overview of the effects of climate on water temperature and ice cover in lakes and rivers, along with some results on the effects of climate on oxygen concentrations in lake hypolimnia, for Task 3(i) of Workpackage 1 of Euro-limpacs. The results summarised here are based largely on the data sets described in an earlier data report (Livingstone 2005), supplemented by other data (e.g., short-term measurements of water temperature fluctuations) as necessary. All the studies summarised here were conducted as part of Euro-limpacs Workpackage 1, Task 3(i), and the list of references consists solely of these studies.

2 WATER TEMPERATURE STUDIES

2.1 Short-term fluctuations

In previous EU projects, miniature thermistors with integrated data loggers were employed to acquire data on lake surface water temperature (LSWT) in various lakes in Europe, often in mountainous areas. Within the current EU project, these data were analysed to determine the large-scale effects of short-term regional climate forcing (as opposed merely to short-term local weather forcing) on LSWT fluctuations (on time-scales of one day to several days).

2.1.1 Short-term fluctuations in the surface temperatures of lakes in Switzerland

Hourly measurements of lake surface water temperature (LSWT) during summer and early autumn 2000 in 29 lakes located between 465 m and 2470 m a.s.l. in the Swiss Alps revealed the presence of two distinct, altitudinally-dependent thermal regimes: a low-altitude regime within which the primary physical response to climatic forcing is comparatively simple and direct, and a high-altitude regime in which it is more complex and indirect (Livingstone et al. 2005a). The threshold separating the two regimes is located at ~2000 m a.s.l. during early summer, rising to higher altitudes as summer progresses. Within the low-altitude regime, LSWTs are strongly related to altitude and surface air temperature. The relationship of LSWT to regional air temperature can be
modelled very well empirically by applying an exponential filter to the air temperature. On crossing the threshold to the high-altitude regime, the relationship of LSWT to both altitude and air temperature weakens considerably (Fig. 2.1a) and the LSWT "lapse rate" increases sharply (Fig. 2.1b). Thus, above the threshold altitude, additional climate-related factors come into play that are essentially irrelevant below it. These include the prevalence of (partial) ice cover and unstable or weak stratification at high altitudes, and the influence of inflowing meltwater from snow in the catchment area. The existence of a qualitative difference in the primary physical response of mountain lakes at low and high altitudes to climatic forcing is significant because of the importance of high-altitude lakes in climate change studies. Not only are lakes above the threshold altitude partially decoupled from direct climatic influence, potentially reducing their value as palaeoclimate indicators, but also, past climate-related shifts in the threshold altitude itself must be taken into account in palaeoclimate reconstructions using lakes close to the threshold. Additionally, any predictions of the impacts of future climate warming on high-altitude mountain lakes must take into account a concomitant rise in the threshold altitude.

Fig. 2.1: Results of linear regressions of 105 sets of daily mean lake surface water temperature (LSWT) on altitude for 29 lakes in the Swiss Alps, 19 June – 1 October 2000. The regressions were computed separately for 15 "low-altitude" (< 2000 m a.s.l.) and 14 "high-altitude" (> 2000 m a.s.l.) lakes. a) Proportion of variance explained ($r^2$), with significance levels. b) Computed daily LSWT "lapse rates", i.e., the rate of decrease of LSWT with increasing altitude above sea level. From Livingstone et al. (2005a).
An additional study (Livingstone et al. 2005b) showed that the pattern of deviations from linearity in the relationship between LSWT and altitude was very similar from month to month and from year to year, indicating that such deviations result primarily neither from interannual differences in regional climate nor from random statistical error, but are mainly due to temporally invariant lake-specific factors such as the degree of exposure of the lake and its catchment area to climatic influences. This suggests that it may be possible to obtain a good estimate of the summer LSWT time-series for any lake in a given year from a knowledge of the linear regression in that year and the time-invariant lake-specific deviation. However, it should be kept in mind that interannual differences in climate can cause modifications to the deviations from linearity at high altitudes, mediated primarily by the effect of such interannual climatic differences on the duration of lake ice cover.

2.1.2 Comparison of short-term fluctuations in the surface temperatures of lakes in Switzerland and Hungary

The LSWTs measured in the Swiss Alpine lakes in summer and early autumn 2000 were compared with LSWTs measured simultaneously in Lake Balaton, Hungary, 750 km to the east (Livingstone and Padisák 2007). The Swiss lakes are small (0.0043 – 0.46 km²), predominantly oligotrophic, and are located in a mountainous environment, some at altitudes exceeding 2,000 m a.s.l., whereas Lake Balaton is a large (593 km²), shallow, mesotrophic lake situated in the much lower-lying Carpathian Basin. Despite the large distance separating the two regions and the extreme differences in character between the lakes, the LSWTs in Switzerland and Hungary exhibited a coherent response to synoptic-scale meteorological forcing. As before, both in Switzerland and Hungary the LSWTs can be modelled well in terms of exponentially smoothed air temperature (which can be viewed as a causal forcing variable in its own right and as a proxy for other forcing variables with which it is correlated). The coherent response of LSWT in very dissimilar lakes in two different geographical regions of Europe demonstrates that large-scale climatic forcing on synoptic time-scales is much more important for lakes than previously thought. This appears to be particularly true for low-altitude lakes, whereas lakes at higher altitudes exhibit more heterogeneity in their response.
2.1.3 Short-term fluctuations in the surface temperatures of lakes in Slovakia and Poland

Also in 2000 and 2001, lake surface water temperatures (LSWTs) were measured at high resolution in lakes in the High Tatras of Slovakia and Poland, allowing their dependence on altitude to be investigated. The results of this study supported the results of Livingstone et al. (2005a): LSWT was found to decrease approximately linearly with increasing altitude from late spring to autumn, and in summer, LSWT can also be modelled well empirically in terms of an exponentially smoothed ambient air temperature (Šporka et al. 2006).

2.1.4 Short-term fluctuations in the surface temperatures of lochs in Scotland

In a previous EU project, miniature thermistors with integrated data loggers were employed in 2000 and 2001 to acquire data on lake surface water temperatures (LSWTs) in 25 lochs in the Grampians and Northwest Highlands of Scotland. An analysis of the data within the current EU project (Livingstone and Kernan, in press) indicates that the LSWTs fluctuate coherently in response to climatic forcing, and that additionally, they differ little in an absolute sense, implying that daily mean LSWTs can be upscaled easily. Regional coherence in LSWT is substantially higher in summer and autumn than in winter and spring. LSWT decreases approximately linearly with increasing altitude above sea level during winter and spring, but not otherwise; this contrasts strongly with the results of studies in other mountain regions, which show the most pronounced linear decrease in LSWT with altitude to occur in summer. LSWT showed no dependence on latitude at any time of the year, but showed a significant dependence on longitude – which can be interpreted as distance from the maritime influence of the Atlantic – especially during autumn and spring. In summer, no consistent dependence of LSWT on either altitude, latitude or longitude was found, implying that any differences in LSWT that may exist among the lochs in summer are predominantly the result of lake-specific local effects. The duration of the period during which LSWT ≤ 4°C depends on altitude and longitude, but not on latitude. The timing of the onset of this period in autumn occurs essentially simultaneously throughout Northern Scotland, whereas the timing of the end of the period in spring becomes later with increasing altitude and increasing distance towards the east. This suggests that the duration of inverse stratification or circulation at temperatures less than the temperature of maximum density will tend to be less in low-
lying lochs and/or lochs close to the Atlantic coastline than in high-altitude lochs and/or lochs located further from the Atlantic coast, and that this difference is entirely due to differences in climatic forcing that occur in spring.

2.1.5 High-frequency automatic sampling in a comparative study of water temperature and particle dynamics in lakes in Switzerland and Italy

The deployment of high-resolution automatic thermistor data loggers and sequencing sediment traps in Lej da Silvaplauna (Switzerland) and Lago Maggiore (Italy) by Kulbe et al. (in press) demonstrated clearly that such a combination of sensors is capable of capturing the effects of both large-scale and small-scale climatic forcing on temperature and particle dynamics in lakes. Both air and water temperature data from Lej da Silvaplauna showed clearly the local imprint of the central European heat wave of 2003, and also showed that the anomaly was confined to summer. The effect of the hot summer of 2003 was apparent not only in the surface water layers, but also in the temperature data even in the deepest parts of the hypolimnion. In 2002 and 2004, the temperature at 72 m rose above 4.4 °C during the first and third weeks of October, respectively; in 2003, however, this occurred during the second week of August, two months earlier. These results complement those of Jankowski et al. (2006), described below, who demonstrated the effect of the anomalously hot summer of 2003 on the temperature regimes of lower-altitude Swiss lakes.

In the shorter term, a severe thunderstorm in August 2003 caused water temperatures in the hypolimnion of Lej da Silvaplauna to increase abruptly, then fall to a level significantly above the level that had prevailed before the thunderstorm. During and shortly after the thunderstorm, particle fluxes were the highest recorded during the entire study period. The mechanisms that can be assumed to be responsible for these events include the downward mixing of warmer water from the metalimnion by seiching induced by the high storm winds, and plunging plumes of dense, sediment-laden water from the inflowing Fedacla River, which contributed to the high particle fluxes. Spectral analysis revealed the presence of a strong diel cycle in hypolimnetic temperatures during the open-water season that occurs in phase throughout the hypolimnion. These fluctuations are probably forced by the local Maloja wind, which is strongly diel in nature.
Results from Lago Maggiore showed that hypolimnetic temperatures are highest in late autumn and winter, presumably as a result of the vigorous downward mixing of heat from the upper water column during these months. The diel temperature fluctuations recorded in the upper hypolimnion during the stratification period are weaker than in Lej da Silvaplauna and their frequency less clearly defined, which would be expected as there is no equivalent of the Maloja wind at Lago Maggiore.

The study of Kulbe et al. (in press) demonstrated the value of long-term, automatic, high-resolution thermistor and particle flux measurements in describing both the long-term and short-term response of water temperature and particle dynamics in two very dissimilar Alpine lakes to climatic forcing. However, while such high-resolution measurements help to elucidate the mechanisms responsible for short-term events, only long-term measurements can provide the baseline data necessary to define and compare anomalous and normal years.

2.1.6 Comparison of short-term fluctuations in lake surface water temperature with short-term fluctuations in river and stream water temperature

A comparative analysis of short-term fluctuations in air temperature (AT), river water temperatures (RWT) and lake surface water temperature (LSWT) during two summers in the Alps showed a high degree of coherence among all three (Livingstone and Hari in press). In 1997, river water temperature (RWT) data were available from 47 measuring stations on rivers and streams, and lake surface water temperature (LSWT) data from 10 lakes. In 2000, data were available from 92 river and stream stations and 29 lakes. Both the RWT and the LSWT measurements spanned a large range of altitudes. During the two study periods, daily AT measurements were available from 40 meteorological stations lying between 316 and 3580 m a.s.l.

Separately for each of the months of July, August and September in 1997 and 2000, the overall degree of short-term regional coherence among the time-series of AT, LSWT and RWT was assessed. As expected, coherence was very high for the air temperature data. For the water temperature data the coherence was lower, but still considerable. Although coherence in AT differed little between 1997 and 2000, coherence in LSWT, and even more so in RWT, was lower in 1997 than in 2000, suggesting that the relative dominance of regional air temperature as a forcing factor in the Alpine region may have been less in 1997 than in 2000.
Both RWT and LSWT were able to be modelled empirically as a function of AT by applying an exponential smoothing function. Short-term fluctuations in both LSWT and RWT were found to be extremely tightly related to fluctuations in smoothed regional air temperature (Fig. 2.2). Thus LSWT and RWT also fluctuate coherently: the proportion of variance shared between the LSWT and RWT time-series is 88% for 1997 and 89% for 2000.

![Fig. 2.2: Comparison of standardised (non-dimensional) time-series of regional means of a) lake surface water temperature (LSWT) and b) river water temperature (RWT) in Switzerland with standardised time-series of smoothed regional mean air temperature (AT) for 1 July - 30 September 2000. The regional mean time-series are based on measurements from 29 lakes, 92 river and stream monitoring stations and 40 meteorological stations. The AT time-series was exponentially smoothed and the time-series were standardised by subtracting the mean and dividing by the standard deviation. From Livingstone and Hari (in press).](image)

Despite the coherent response to smoothed regional AT exhibited by the regional mean time-series of LSWT and RWT, the three temperature variables differ substantially
in the way that the degree of coherence is modified by altitude above sea level. Although coherence in AT, RWT and LSWT was statistically significant (p < 0.05) in all months at all altitudes, all three variables generally showed a decrease in coherence with increasing altitude.

On time-scales of days to weeks, both lake surface temperatures and river temperatures fluctuate coherently in response to regional-scale climatic forcing, expressed in terms of exponentially smoothed regional mean air temperature. This coherence is apparent not only among lakes and among rivers, but also between lakes and rivers. This is despite the fundamental differences between these two types of water body: lakes are stationary in the landscape and their surface water temperatures depend partly on wind-driven vertical mixing, whereas rivers are in continual motion through different local landscapes, and owing to internal turbulence are generally well-mixed regardless of external meteorological conditions. The fact that water temperatures in both lakes and rivers respond tightly and coherently to short-term fluctuations in regional air temperature indicates that such fluctuations are the major determinant of short-term variability in the thermal habitats of many aquatic flora and fauna.

For both lakes and rivers, the degree of coherence present in their response to climatic forcing is dependent on altitude above sea level. In lakes, this dependence is only apparent during early summer, and then only at very high altitudes. This suggests that factors such as partial ice cover, local topographic shading, meltwater from snow or glaciers and lack of stratification can reduce coherence in LSWT at high altitudes, but that otherwise coherence in LSWT is likely to be uniformly high. By contrast, coherence in RWT appears to diminish gradually with increasing altitude at all altitudes. However, at all altitudes, there is a high degree of variability in RWT coherence, presumably because of differences in the character of the catchment areas of the various stations. The RWT measured at a particular station represents the integrated, cumulative response of all streams in the catchment area of the measuring station to climatic forcing over a range of altitudes; thus the presence of lakes, hydro-power stations, snow or glaciers in a station catchment area can heavily modify the response of measured RWT to regional climatic forcing. In general, however, for both lakes and rivers, the likelihood of local effects modifying the response of water temperature to regional climatic forcing is substantially greater at high altitudes than at low altitudes.
2.2 Long-term changes

Several studies have now shown that lakes are undergoing long-term warming, that their thermal stability is increasing, and that the duration of stratification is increasing while the duration of homothermy is correspondingly decreasing. The analyses of long-term historical lake and river temperature data in Euro-limpacs were designed to complement these earlier studies and carry forward our knowledge of the potential impact of long-term changes in external physical forcing on European surface water bodies.

2.2.1 Case study of the impact of the extremely hot European summer of 2003 on lakes

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. A long data set consisting of over half a century of water temperature data from two lakes in Switzerland were used by Jankowski et al. (2006) to determine the effect of the 2003 heat wave on lake temperatures 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.

2.2.2 The long-term response of daily epilimnetic temperature extrema to climate forcing

The phenomenon of global dimming has led to a difference in the behaviour of daytime and night-time air temperatures, expressed as daily maximum and daily minimum air temperatures. Lack of data makes it difficult to assess the behaviour of daytime and night-time water temperatures in lakes. However, 20 years (1983-2002) of hourly summer temperature data were available from the epilimnion of Müggelsee, a shallow lake in northern Germany, which allowed us to conduct such an analysis (Wilhelm et al. 2006). The temperatures showed a long-term increase, with the rate of increase of the daily minima (night-time temperatures) exceeding that of the daily maxima (daytime
temperatures). However, this does not simply reflect the long-term behaviour of air temperature, which did not exhibit a significant degree of day/night asymmetry. A sensitivity analysis based on a heat balance model revealed that the daily extrema of the lake surface equilibrium temperature responded differently not only to shifts in air temperature, but also to shifts in wind speed, relative humidity and cloud cover, suggesting that long-term changes in all four variables contribute to day/night asymmetry in the epilimnetic temperature. A comparison of night-time and daytime estimates of the heat flux components into the lake indicates that the emission of long-wave radiation from the atmosphere is likely to be the main process responsible for day/night asymmetry in the epilimnetic temperature. While this process is partially dependent on air temperature, it is also dependent on relative humidity and cloud cover. The influence of long-term changes in these additional driving variables on epilimnetic temperatures cannot therefore be neglected.

2.2.3 Effect of climate warming on the timing of the onset of the spring phytoplankton bloom: a temperature effect or a mixing effect?

The decoupling of trophic interactions is potentially one of the most severe consequences of climate warming. In lakes and oceans the timing of phytoplankton blooms affects competition within the plankton community as well as food-web interactions with zooplankton and fish. Using Upper Lake Constance as an example, Peeters et al. (2007) conducted a model-based analysis that predicts that in a future warmer climate, the onset of the spring phytoplankton bloom will occur earlier in the year than it does at present. This is a result of the earlier occurrence of the transition from strong to weak vertical mixing in spring, and of the associated earlier onset of stratification. According to the simulations, a shift in the timing of phytoplankton growth resulting from a consistently warmer climate will exceed that resulting from a single unusually warm year. A statistical analysis of long-term data from Upper Lake Constance demonstrates that oligotrophication has a negligible effect on the timing of phytoplankton growth in spring and that an early onset of the spring phytoplankton bloom is associated with high air temperatures and low wind speeds.
2.2.4 Long-term changes in river and stream temperature data
A study of 25 years of extensive water temperature data spanning a large altitude range in the European Alps (Hari et al. 2006) show regionally coherent warming to have occurred in Alpine rivers and streams at all altitudes (Fig. 2.3a) that reflect changes in regional air temperature (Fig. 2.3b). The absolute differences in water temperature from river to river are primarily a result of the general decrease in water temperature that occurs with increasing altitude, but the degree of coherence also decreases somewhat as the mean altitude of the catchment area of the sampling station increases (and is disproportionately low under the influence of glaciers or hydro-electric power stations).

Much of the warming occurred abruptly around 1987/1988, possibly linked to a change in the North Atlantic Oscillation. This agrees with other studies that have shown an abrupt shift in physical and biological variables to have occurred at this time. The warming may have affected fish populations. For brown trout populations, the warming resulted in an upward shift in thermal habitat that was accelerated by an increase in the incidence of temperature-dependent Proliferative Kidney Disease at the habitat’s lower boundary. Because physical barriers restrict longitudinal migration in mountain regions, an upward habitat shift in effect implies habitat reduction, suggesting the likelihood of an overall population decrease. Extensive brown trout catch data documenting an altitudinally dependent decline in Alpine rivers and streams indicate that such a climate-related population decrease has in fact occurred.

2.2.5 A change of climate, a change of paradigm?
Physically, lakes are traditionally viewed as individual systems forced by statistically stationary local weather. This view implies that the physical response of a lake to external physical forcing is unique and stationary. Recent recognition of the importance of large-scale climatic forcing in driving physical lake processes, combined with the realisation that this forcing is undergoing a long-term trend as a result of climate change, has led to a shift in this paradigm view. Livingstone (submitted) explored conceptually the new physical paradigm that is gradually taking hold, a paradigm which views lakes more in terms of a local response to large-scale climatic forcing, modulated by the addition of local noise, rather than individuals subject to unique external physical forcing. A strong climate signal leads to large-scale spatial coherence in the physical lake response, while the existence of trends in large-scale climatic forcing associated with climate change
means that both the forcing and the physical lake response are statistically non-stationary. Thus the increasing importance of climate and climate change are invalidating the tacit assumptions of individuality and stationarity that underlie the old conceptual framework, resulting in a new paradigm based on the concepts of spatial coherence and temporal non-stationarity.

![Graph A](image1.png)

**Fig. 2.3.** a) River and stream temperatures measured at 25 stations in Switzerland. b) Comparison of the arithmetic mean of the water temperatures illustrated in (a) (thick black curve) with the mean air temperature measured at the meteorological stations of Basle and Zurich (annual running means; thin blue curve), which is representative of the mean air temperature prevailing on the Swiss Plateau. The data illustrated are annual running means. Adapted from Hari et al. (2006).
3 ICE COVER

3.1 Distinguishing between the effects of climate on the timing of ice-on and the timing of ice-off

Long-term data on the ice cover of rivers and lakes are confined essentially to phenological data; i.e. to historical observations of the timing of ice-on and ice-off. In ice phenology studies, it is important to distinguish between the effects of climate on the timing of ice-on and its effects on the timing of ice-off. Although the duration of ice cover on a lake is given simply by the difference of the timing of ice-off and the timing of ice-on, the processes involved in determining these are not the same, and they therefore do not necessarily exhibit the same response to climatic forcing. To investigate this, miniature thermistors with integrated data loggers were deployed in high-altitude lakes in the Tatra Mountains in 2000 and 2001, which allowed the dependence of the timing of both ice-on and ice-off in these lakes on altitude above sea level to be studied (Šporka et al. 2006). Because air temperature decreases approximately linearly with increasing altitude in summer, this study essentially investigated the dependence of the timing of ice-on and ice-off on air temperature, with altitude above sea-level being used as a proxy for air temperature. For the purposes of the study, the calendar date on which the measured lake surface water temperature decreased to 0 °C was taken to represent the date of ice-on, and the calendar data on which it increased above 0 °C was taken to represent the date of ice-off. Although this assumption might not always hold in an absolute sense, it does allow some general conclusions to be drawn about the altitudinal dependence of the timing of ice-on and ice-off. Defined thus, the timing of ice-on in the study lakes spanned 52 d, and the timing of ice-off spanned 59 d. The timing of ice-on exhibited no detectable dependence on altitude (Fig. 3.1a). By contrast, the timing of ice-off exhibited a strong dependence on altitude, with the highest lakes thawing much later than the lower lakes (Fig. 3.1b). A linear regression of the timing of ice-off on altitude was highly significant, with a high proportion of explained variance. The rate of change of the timing of ice-off with altitude, given by the gradient of the regression, was 9.1 d per 100 m. The duration of ice cover varied from 136 d to 232 d, and also exhibited a significant linear dependence on altitude, at a rate of 10.2 d per 100 m (Fig. 3.1c). As the timing of ice-on is essentially independent of altitude, the altitudinal dependence exhibited by the duration of ice cover is therefore due almost completely to the altitudinal
dependence of the timing of ice-off in late spring and early summer. The more general implication of this study is that the timing of ice-off will be influenced directly by climate warming, whereas the timing of ice-on will be influenced only indirectly, via a multiplicity of internal lake processes that depend to a large extent on local factors, both external (e.g., lake setting, local winds) and internal (e.g., lake morphometry). This makes the timing of ice-off a more interesting study variable within the context of direct climate influence on surface water bodies.

Fig. 3.1. The altitudinal dependence of the timing of ice-on in 2000 (A), the timing of ice-off in 2001 (B) and the resulting duration of ice cover for the lakes of the Tatra Mountains (C). Linear regressions of the timing of ice-off and the duration of ice cover are also illustrated, and the relevant gradients, coefficients of determination ($r^2$) and significance levels ($p$) of the regressions are given. From Šporka et al. (2006).

### 3.2 Trends and relationships between climate and the timing of ice-off during the IPCC reference period (1961-1990)

Because of the dominant role played by air temperature in the thawing of lake ice, the timing of ice-out is closely related to ambient air temperature. Because of the large-scale spatial coherence of air temperature, the timing of ice-out of lakes over large regions are also spatially coherent. A large number of lakes and rivers in the study described here, the time period covered was restricted to the 30-yr IPCC baseline period, 1961–1990. Data on the timing of ice-out from 129 Northern Hemisphere lakes and rivers in six countries during the IPCC reference period (1961 - 1990) were analysed to investigate whether consistent trends existed during this period and whether an influence of the North Atlantic Oscillation (NAO) on the timing of ice-out could be detected (Livingstone et al. in prep.). Twenty-nine of the water bodies exhibited a statistically significant ($p<0.05$) trend towards earlier ice-out, but only one towards later ice-out. Despite the fact that
there was a statistically significant trend toward earlier ice-out in less than 25% of the water bodies taken individually, the gradients of linear regression lines computed for each series were negative in 122 of the 129 cases, suggesting the existence of a general tendency to earlier ice-out, but one which is often weak in comparison to interannual variability. All 129 water bodies taken together exhibited a statistically significant trend of 0.24 d/yr over the 30-yr period, which is much higher than the mean linear trend computed for ice-out since the middle of the 19th century. Comparison of the ice-off dates with the winter NAO showed a consistent, strong relationship between in Eurasia, with 52 Eurasian lakes exhibiting a negative correlation with the winter NAO index.

An analysis concentrating on 54 Swedish lakes (Weyhenmeyer et al. 2005) confirmed the existence of trends in the timing of ice-out during the IPCC reference period, but also showed that these trends were not constant along the gradient in latitude covered by the lakes. Trends were dependent on latitude, being substantially greater in warmer, southern Sweden than in colder, northern Sweden. This is hypothesized to be a result of the non-linear dependence of the timing of ice-out on air temperature: when air temperatures are below 0 °C, ice phenology will respond more sensitively to fluctuations in air temperature when air temperatures are close to 0 °C than when they are well below zero. This non-linear dependence can be described in terms of an arc cosine function. An analysis of 196 lakes in Sweden (Weyhenmeyer et al. 2004) showed that the timing of ice-out can be modelled quite well based on an arc cosine function.

3.3 The empirical modelling of lake ice phenology
The arc cosine approach of Weyhenmeyer et al. (2004) was extended by Livingstone and Adrian (submitted) to yield a more generalized empirical approach to the problem of the prediction of lake ice cover, including intermittent lake ice cover, for climate-change studies. Their model, based on probability distributions, was applied to historical ice data from Müggelsee, a shallow lake in northern Germany that experiences either no ice cover, intermittent ice cover, or continuous ice cover, depending on the severity of the winter. The approach allows the total duration of ice cover in any winter to be estimated in terms of an air temperature probability function alone. Advantages over traditional empirical methods based on the mean air temperature during a fixed period or on the computed number of negative degree-days are: that it is valid for both continuous and
intermittent ice cover; that it is not necessary to specify a fixed time period for integration in advance; that the results emerge in time units, allowing them to be directly compared with the measured duration of ice cover without prior calibration; and that it is based on statistical properties of the seasonal and diel variability of the ambient air temperature that are routinely forecast by climate models, making it easy to apply predictively. Regional climate model forecasts for northern Germany imply that for Müggelsee, the percentage of ice-free winters will increase from ~2% now to over 60% by the end of the current century. This corresponds to predictions made under current climate conditions for northern Italy, 800 km to the south of Müggelsee.

4 OXYGEN STUDIES

Although not mandatory, some studies of the effects of climate on oxygen concentrations in lakes - mainly in the hypolimnion - were undertaken facultatively. A thesis on the effect of climate on hypolimnetic oxygen concentrations (Rempfer 2007) studied historical temperature and oxygen concentrations in three perialpine lakes in Switzerland that differ strongly with respect to morphometry and trophic status (the Lake of Walenstadt, Upper Lake Zurich and Lower Lake Zurich). The availability of temperature and oxygen time-series at least 28 yr long from these lakes allowed the response of hypolimnetic oxygen concentrations to interannual variations in climate forcing to be analysed with the aim of gaining information about the evolution of oxygen concentrations in the deep water of lakes under changing climate conditions.

Using a superposed epoch analysis, the dependence of the hypolimnetic oxygen concentration \( C_h \) on the duration of the period of homothermy \( D_{hom} \) - which is determined to a large degree by climatic forcing - was analysed (Rempfer et al. in press). The duration of homothermy appeared to affect hypolimnetic oxygen concentrations very differently in the three neighbouring perialpine lakes. In the case of the Lake of Walenstadt, an oligotrophic lake exposed to high winds, no impact was detected. In mesotrophic Upper Lake Zurich, a relationship was found between \( C_h \) and \( D_{hom} \), but this relationship is unlikely to have been causal, because although minimum values of \( C_h \) in autumn were affected, maximum values of \( C_h \) in spring were not. This suggests that in this lake, climate forcing in winter and spring may be governing both \( D_{hom} \) (directly) and hypolimnetic oxygen depletion rates in summer (indirectly, by influencing biological productivity). In Lower Lake Zurich, the perceived impact of the duration of homothermy
on hypolimnetic oxygen concentrations depends critically on the time window examined. This highlights the importance of long time-series in determining the potential impact of climate change on lake oxygen conditions. There was no evidence from any lake that $D_{\text{hom}}$ might affect $C_h$ for longer than a year. Thus the individual characteristics of lakes appear to be of great importance in determining the response of their deep-water oxygen concentrations to variations in winter climate, and thus, potentially, to climate change.

The winter of 2006/2007 in central Europe was extremely mild. Based on air temperature measurements at Zurich, it was the mildest in the entire 116-yr period from 1891/1892 to 2006/2007. A study was therefore undertaken to ascertain the effects of this extremely mild winter on the thermal conditions and oxygen concentrations in Lower Lake Zurich and Greifensee, based on data from the winter of 1972/1973 to the winter of 2006/2007 (Rempfer et al. in prep.). In both lakes, the highest mean lake water temperatures ever recorded were found during this mild winter. The same was true of the temperature of the epi/metalimnion in both lakes, but the deviation from the long-term mean was even more extreme. However, the two lakes differed with regard to the mean temperature of the hypolimnion ($T_h$). In Greifensee, $T_h$ during the winter of 2006/2007 was also the highest recorded. In Lower Lake Zurich, however, $T_h$ did not deviate notably from its long-term mean. In both lakes, thermal stability during the winter of 2006/2007 was generally extremely high, implying that vertical mixing was extremely weak.

In contrast to the anomalous behaviour of water temperature, anomalies in the oxygen concentrations in the mild winter of 2006/2007 were much less striking. In this winter, the mean oxygen concentration in the epi/metalimnion of Lower Lake Zurich was the second highest of the entire study period, but the hypolimnetic oxygen concentration lay well within its normal range. This combination resulted in extremely high oxygen concentration gradients, providing further evidence for the abnormal lack of vertical mixing during the mild winter. In Greifensee the situation was different: in December 2006, oxygen concentrations below 15 m were substantially lower than average, but oxygen concentrations closer to the surface were abnormally high. In January and February 2007, oxygen concentrations at all depths were normal and the oxygen profiles were essentially orthograde. The explanation for the difference lies in the occurrence of a strong winter storm in January, which was able to bring about turnover in Greifensee, but not in Lower Lake Zurich, which is much deeper than Greifensee. Thus it cannot be
assumed that an extraordinarily mild winter will automatically result in similar responses in temperature and oxygen in neighbouring lakes. Not only do individual lake properties – e.g. morphometry – play a very important role in mediating the impact of climatic forcing, but the impact of wind events can differ considerably from lake to lake.

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