IMPACT OF SECULAR CLIMATE CHANGE ON THE THERMAL STRUCTURE OF A LARGE TEMPERATE CENTRAL EUROPEAN LAKE

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Abstract. Strong climate-related secular trends are apparent in a 52-yr long (1947–1998) uninterrupted series of monthly temperature profiles from Lake Zurich, a large, deep (136 m), temperate lake on the Swiss Plateau. Decadal mean water temperatures have undergone a secular increase at all depths, reflecting the high degree of regional warming that occurred in the European Alpine area during the 20th century. From the 1950s to the 1990s, high warming rates ($\sim$0.24 K per decade) in the uppermost 20 m of the lake (i.e., the epi/metalimnion) combined with lower warming rates ($\sim$0.13 K per decade) below 20 m (i.e., in the hypolimnion), have resulted in a 20% increase in thermal stability and a consequent extension of 2–3 weeks in the stratification period. In common with many other parts of the world, 20th-century climate change on the Swiss Plateau has involved a steep secular increase in daily minimum (nighttime) air temperatures, but not in daily maximum (daytime) air temperatures. With respect to both secular change and decadal-scale variability, the temporal structure of the temperature of the surface mixed layer of Lake Zurich faithfully reflects that of the regional daily minimum air temperature, but not that of the daily maximum. The processes responsible for longer-term changes in the temperature structure of the lake therefore act during the night, presumably by suppressing nighttime convective cooling of the surface mixed layer. Application of a one-box heat exchange model suggests that the observed secular changes in thermal structure are due to shifts in the nighttime rate of emission of infrared radiation from the atmosphere and in the nighttime rates of latent and sensible heat exchange at the air-water interface. The increase in hypolimnetic temperatures is mainly a result of the increased prevalence of warm winters in Europe.

1. Introduction

Regardless of its ultimate cause, any future long-term change in the global radiative heat balance will result in global and regional climate change that will have an impact not only on the atmosphere and oceans, but also on surface water bodies (Arnell et al., 1996). Model predictions suggest that increasing atmospheric CO_2 concentrations, in addition to resulting in increases in surface air temperatures and sea surface temperatures (Kattenberg et al., 1996), will cause increasing temperatures in rivers (Stefan and Sinokrot, 1993) and lakes (Robertson and Ragotzkie, 1990; Hondzo and Stefan, 1991, 1993; Stefan et al., 1998; Peeters et al., 2002). The main physical mechanisms that determine the heat balance of a lake act at the lake surface. In order of importance, these are: (i) the absorption of atmospheric long-

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wave radiation; (ii) the emission of long-wave radiation from the lake surface; (iii) the absorption of direct and diffuse short-wave solar radiation; (iv) the exchange of latent heat of evaporation/condensation; and (v) the convective exchange of sensible heat (Edinger et al., 1968). Four of these five processes are likely to be influenced directly by climate change on global or regional scales. A secular shift in air temperature would affect the amount of atmospheric radiation incident on the lake surface and the rates of exchange of both latent and sensible heat. A shift in the amount of cloud cover and/or atmospheric turbidity due to air pollution would affect (in opposite ways) the amounts of both long-wave and short-wave radiation impinging on the lake. A shift in relative humidity would influence the exchange of latent heat, and a shift in wind speed would influence the exchange of both latent and sensible heat. In addition to affecting the overall lake heat balance, secular shifts in the above-mentioned climatic variables would also result in changes in the vertical heat distribution within the water column, thus altering the lake surface temperature and affecting indirectly the rate of emission of long-wave radiation from the lake to the atmosphere and the rates of exchange of latent and sensible heat. Since climate change is likely to involve several meteorological variables that are themselves interdependent, prediction of the effect of of climate change on the heat balance and thermal regime of a lake is not trivial. However, it can at least be said that increasing air temperatures are likely to result in increasing lake temperatures (e.g., Peeters et al., 2002).

Data available from the Canadian Experimental Lakes Area from 1970 onwards tend to confirm that lake temperatures are increasing (Schindler et al., 1990, 1996). Because secular trends in a physical parameter of such great environmental importance as ambient water temperature are likely to have significant effects on the viability of aquatic ecosystems (e.g., Regier et al. 1990 and references therein), the potential importance of the effects of global and regional warming on lake ecosystems is increasingly beginning to be acknowledged (Arnell et al., 1996; McKnight et al., 1996; Cushing, 1997).

However, whereas monthly mean surface air temperature data sets exist that stretch back two or three centuries without interruption, uninterrupted lake water temperature profile data sets longer than two or three decades are very rare. Where they do exist, such data sets represent a valuable source of information on the immediate physical effects of climate change on lacustrine systems. Full temperature profiles measured at approximately monthly intervals over a period of a few decades are available from several lakes in central Europe, specifically in Switzerland (Livingstone, 1993). This paper is concerned with secular trends in temperature and stratification in the lake with the longest uninterrupted monthly temperature record (>50 yr) of any of these lakes: Lake Zurich.

The Lake Zurich temperature profile data complement and augment a palette of other water-related long-term climate proxies from the European Alpine region that are acknowledged to be of supraregional relevance. The advances and retreats of Swiss Alpine glaciers, for instance, reflect the same large-scale climate changes that are recorded in North American alpine glaciers, polar ice cores and tree rings from various Northern Hemisphere locations (Denton and Karlén, 1973; Hormes et al., 1998; Röthlisberger et al., 1980). Secular changes in the timing of thawing of lakes in Switzerland not only agree with Northern Hemisphere trends towards earlier thawing (Magnuson et al., 2000), but also appear to contain significant signals derived from large-scale climate-related phenomena such as global volcanism and the North Atlantic Oscillation (Livingstone, 1997a, 2000). The signature of the North Atlantic Oscillation has also been detected in lake surface temperatures in neighbouring Austria (Livingstone and Dokulil, 2001). Any information on shifts in climatic forcing reflected in the long series of Lake Zurich temperature profiles is therefore likely to be relevant to climatic change occurring not only on regional scales, but also on synoptic to hemispheric scales.

2. Site Description

Lake Zurich (47.3° N, 8.6° E), the lowest in a chain of three large perialpine lakes of glacial origin, is located at 406 m a.s.l. on the Swiss Plateau, immediately to the north of the Swiss Alps. With a maximum depth of 136 m, a surface area of 65 km^2 and a volume of 3.3 km^3, it is one of the larger European perialpine lakes and serves as an important source of drinking water for almost 1 million people (Gammeter et al., 1998). Based on long-term hydrological measurements, about 84% of the 90 $m^3 \cdot s^{-1}$ of water entering the lake comes directly from the epilimnion of the second lake in the chain, Upper Lake Zurich (Omlin et al., 2001), which is separated from Lake Zurich proper by a sill about 3 m below the surface. This fact means that the impact of hydrology on internal lake processes is slight. Specifically, heat exchange via throughflow has only a negligible effect on the lake heat balance, and the temperature profile is not affected by plunging plumes. This makes Lake Zurich particularly suitable for studying the effects of climatic forcing on lakes (Peeters et al., 2002).

Lake Zurich possesses one of the longest regular time series of lake temperature profiles in existence anywhere. With the exception of several years in the 1940s, full temperature profiles have been measured monthly at the deepest point of the lake since June 1936 (Kutschke, 1966; Livingstone, 1993) at a depth resolution that is comparatively high for historical lake temperature data (typically 0.3, 1, 2.5, 5, 7.5, 10, 12.5, 15, 20, 30, 40, 60, 80, 90, 100, 110, 120, 130 and 135 m). Data from the 1960s onwards were obtained by thermistor, either manually using a Wheatstone Bridge or automatically using a digital thermistor meter. Earlier data were measured using a high-quality reversing thermometer (E. A. Thomas, pers. comm.). All temperatures are considered to be accurate to within ± 0.1 K. Thus the Lake Zurich temperature series represents a long and unusually detailed data set suitable for the study of secular change and interdecadal variations in lake thermal structure.

A detailed statistical description of the early part of the data series has been given by Kutschke (1966). The long-term development of the thermal structure of the lake has been described by Livingstone (1993, 1997b) and modelled by Peeters et al. (2002). The thermal regime of the lake can vary substantially from year to year depending on the meteorological conditions prevailing in winter and early spring, but can also exhibit a certain degree of persistence because of the importance of heat carryover from one year to the next during warm winters (Livingstone, 1993, 1997b; Peeters et al., 2002). Figure 1a illustrates the seasonal variation in the thermal structure of Lake Zurich occurring in a representative 'cold year' (1956) and a representative 'warm year' (1995). Figure 1b summarises the seasonal variation in terms of the mean lake temperatures (T_l), a measure of the heat content of the lake.

Lake Zurich is holomictic, i.e., it can mix completely in spring (in contrast to meromictic lakes, which are prevented from doing so by chemical stratification in the deep water). Cold winters result in the occurrence of inverse stratification from late winter to early spring. During extremely cold winters, Lake Zurich can freeze over, although this occurs as a rule only a few times a century. During the period dealt with here, the lake froze over only once, viz. in 1963. Vigorous vertical mixing induced by surface cooling results in homothermy both immediately before and immediately after the period of inverse stratification, a condition known as dimixis. During less cold winters, there is virtually no inverse stratification and only one period of essentially uninterrupted vertical mixing and homothermy: this condition is known as monomixis. Following a cold winter, in both the dimictic and monomictic cases the deep-water temperature generally falls to between 4.0 °C (the temperature of maximum density) and 4.5 °C by late spring.

During warm winters, positive stratification can persist without interruption from one summer to the next, inhibiting complete spring turnover and resulting in deep-water heat carryover. In this case, deep-water temperatures can exceed the temperature of maximum density by as much as 1 °C. In Figure 1a, it can be seen that the 5 °C and 6 °C isotherms in 1995 were at approximately the same depths as the 4 °C and 5 °C isotherms, respectively, in 1956.

Regardless of whether the year is cold or warm, stratification generally sets in during April. Because the summer stratification shields the deep water to a large extent from further direct meteorological forcing, the deep-water temperature attained during the last phases of the spring turnover remains essentially constant throughout the entire year. Lake heat content, expressed as mean lake temperature, attains its annual minimum (3.5–5.0 °C) in March and its annual maximum (8.0–9.5 °C) in August (Figure 1b).

Traditionally, lakes are divided into three regions: an epilimnion, or well-mixed layer of variable depth at the lake surface; a metalimnion, or region of high temperature gradient directly below the epilimnion; and a hypolimnion, or region of relatively low temperature gradient below the metalimnion. These regions are not precisely defined, but a temperature gradient of 1 $K \cdot m^{-1}$ is usually taken to

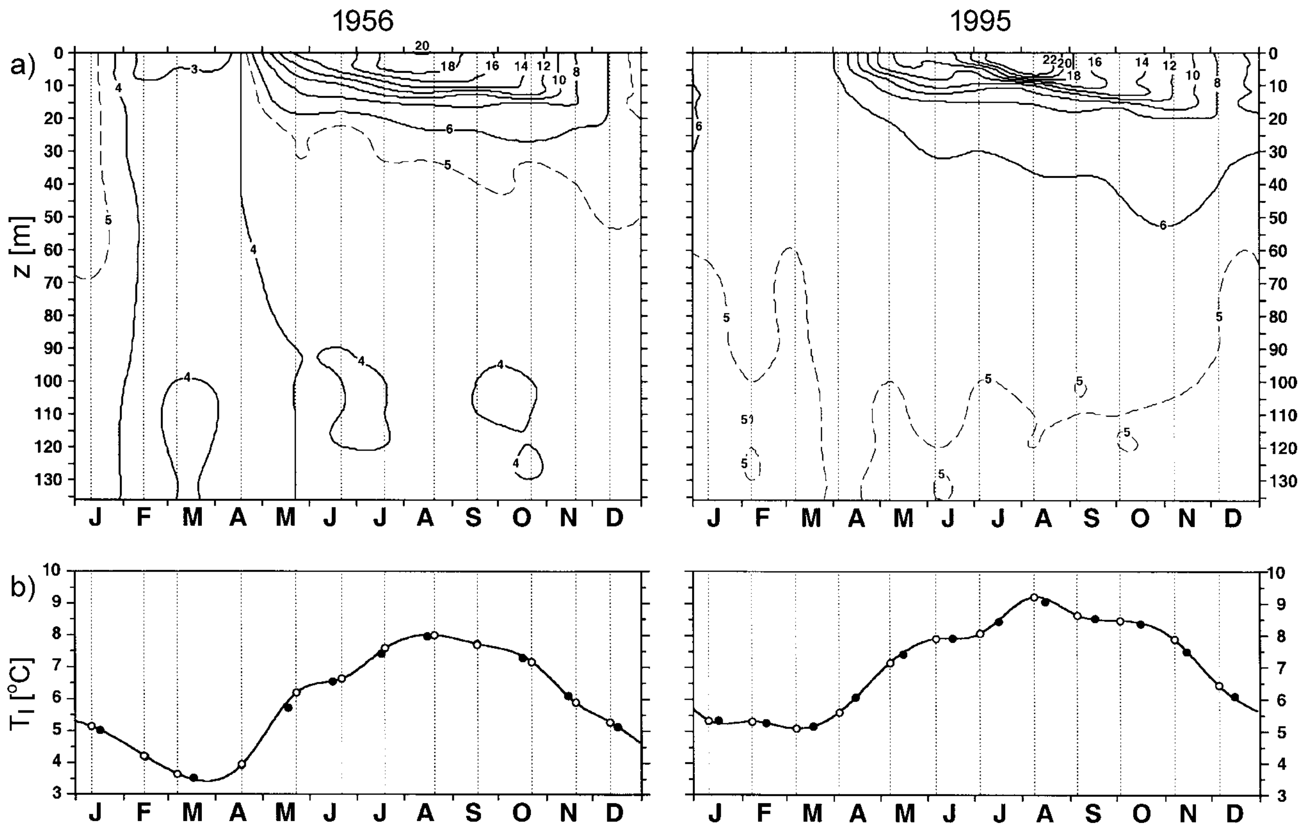

Figure 1. Seasonal variability in the thermal regime of Lake Zurich: (a) isotherm plots and (b) corresponding volume-weighted mean lake temperatures (T_l). Measured profiles are represented by vertical dotted lines. In (b) the white circles represent values of T_l calculated from measured profiles, the solid line represents the cubic spline interpolation of these values at daily intervals and the black circles represent the 12 monthly mean values of T_l computed from the spline-interpolated daily values. The two years shown, representing 'cold' (1956) and 'warm' (1995) conditions in the lake, were chosen based on the annual mean of T_l, which was second lowest in 1956 (5.9 °C) and highest in 1995 (7.1 °C). (Although T_l was 0.1 °C lower in 1963 than in 1956, 1963 was atypical because the lake was frozen over for 2 months.)

mark the boundaries between them (Hutchinson, 1957). The thicknesses of the three regions vary seasonally. For simplicity's sake, in this paper three regions will be considered that are defined in terms of depth rather than seasonally-variable temperature gradient. The uppermost 2.5 m of the epilimnion, which is generally well-mixed in all seasons, will be denoted here as the surface mixed layer. Because the traditional (depth-variable) epilimnion is, by definition, well-mixed, the mean temperature T_s of the 0–2.5 m surface mixed layer is very close to the mean epilimnetic temperature. Following Örn (1980), the hypolimnion of Lake Zurich will be defined here as the region below 20 m depth. Within this region, seasonal temperature variability is low and temperature gradients never exceed 1 $K \cdot m^{-1}$ (see Figure 1a). Finally, the region from 0–20 m, in which seasonal temperature variability is high, encompasses both the epilimnion and metalimnion and will be denoted here as the epi/metalimnion.

3. Methods

Because of unavoidable irregularities in sampling, the measurements were standardised with respect to depth and time before attempting any comparison with the more regularly measured meteorological variables. Each measured profile was first converted to a finer grid of standard depths by linear interpolation at intervals of 5 m in the hypolimnion and 2.5 m in the epi/metalimnion. For each profile, the mean volume-weighted temperatures of the entire lake (T_l), of the surface mixed layer (T_s), of the epi/metalimnion (T_{em}) and of the hypolimnion (T_h) were then calculated, as was the Schmidt stability S, defined as the work which would hypothetically be necessary to transform the observed density distribution into a vertically homogeneous density distribution by mixing with no net gain or loss of heat (Schmidt, 1928; Idso, 1973). In a holomictic lake such as Lake Zurich, in which the density profile depends essentially only on the vertical distribution of heat in the water column, S gives a good overall quantitative measure of the degree of thermal stratification prevailing in the lake. Salinity, which can affect the value of S, has changed only slightly in the long-term in Lake Zurich. The annual mean temperature-corrected electrical conductivity (a measure of salinity) showed very little secular change at any depth from 1972 (the first available data) to 1997. At the lake surface, it remained essentially constant at $\sim$232 $\mu S \cdot cm^{-1}$ during the whole period. At the deepest measured point (135 m) it increased only slightly, viz. from 253 to 268 $\mu S \cdot cm^{-1}$ (an increase that is well within the standard deviation of $\pm$12 $\mu S \cdot cm^{-1}$ from the 1972–1999 mean of 261 $\mu S \cdot cm^{-1}$). Thus salinity changes have had essentially no long-term effect on S. The values of S computed here are based solely on temperature profiles and hence reflect only the impact of changing thermal structure on stability.

As the temperature profiles were not always sampled at intervals of exactly one month, estimated monthly means of the quantities T_l, T_s, T_{em}, T_h and S were calculated by first interpolating at daily intervals using a cubic spline and then averaging the interpolated values over each calendar month. The same approach was employed to obtain monthly mean time series of the water temperature T_z at each of the standard depths. A comparison of the monthly mean estimates thus obtained with the original measured values reveals no large discrepancies, indicating that the estimates are reliable. Figure 1b illustrates this for the specific case of T_l. The monthly mean data on which this paper is based span the 52-yr period from January 1947 to December 1998. Climate-related secular changes in water temperature were investigated using decadal means computed from these monthly means. Each decadal mean contains information from approximately 120 independent temperature measurements, so that the influence of individual outliers, whether due to unrepresentative local weather conditions or measurement error, is slight.

4. Results

4.1. SECULAR CHANGES IN LAKE THERMAL STRUCTURE

4.1.1. *Lake Water Temperature*

Over the period 1947–1998, despite being masked to a large degree by seasonal and interannual variability, a distinct secular increase in the mean lake temperature (T_l) of Lake Zurich is obvious even in the untreated data (Figure 2a). After applying a spline interpolation and decadal running mean, the secular trend and decadal-scale variability in T_l become even more apparent (Figure 2b). During the second half of the 20th century, Lake Zurich warmed distinctly. The decadal mean of T_l increased by 0.6 K (corresponding to an increase of 8.8 PJ in total heat content) from a minimum in the 1950s, centred on 1955, to a maximum in the 1990s, centred on 1993 (Figure 2b), giving a mean rate of increase of 0.16 K per decade. The general secular increase was punctuated by a relatively short-lived decreasing tendency centred on the early 1980s, but the subsequently occurring extremely steep increase of 0.5 K in the decadal mean of T_l from 1983 to 1993 more than compensated for this.

Secular trends and decadal-scale variability in the mean temperatures of the surface mixed layer, the epi/metalimnion and the hypolimnion are illustrated in Figure 3. The secular increase in lake water temperature has been most extreme in the surface mixed layer (Figure 3a), where the decadal mean increased by 1.1 K from its minimum in 1967 to its maximum in 1994, corresponding to a mean rate of increase of 0.41 K per decade during this period. It is obvious in general that the secular increase in lake water temperature has been much stronger in the epi/metalimnion, where the decadal mean increased by 0.9 K from 1955 to 1993, or 0.24 K per decade on average (Figure 3b), than in the hypolimnion, where the corresponding increase was only 0.5 K, or 0.13 K per decade on average

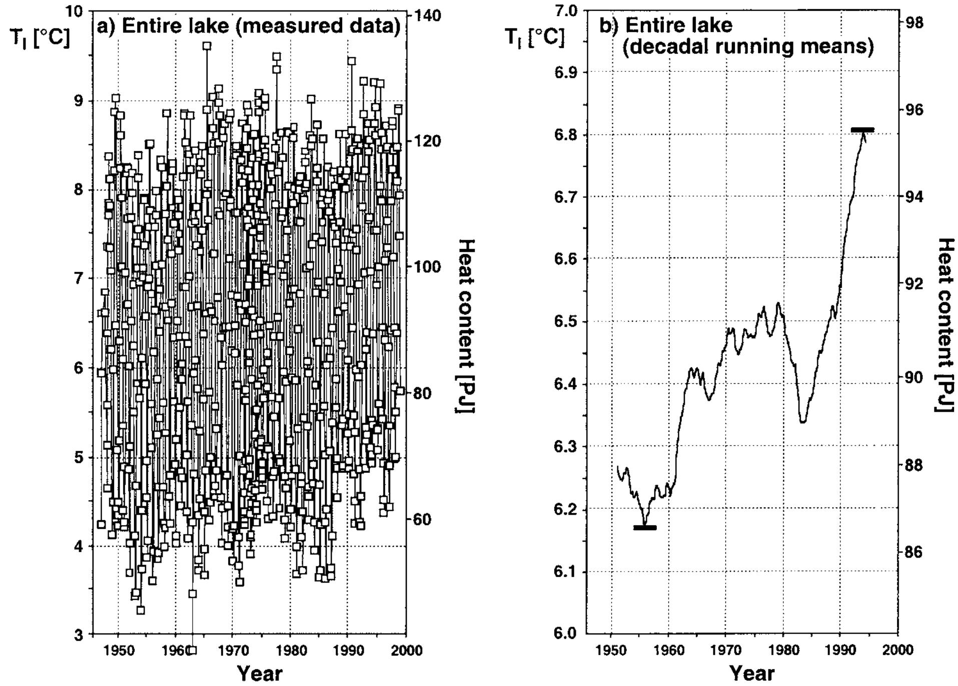

Figure 2. Secular changes and decadal variability in the mean temperature (T_l) of Lake Zurich and the equivalent heat content: (a) T_l calculated from measured profiles; (b) T_l after cubic spline interpolation at daily intervals, computation of monthly means, and application of a centred decadal (120-month) running mean. The horizontal bars show the minimum and maximum decadal means of the series.

(Figure 3c). The discrepancy between the epi/metalimnion and the hypolimnion was greatest between the mid 1960s and the late 1970s, when increasing values of T_{em} were accompanied by approximately constant values of T_h. Steep increases in temperature were experienced in both depth regions before and after this period.

Secular increases in T_l, T_s, T_{em} and T_h were found in all seasons, and indeed in all months of the year. However, there are distinct seasonal differences in the magnitude of the increases (Table I), which are associated with the degree to which the various water layers are exposed to direct climatic influence. In winter, spring and summer, when the temperature of the uppermost water layers is determined predominantly by direct heat exchange at the air-water interface, the secular increases in T_s and T_{em} are large. In autumn, when T_s and T_{em} are governed primarily by vertical mixing with cooler hypolimnetic water, and are therefore determined predominantly by the degree of deepening of the thermocline via convection and wind mixing, the secular increases are substantially lower. Hypolimnetic temperatures also undergo their greatest secular increase in those seasons in which the hypolimnion is exposed most directly to climatic forcing, i.e., during the homothermic or near-homothermic conditions that usually prevail

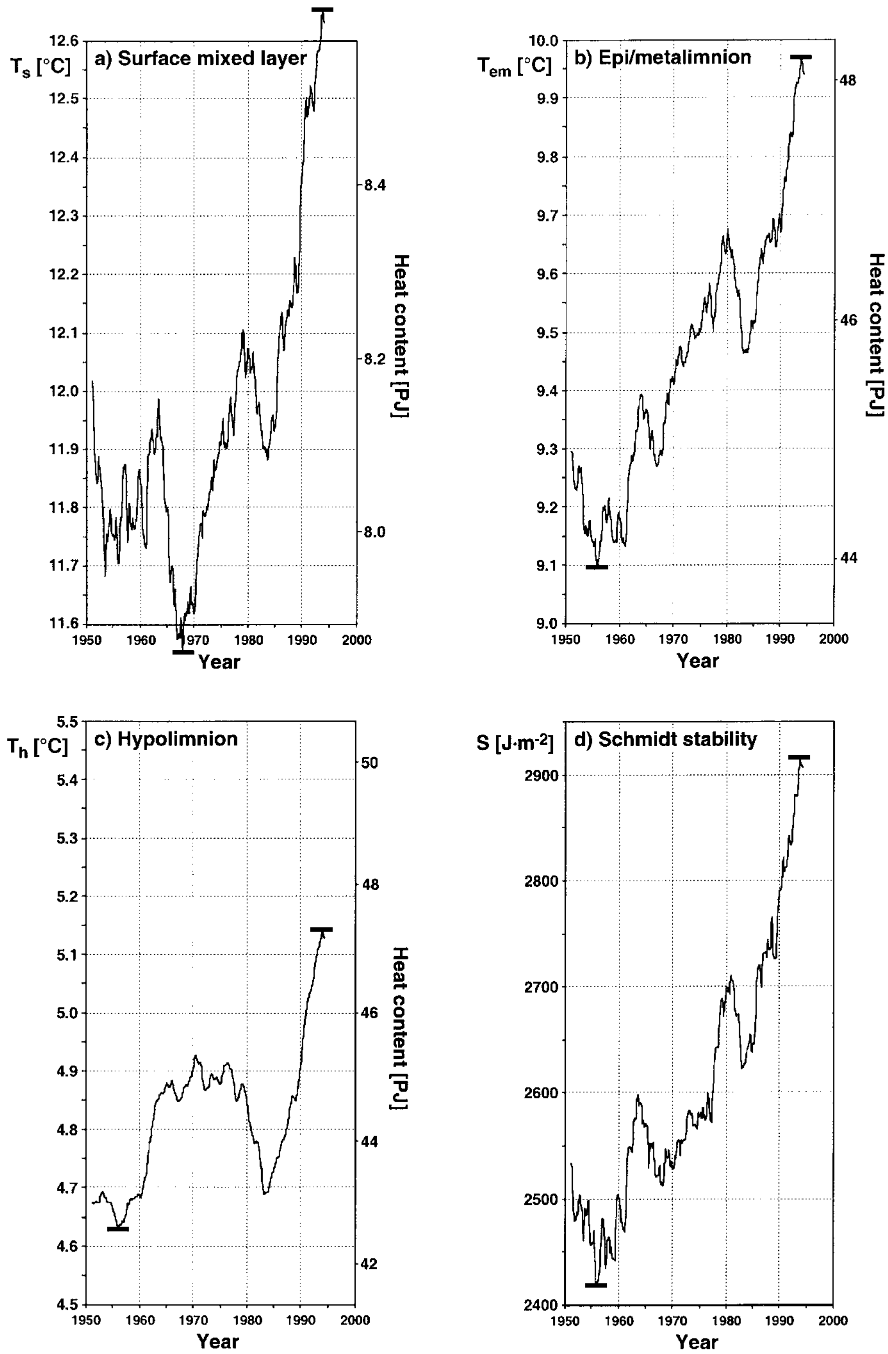

Figure 3. Secular changes and decadal variability in Lake Zurich water temperatures: (a) mean temperature (T_S) and equivalent heat content of the surface mixed layer (0–2.5 m); (b) mean temperature (T_{em}) and equivalent heat content of the epi/metalimnion (0–20 m); (c) mean temperature (T_h) and equivalent heat content of the hypolimnion (20–136 m); (d) Schmidt stability (S). All curves shown are centred decadal (120-month) running means. The horizontal bars show the minimum and maximum decadal means of the series. Note that the scales used allow direct comparison of the temperature changes in Figures 3a–c with each other and with Figure 2b.

Table I

Maximum increase in decadal mean lake temperatures and thermal stability for Lake Zurich from the 1950s/1960s to the 1990s, by season. The volume-weighted mean lake temperatures shown are those of the entire lake (0–136 m, T_l), the surface mixed layer (0–2.5 m, T_s), the epi/metalimnion (0–20 m, T_{em}) and the hypolimnion (20–136 m, T_h). The percentage increase in thermal stability (S) refers to the increase in Schmidt stability (Schmidt, 1928) that occurred in each season relative to the 1950s minimum value of S

	Winter	Spring	Summer	Autumn
T_l [K]	0.64	0.57	0.48	0.41
T_s [K]	0.91	1.17	1.30	0.61
T_{em} [K]	0.85	0.83	0.87	0.58
T_h [K]	0.53	0.45	0.28	0.33
S [J · m^{-2}]	76	213	892	498
S [%]	68	27	17	15

during a large part of winter and spring. In summer and early autumn, when the hypolimnion is shielded to a large degree from direct climatic influence by the stable thermocline, T_h is determined largely by the value it achieved during the period of homothermy immediately preceding the advent of stratification (Robertson and Ragotzkie, 1990; Hondzo and Stefan, 1993; Livingstone, 1993). A secular increase in T_h in summer/autumn is therefore most probably the result of a secular change in climate forcing in the previous winter/spring homothermic period. Because of the indirectness of this coupling and the significant influence of other factors such as downward heat transport by turbulent diffusion during the stratification period (Livingstone, 1997b), secular changes in T_h are unlikely to be greater in summer/autumn than in winter/spring. Because the hypolimnion accounts for 66% of the total lake volume, secular changes in T_l reflect those in T_h more strongly than those in T_{em}. The fact that annual minimum values of T_l (winter) have been increasing faster than annual maximum values (summer) is also apparent from the measured data illustrated in Figure 2a.

4.1.2. *Thermal Stability and the Duration of Homothermy and Stratification*

Because of the non-linear form of the temperature dependence of the density of water (Chen and Millero, 1986), a uniform increase in the heat content of a stratified lake at temperatures exceeding the temperature of maximum density (4 °C) will automatically result in an increase in the stability of the thermal stratification. This increase in thermal stability will of course be greatly enhanced if the increase in heat content is distributed unevenly, with a temperature increase in the surface layers exceeding that in the deeper water. Thus in Lake Zurich, the existence of a strong secular increasing trend in T_{em}, coupled with a comparatively weak increasing trend in T_h, must result in a strong secular increase in thermal stability. From the 1950s to the 1990s, the decadal mean of the Schmidt stability (S) of the lake did indeed increase by 20%, at an average rate of about 130 J $\cdot$ m^{-2} per decade (Figure 3d). The predominant cause of the secular increase in S in Lake Zurich is the increase in the vertical temperature gradient rather than the increase in mean lake temperature; this is apparent in the fact that the temporal structure of S reflects that of T_{em} (Figure 3b) rather than T_l (Figure 2b).

Seasonal increases in S (Table I) are considerably higher in summer/autumn than in winter/spring. This is because in summer/autumn, temperature gradients and mean lake temperatures are both high, so that even slight changes in the rate of heat exchange at the air-water interface result in large changes in thermal stability. In winter/spring, when temperature gradients are small and mean lake temperatures are close to the temperature of maximum density, shifts in the heat exchange rate have only a slight effect on thermal stability. However, because absolute values of S during this time of year are very low, by far the largest percentage increase in S since the 1950s occurred in winter (Table I), implying a significant long-term shift in the winter/spring thermal structure of the lake towards steeper temperature gradients.

Viewed ecologically, such a shift in thermal structure is of great significance. Although the degree of thermal stratification is relevant to the physical processes occurring in a lake at all times of the year, this is not true to nearly the same extent for biological processes. Of major relevance to the general ecology of a lake is the duration of the period of homothermy in winter/spring. Only during this period can the lake circulate fully, allowing the transport of oxygen from surface to deep waters and the transport of dissolved nutrients in the reverse direction. Conversely, the duration of the period of stratification in summer/autumn is also important, because stratification presents a barrier to the vertical transport of oxygen and nutrients. In addition, stratification can result in the confinement of non-motile phytoplanktonic primary producers to the photolytic zone (thus ensuring that photosynthesis is not limited by light availability), and in a continual decrease in hypolimnetic oxygen concentrations. An extension of the period of hypolimnetic oxygen consumption at the sediment-water interface, coupled with the fact that the ratio of sediment area to water volume increases drastically with depth in the hypolimnion, can lead to an upward extension of the anoxic zone that represents a potential ecological hazard in eutrophic lakes (Livingstone and Imboden, 1996). In several Swiss lakes, including Lake Zurich, a series of three consecutive warm winters (1987/88–1989/90, associated with an extremely positive phase of the North Atlantic Oscillation) with persistent stratification has been shown to have been responsible for extremely low deep-water oxygen concentrations (Livingstone, 1997b).

A value $S_{crit} = 200$ J $\cdot$ m^{-2} (corresponding in Lake Zurich, for instance, to a uniform T_{em} of 6.0 °C and a uniform T_h of 4.0 °C) was taken as the critical value to define the transitions between periods of stratification ($S \geq S_{crit}$) and homothermy

($S < S_{crit}$). By applying a cubic spline to interpolate the values of S computed from each temperature profile along the time axis, the durations of the summer/autumn stratification period and the winter/spring homothermic period according to this definition were estimated for each year. Because these individual estimates are based on monthly temperature profiles, they are necessarily inexact; however, the statistically more reliable decadal means of these estimates suggest that the duration of summer/autumn stratification increased by 2–3 weeks on average from the 1950s to the 1990s, while the duration of winter/spring homothermy decreased correspondingly (Figures 4a,b). Figures 4c,d illustrate the long-term variations in the decadal means of the estimated calendar dates of the transitions from homothermy to stratification (in April), and from stratification to homothermy (in December). Whereas the former date exhibits a high degree of decadal-scale variability superimposed on weak secular change, the latter exhibits less decadal-scale variability superimposed on stronger secular change. Thus, although decadal-scale variability in the durations of the homothermic and stratification periods is dominated by variability in the timing of the onset of stratification in spring, the long-term change in these durations is primarily the result of a secular shift in the timing of the end of stratification in early winter.

4.2. LAKE RESPONSE TO DIURNALLY ASYMMETRIC CLIMATE CHANGE

4.2.1. *Daytime/Nighttime Air Temperatures*

Long-term meteorological records show that mean surface air temperatures in both lowland and alpine areas of Switzerland have been increasing at rates of 0.08–0.14 K per decade since the end of the 19th century (Beniston et al., 1994; Lister et al., 1998). Although urban warming may account for some of this increase, even in the rural areas of Switzerland long-term rates of increase are still about 50% to 100% higher than the global warming rate of $\sim$0.05 K per decade (Lister et al., 1998), so that the European Alpine region appears to be responding particularly sensitively to global warming (Beniston et al., 1994). Air temperature is only one of several meteorological factors responsible for determining lake surface temperatures (Edinger et al., 1968; Sweers, 1976). Nevertheless, because lake surface equilibrium temperatures are closely related to air temperature (Dingman, 1972), epilimnetic temperatures in lakes of the European Alpine region tend to correlate strongly with regional-scale surface air temperatures (Livingstone and Lotter, 1998; Livingstone et al., 1999; Livingstone and Dokulil, 2001). Therefore, given the high rate of secular increase in regional surface air temperature in Switzerland, a correspondingly high increase in lake temperatures over the same period of time is not unexpected.

The increase of $\sim$0.5 K in global mean air temperature that has been observed since the middle of the 19th century (e.g., Jones and Briffa, 1992) is known to be essentially confined to nighttime (Plantico et al., 1990; Karl et al., 1991; Kukla and Karl, 1993), implying that, on a global scale, secular increases in anthropogenic

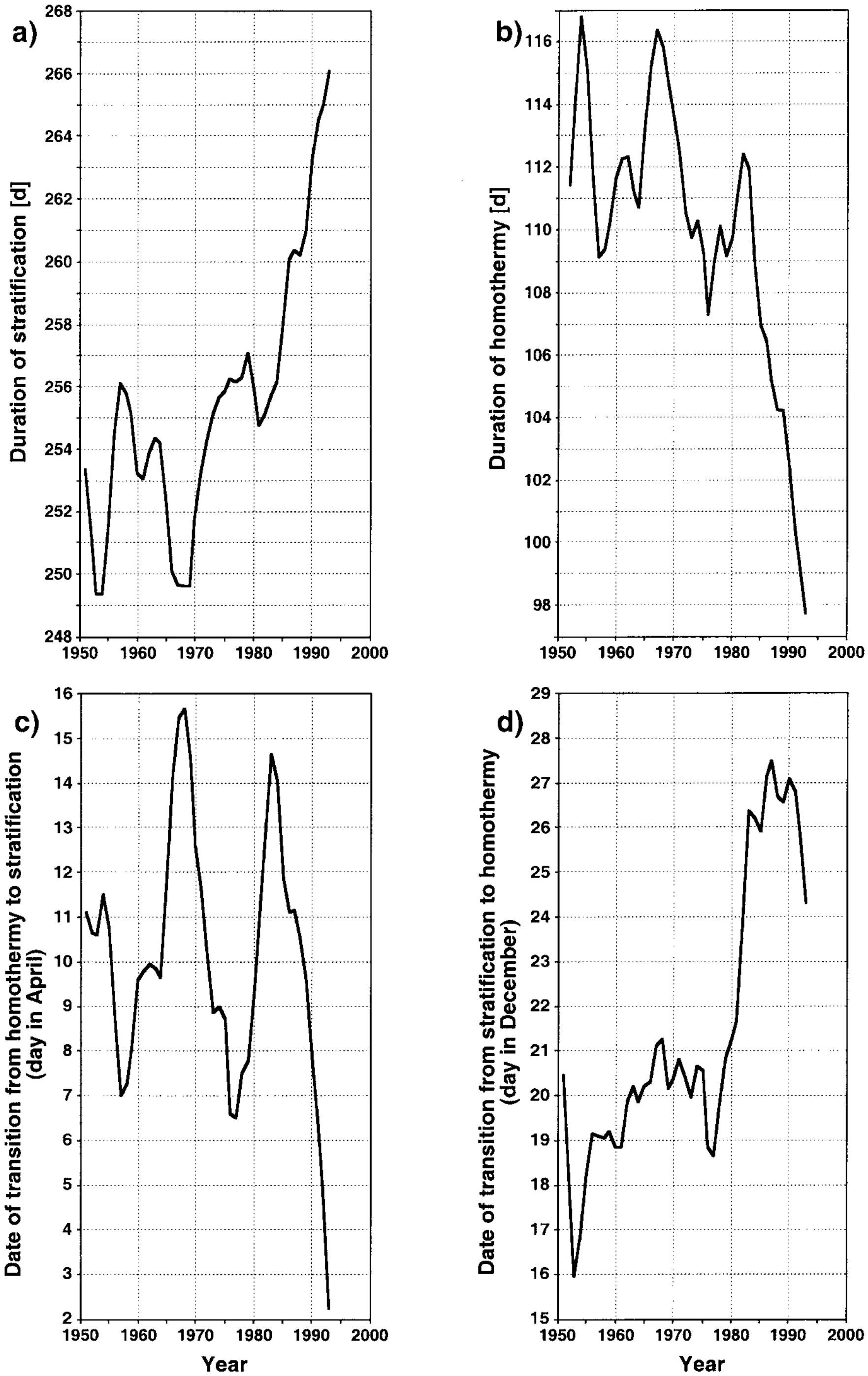

Figure 4. Secular changes and decadal-scale variability in stratification and homothermy in Lake Zurich: (a) duration of stratification; (b) duration of homothermy; (c) date of transition from homothermy to stratification; (d) date of transition from stratification to homothermy. All curves shown are centred decadal running means.

atmospheric turbidity and/or cloud cover in the lower troposphere are tending to reduce incident short-wave solar radiation during the day, while producing an increase in incident long-wave atmospheric radiation during the night (Kukla and Karl, 1993). Studies have shown that on the Swiss Plateau, daily minimum (nighttime) air temperatures have indeed been undergoing a secular increase, while daily maximum (daytime) air temperatures have not (Beniston et al., 1994; Weber et al., 1994, 1997; Rebetez and Beniston, 1998). This fact, which is typical of central Europe except at very high altitudes (Weber et al., 1997), is illustrated in Figure 5, where air temperature data from two representative stations on the Swiss Plateau (Basle and Zurich, 85 km apart) are presented. The similarity of the two data sets indicates that the secular changes and decadal-scale variability present in the Zurich air temperature data are not merely local, but are a feature of the regional climate. Although an essentially uninterrupted secular increase is present in the daily minimum air temperature T_n (+0.20 K per decade, 1901–1998), this is not the case for the daily maximum air temperature T_x (–0.05 K per decade, 1901–1998).

A comparison of these air temperature data with water temperature data from Lake Zurich (Figure 5) shows that, with respect to both secular change and decadal-scale variability, temperatures in the epilimnion exhibit essentially the same temporal structure as T_n, but not T_x. This is especially noticeable in the 1960s and 1970s, when the lake temperatures faithfully follow the increase in T_n rather than the decrease in T_x. This suggests that secular climatic change on at least a regional scale is likely to be affecting lake temperatures primarily via processes that occur during the night rather than during the day. The most important of these processes is nighttime convective cooling (Imberger, 1985). It is therefore likely that secular nighttime warming is gradually suppressing this process.

4.2.2. *Daytime/Nighttime Air-Water Heat Exchange*

Further evidence to support the hypothesis that secular changes in epilimnetic temperature are due to secular changes in nighttime climatic forcing was sought by applying a one-box heat-exchange model of the type described by Edinger et al. (1968) and Sweers (1976) to Lake Zurich. This model is forced by air temperature, cloud cover, water vapour pressure and wind speed acting through the five main heat exchange processes described in Section 1. The equations used in this specific case are those given by Livingstone and Imboden (1989), with the exception of that for incident solar radiation. This was computed from cloud cover by applying the empirical equation and coefficients of Kasten and Czeplak (1980) to the clear-sky radiation calculated for the lake using the approach of Brock (1981). Estimates of the partitioning of secular changes in net heat exchange between daytime and nighttime were obtained by replacing the daily mean air temperature T_m in the model by rough estimates of the mean daytime and nighttime air temperatures, T_{day} and T_{night}. Defining T_m as the mean of T_n and T_x, T_{day} was estimated as $0.5\ (T_m + T_x) = 0.75\ T_x + 0.25\ T_n$, and T_{night} as $0.5\ (T_m + T_n) = 0.75\ T_n + 0.25\ T_x$. Results indicate that the lake gains heat at a net decadal mean rate of between 82

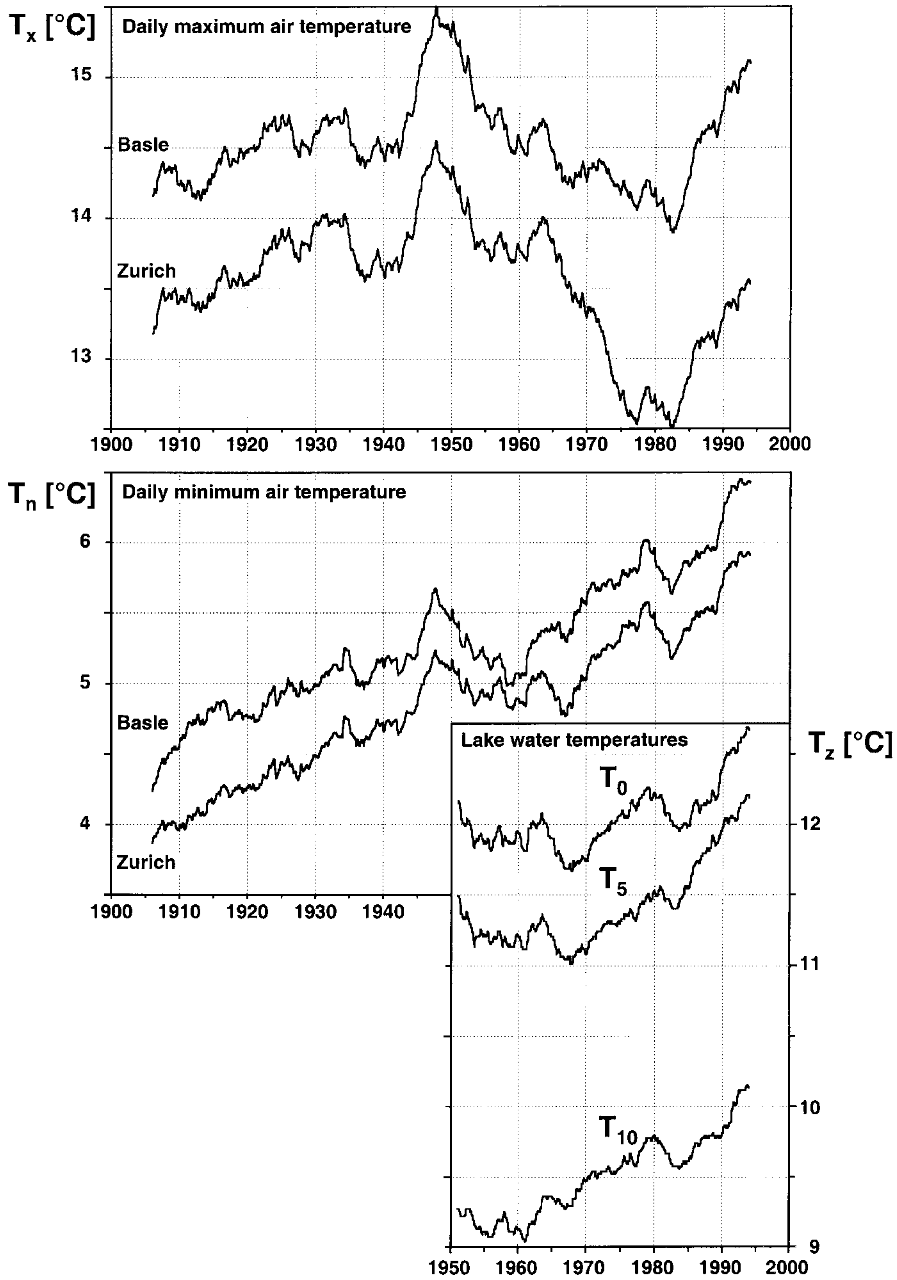

Figure 5. Comparison of secular changes and decadal-scale variability in the epilimnetic water temperature of Lake Zurich with secular changes and decadal-scale variability in daily maximum (T_x) and daily minimum (T_n) air temperatures on the Swiss Plateau. The water temperatures were measured at 0.3 m (T_0), 5 m (T_5) and 10 m (T_{10}). The air temperatures were measured at the Basle and Zurich meteorological stations (see Schüepp (1968) for the early part of these series). All curves shown are centred decadal (120-month) running means.

and 92 W · m^{-2} during daytime and loses it at a similar rate during nighttime. Within these bounds, however, shifts in the heat balance of the lake can be ascertained. Although a high degree of decadal-scale variability is present in both daytime and nighttime forcing, there was essentially no net change in the decadal mean rate of daytime heat uptake from the beginning of the series in the 1950s (89.5 W · m^{-2}) to the end of the series in the 1990s (89.4 W · m^{-2}), whereas the rate of nighttime heat loss underwent a clear secular decrease of 3.1 W · m^{-2} (from 91.0 W · m^{-2} to 87.9 W · m^{-2}) during the same period. This lends support to the hypothesis that the observed secular increase in mean lake temperature is predominantly due to a reduction in the heat lost by the lake to the atmosphere during the night. Of the five heat exchange processes modelled, only three (absorption of long-wave atmospheric radiation, evaporative heat exchange and the convective exchange of sensible heat) are both meteorologically forced and occur during nighttime. All three of these were found to have undergone shifts from the 1950s to the 1990s, so that each of these three processes can be surmised to have contributed significantly to the overall secular increase in lake temperatures.

5. Discussion

The results presented here agree to a large extent with the results of modelling studies designed to predict the general effects of climate change on the thermal structure of lakes. Such studies (e.g., Robertson and Ragotzkie, 1990; Hondzo and Stefan, 1993) suggest that the increase in surface air temperature resulting from a doubling of atmospheric CO_2 will be paralleled by an increase in epilimnetic temperatures ranging from about 50% to 100% of the corresponding increase in surface air temperature. The historical data from Lake Zurich confirm that epilimnetic temperatures have been increasing in step with ambient air temperatures, but contradict the modelling results to the extent that the increase occurs at about the same rate as the increase in daily minimum air temperature, and therefore more steeply, not less steeply, than the increase in daily mean air temperature. This suggests that wherever possible, predictions of the effects of climate change on lakes should attempt to take account of the effect of possible diurnal asymmetry in the secular changes of meteorological driving variables – especially air temperature – by explicitly including estimates of the relevant daily cycles in simulations.

Model predictions also suggest that hypolimnetic temperatures are likely to increase much less strongly than epilimnetic temperatures, or even to decrease, due to the earlier establishment of a stable water column at lower hypolimnetic temperatures (e.g., Robertson and Ragotzkie, 1990; Hondzo and Stefan, 1993). However, Peeters et al. (2002) point out that such studies have generally been confined to strictly dimictic ice-covered lakes, in which no heat is carried over during the winter from one year to the next, and show that, in lakes like Lake Zurich that are not strictly dimictic, significant long-term hypolimnetic warming, such as that illustrated in Figure 3c, can and does occur. It should be kept in mind here, however, that an increase in the decadal mean hypolimnetic temperature does not necessarily imply that Lake Zurich – or any holomictic lake subject to secular climate warming – will always circulate at increasingly higher temperatures each year. This is because an increase in the decadal mean hypolimnetic temperature can result from an increase in the frequency of occurrence of 'sawtooth' deep-water warming/cooling episodes that can extend over several years if winter circulation is suppressed, or its vigour reduced, by unusually mild winters. These sawtooth episodes, which are a characteristic feature of Lake Zurich and many other deep temperate lakes in central Europe (Livingstone, 1993, 1997b; Ambrosetti and Barbanti, 1999), consist initially of several years of gradual deep-water warming at a constant rate due to the relatively slow downward transport of heat by turbulent diffusion within the hypolimnion of the stratified lake. The warming period is then terminated by sudden cooling brought about by deep circulation that can be triggered either by a cold winter or by the achievement of a sufficiently high deep-water temperature. Only in the second of these cases – which can be looked upon as a type of internal negative feedback limiting the duration of multi-year stratification – does the temperature of circulation automatically increase. The occurrence of only one sufficiently cold winter, however, will reset the temperature of circulation of a holomictic lake back close to the temperature of maximum density (4 °C).

In Lake Zurich and in several neighbouring lakes, many such sawtooth episodes of various duration are known to have occurred, often superimposed on one another to yield a jagged sawblade structure (Livingstone, 1993). During the 1980s and 1990s, the relatively frequent occurrence of unusually warm winters resulted in two pronounced sawtooth episodes, one lasting from 1987–1991 and a second from 1992–1996 (Livingstone, 1997b; Peeters et al., 2002). These two multi-year events are the main reason for the unusually steep increase in the decadal mean hypolimnetic temperature of Lake Zurich in the 1980s and 1990s (Figure 3c). Although the recent prevalence of warm winters in Europe may be partly attributable to global greenhouse-gas warming, it is almost certainly also related to the currently prevailing persistently positive phase of the North Atlantic Oscillation (NAO) (Hurrell, 1995). Assuming this to be so, we might expect the NAO in the near future to revert to a less positive state on average, resulting in generally cooler winters, and hence in more normal hypolimnetic temperatures. However, Paeth et al. (1999) suggest that greenhouse-gas forcing may act to stabilise the NAO in its present positive phase. If this is correct, warm winters are likely to become the rule in Europe, implying a stabilisation or further increase in the hypolimnetic temperatures of deep European lakes.

6. Conclusions

Over the last half century, a secular increase in water temperature has occurred at all depths in Lake Zurich. However, because water temperatures in the epilimnion and metalimnion have been increasing faster than those in the hypolimnion, thermal stability in the lake has also undergone a secular increase, leading to a lengthening of the period of stratification by about 2–3 weeks and a corresponding shortening of the period of homothermy. With respect to both secular change and decadal-scale variability, the temporal structure of the temperature in the epilimnion faithfully reflects that of the daily minimum air temperature, but not that of the daily maximum air temperature, implying that the processes responsible for the secular changes in the temperature structure of the lake act during the night, suppressing nighttime convective cooling in the epilimnion. Specifically, secular changes appear to have occurred in the nighttime rates of absorption of infrared radiation from the atmosphere and in the nighttime rates of latent and sensible heat exchange. Because hypolimnetic temperatures tend to become established in late winter and early spring, but persist throughout the summer, the steep increase in the hypolimnetic temperature of the lake that has occurred since the 1980s can be explained by the prevalence of unusually warm winters in Europe during the last two decades of the 20th century.

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