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The relationship between air and water temperatures in lakes of the Swiss Plateau: a case study with palæolimnological implications

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Abstract

In palæolimnological studies, inference models based on aquatic organisms are frequently used to estimate summer lake surface water temperatures. However, the calibration of such models is often unsatisfactory because of the sparseness of measured water temperature data. This study investigates the feasibility of using air temperature data, usually available at much higher resolution, to calibrate such models by comparing regional air temperatures with surface water temperatures in 17 lakes on the Swiss Plateau. Results show that altitude-corrected air temperatures are sufficiently uniform over the entire Swiss Plateau to allow local air temperatures at any particular lake site to be adequately estimated from standard composite air temperature series. In early summer, day-to-day variability in air temperature is reflected extremely well in the temperature of the uppermost metre of the water column, while monthly mean air temperatures correspond well, with respect to both absolute value and interannual variations, with water temperatures in most of the epilimnion. Standardised altitude-corrected air temperature series may therefore be a useful alternative to surface water temperatures for the purposes of calibrating lake temperature inference models. In Northern Hemisphere temperate regions, mean air and water temperatures are likely to correspond most closely in July, suggesting that calibration and reconstruction efforts be concentrated on this month.

Introduction

Publication of the most recent IPCC reports (Houghton et al., 1996; Watson et al., 1996; Bruce et al., 1996) has emphasized the importance of global warming as one of the major issues with which mankind is likely to be confronted in the near future. A warming of the Earth's surface is likely to have vital ecological, economic and political consequences, not only because of its effect on terrestrial environments and ecosystems, agriculture and forestry (e.g. Gates, 1993; Strzepek & Smith, 1995), but also, not less importantly, because of its effect on aquatic environments and ecosystems, water supplies and fisheries (Houghton et al., 1996; Watson et al., 1996). Any effect global warming might have on lacustrine ecosystems must be mediated by the physical lake environment, of which water temperature is one of the most important aspects. Parallel to an increase in air temperature, model studies (Robertson & Ragotzkie, 1990; Hondzo & Stefan, 1993; De Stasio et al., 1996; Stefan et al., 1996) supported by observations (Schindler et al., 1990) suggest that global warming is likely to result in an increase in the heat uptake of lakes and reservoirs, resulting in higher epilimnetic temperatures, but not necessarily in higher hypolimnetic temperatures. This is of great importance for aquatic ecology. Direct ecological effects are to be expected on fish habitats, for instance (Meisner et al., 1987; Magnuson et al., 1990; De Stasio et al., 1996; McDonald et al., 1996), while indirect ecological effects might be expected from changes in lake oxygen concentrations, which on the one hand are likely to increase as the duration of lake ice cover decreases (Livingstone, 1993a, 1997a), but on the other hand to decrease as the duration of summer stratification increases (Livingstone & Imboden, 1996; Stefan et al., 1996; Livingstone, 1997b).

An important question of great relevance to the global climate change discussion concerns background conditions and natural variability. Instrumental meteorological data cover a time-span of decades to centuries at the most, and long-term monitoring data on aquatic ecosystems are even more limited. Palæolimnological approaches can provide long time-series of proxy data that may help in assessing background values and natural variability on time-scales extending from decades to millennia. Physical, chemical and biological indicators preserved in sedimentary records have the potential to provide a considerable amount of information on past climate (Birks & Birks, 1980; Smol, 1990; Smol et al., 1991, 1994). The development of powerful statistical methods (ter Braak et al., 1993; Birks, 1995) has allowed increasingly better quantitative reconstruction of past limnological conditions.

Such methods commonly require the prior estimation of biotic species optima and tolerances to particular environmental variables using modern surface sediment training sets (Birks, 1995). One of the most important environmental variables in this context is water temperature. For calibration purposes, in addition to sampling surficial sediment from many lakes along a climatic gradient, these methods of course require information on the water temperatures themselves. However, information on variations in water temperature in remote lakes is usually scarce, since a temperature profile is often only measured once, namely during sediment sampling. This situation is unsatisfactory, and transfer function approaches based on such single water temperature measurements have been criticised (Hann et al., 1992). In contrast to water temperatures, air temperatures are usually available at much higher temporal resolution (monthly or even daily means), and, if the meteorological network is dense enough, can often be interpolated both vertically and horizontally to give a good estimate of the air temperature prevailing at a given remote site. This suggests that improved reliability might be achieved by employing mean air temperatures for calibration purposes rather than a single random water temperature measurement. Based on this premise, Lotter et al. (1997) have used canonical correspondence analysis to assess the potential of different aquatic organisms as indicators of mean air temperature without involving measured lake water temperatures explicitly in the calibration process. However, because the abundance of aquatic organisms is more likely to be influenced by water temperature than air temperature, a prerequisite of such a calibration procedure should be to relate epilimnetic water temperature to air temperature convincingly. The aim of the present study is to investigate the possibility of achieving this, with the goal of rendering the inference model relating the abundance of aquatic organisms to water temperature more realistic. In addition, reconstructing air temperatures is of more inherent palæoclimatological interest than reconstructing lake water temperatures. Investigating the relationship between the two is therefore of great interest not only for calibration purposes, but also for reconstruction purposes.

Here, therefore, we explore the degree of correspondence existing between modern air and lake water temperatures using as an example temperature data from 15 meteorological stations and 17 lakes situated on the Swiss Plateau, a fairly homogeneous region extending about 300 km from Lake Geneva in the south-west to Lake Constance in the north-east of Switzerland, and encompassing most of Switzerland north of the Alps (Figure 1). The Swiss Plateau is a good choice for such a study because of the large number of palæolimnological studies already carried out in this region (e.g. Züllig, 1982; Chaix, 1983; Lotter & Boucherle, 1984; Hofmann, 1985; Lotter, 1988, 1989a; Ammann, 1989; Straub, 1990).

Lake heat balance and surface equilibrium temperature

As the relationship between air temperature and surface water temperature is not primarily one of cause and effect, a purely process-based approach to the problem of relating lake surface temperature to air temperature is unlikely to achieve success. The heat balance of a lake is determined primarily by three radiative and two non-radiative heat exchange processes; viz. the absorption of direct and diffuse short-wave radiation from the sun and the atmosphere, respectively; the absorption of long-wave radiation from the atmosphere; the emission of long-wave radiation from the lake surface; the exchange of latent heat between lake surface and atmosphere due to evaporation and condensation; and the convective exchange of sensible heat between lake surface and atmosphere (e.g. Edinger et al., 1968; Sweers, 1976; Marti & Imboden, 1986; Livingstone & Imboden, 1989). The three radiative processes are the most important for lake heat budgets in absolute

Table 1. a) Meteorological stations located on the Swiss Plateau (Figure 1a) supplying the data upon which the two composite air temperature series are based and b) lakes on the Swiss Plateau (Figure 1b) supplying water temperature data

a) *Meteorological stations*

Name	Abbreviation	Altitude [m a.s.l.]
Basel-Binningen	BS	316
Wynau	WY	422
Changins	CH	435
Schaffhausen	SH	437
Guettingen	GU	438
Luzern	LU	456
Vaduz	VZ	460
Wädenswil	WA	463
Neuchâtel	NE	487
Payerne	PA	489
Tänikon	TN	536
Zürich-MZA	ZH	556
Bern-Liebefeld	BE	570
Interlaken	IN	574
St. Gallen	SG	779

b) *Lakes*

Name	Abbreviation	Altitude [m a.s.l.]	Max. depth [m]	Surface area [km^2]
Zürichsee	LZ	406	136	66.6
Zugersee	ZG	413	197	38.3
Rotsee	RO	419	16	0.5
Bielersee	BI	429	74	39.3
Vierwaldstättersee	VW	434	215	113.8
Alpnachersee	AL	434	35	4.7
Greifensee	GR	435	32	8.5
Katzensee	KA	439	8	0.2
Baldeggersee	BA	463	66	5.2
Burgäschisee	BU	465	31	0.2
Lützelsee	LS	500	6	0.1
Moossee	MO	521	21	0.3
Thunersee	TH	558	215	47.9
Brienzersee	BR	564	260	29.8
Soppensee	SO	596	27	0.3
Burgseeli	BG	613	19	0.1
Seelisbergsee	SE	738	38	0.2

terms, whereas the direct causal influence of air temperature (mainly on the evaporative and convective heat-exchange terms) is of only minor importance. The lake surface temperature tends towards an equilibrium temperature, defined as the temperature at which the net heat flux would theoretically be zero (Edinger et al., 1968). From late spring to early autumn, the mixed layer is relatively thin, which means its temperature responds rapidly to changes in the surface heat flux and is usually close to the equilibrium temperature. From late autumn to early spring, however, the mixed layer is thick and its temperature responds only sluggishly to changes in the surface heat flux (this sluggishness reaches an extreme during homothermy). The equilibrium temperature would be identical with the air temperature at the lake surface if radiative heat exchange were negligible (Dingman, 1972), but often coincides roughly with air temperature during much of

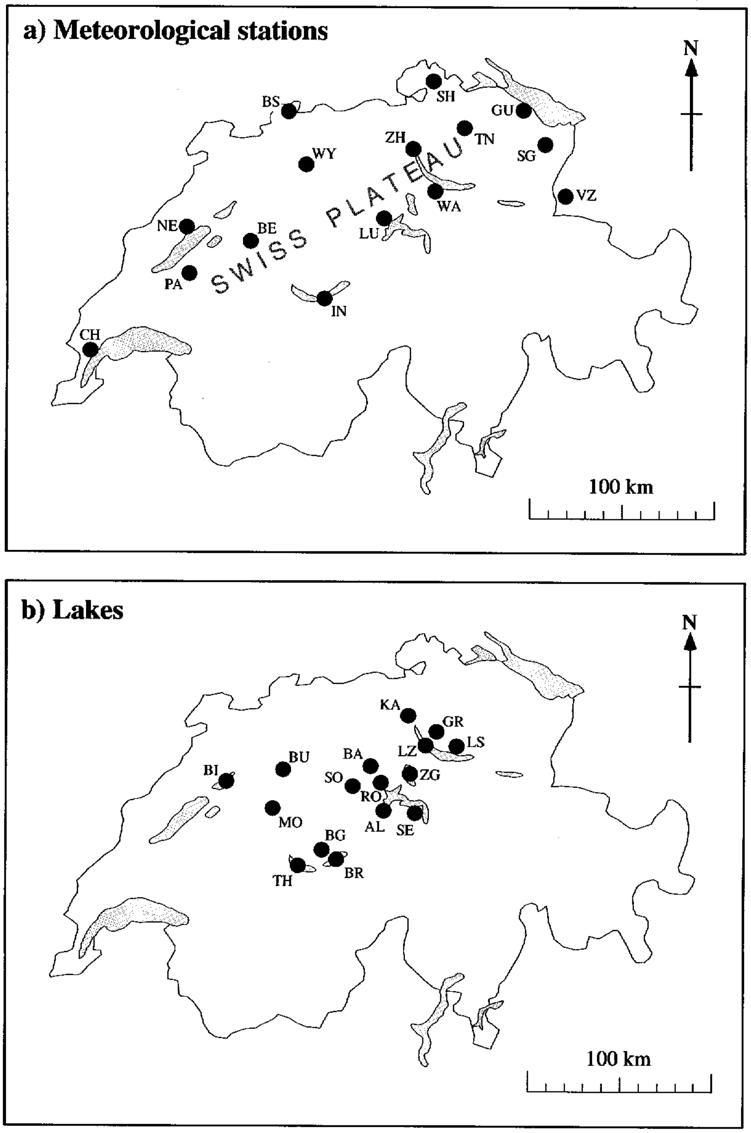

Figure 1. Map of Switzerland indicating (a) the meteorological stations and (b) the lakes referred to in the text (see Table 1 for names and altitudes).

the year in shallow lakes, and during summer, when the mixed layer is thin, in deeper lakes (Arai, 1981).

Because the equilibrium temperature is partially dependent on radiative heat exchange and evaporation/condensation, and because processes such as wind mixing increase the discrepancy between the actual surface water temperature and the equilibrium temperature to which it tends, the causal connection between air and surface water temperature is not particularly strong. Despite this, the essential similarity in the physical processes which determine surface air temperature and surface water temperature can result in a high degree of correlation between the two, allowing at least some inferences on the one to be drawn from the other. Thus, some attempts have been made to relate lake surface water temperatures to air temperature empirically (e.g. McCombie, 1959; Webb, 1974; Shuter et al., 1983).

Uniformity of air temperatures across the Swiss Plateau

The Swiss Plateau is situated largely between about 300 and 600 m a.s.l.; most of it is relatively flat, which implies a considerably greater degree of uniformity with respect to weather and climate than that found in the morphologically much more heterogeneous Alpine region to the south. This is important because of the detrimental effect a high degree of local variability will necessarily have on the use of palæolimnological information from individual lakes to reconstruct climate on a regional scale. A prerequisite for any palæolimnological study aiming to reconstruct regional air temperatures on the basis of information obtained from individual lakes, which respond to the local microclimate rather than the regional macroclimate, is therefore an investigation of the degree to which the temporal structure of air temperature time series in the region can be considered uniform.

Daily air temperature data from 15 meteorological stations scattered over the whole of the Swiss Plateau (Figure 1a) and spanning altitudes from 316–779 m a.s.l. (Table 1a) were used to investigate this question. To reduce the likelihood of changes in observer and observation time resulting in inhomogeneities in the time series of daily means, for the purposes of this paper the daily mean air temperature was defined as the mean of the daily minimum and daily maximum and computed accordingly. From four of the 15 stations, viz. Basel-Binningen (BS), Neuchâtel (NE), Zürich-MZA (ZH) and Bern-Liebefeld (BE), uninterrupted machine-readable daily air temperature data are available from 1901 to the present. Time series of daily mean air temperature were computed for each of these stations for this period. The fact that these series are extremely highly correlated (Table 2a) is trivial because of the dominance of the seasonal cycle, which must first be removed from the time series before any useful information on the degree of regional uniformity can be obtained. This was accomplished by applying a high-pass elliptical filter (Rabiner & Gold, 1975) to remove from the data variations with periods greater than one month, including the fundamental seasonal cycle and its first few harmonics (spectral analysis detected the presence of only the fundamental and its first harmonic in the original data). Coefficients of determination (r^2) between the filtered data series lay between 0.79 and 0.89 (Table 2b); air temperature fluctuations on time scales of less than a month are thus very similar across the whole of the Swiss Plateau. Figure 2 illustrates this fact for a typical summer month (July 1995) based on air temperature data from all 15 meteorological stations: the range within which temporal fluctuations occur within this month ($\sim$12 K) is much greater than the spatial range of temperatures spanned by the 15 stations ($\sim$ 2 K). Comparison of air and water temperature signals on short time scales ($<$1 month) therefore does not require an individual local air temperature series for each lake; a composite air temperature series representative of the whole Swiss Plateau, corrected to a standard altitude, will suffice.

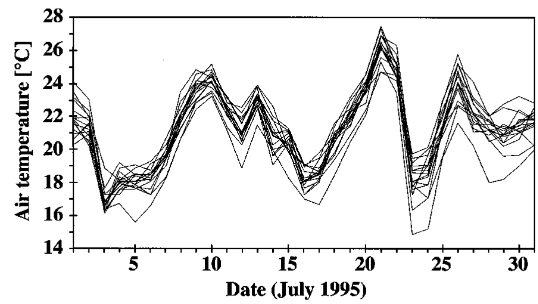

Figure 2. Daily mean air temperatures during July 1995 measured at 15 stations scattered across the Swiss Plateau (Figure 1a) and spanning a range of altitudes from 316–779 m a.s.l. (Table 1a).

Studies of climate, as opposed to weather, require information on fluctuations on longer time scales. The similarity of interannual variations in air temperature across the Swiss Plateau was investigated by computing monthly mean air temperatures from the daily means and correlating these between station pairs for each month separately. Depending on station pair and time of year, pairwise shared variance (r^2) ranges from 81%–97% (Figure 3). For all station pairs r^2 is lowest in summer and highest in winter, implying that the degree of spatial heterogeneity of air temperature over the Swiss Plateau is slightly greater in summer than winter (possibly a result of more uniform cloud cover during winter). Stations BS, ZH and BE are most similar with respect to interannual air temperature variations; correlations involving station NE tend to be lower. Since the NE air temperature data are more homogeneous than those at the other stations (Weber et al, 1994), this is likely to reflect a real difference between interannual variations in air temperature at station NE and at the other stations. This difference is, however, slight. In general, interannual air temperature variations are very similar across the whole of the Swiss Plateau.

Table 2. Values of the coefficient of determination (r^2) between daily air temperature data series from the stations Basel-Binningen (BS), Neuchâtel (NE), Zürich-MZA (ZH) and Bern-Liebefeld (BE). a) Unfiltered data. b) Data filtered to remove the effect of seasonal and longer-term variations on the correlations (high-pass elliptical filter with pass and stop band corner periods of 30.4 d and 33.2 d, respectively, giving an effective cut-off at about one month: see, e.g., Rabiner and Gold, 1975)

	BS & NE	BS & ZH	BS & BE	NE & ZH	NE & BE	ZH & BE
a)	0.962	0.976	0.970	0.969	0.981	0.978
b)	0.791	0.859	0.830	0.830	0.886	0.866

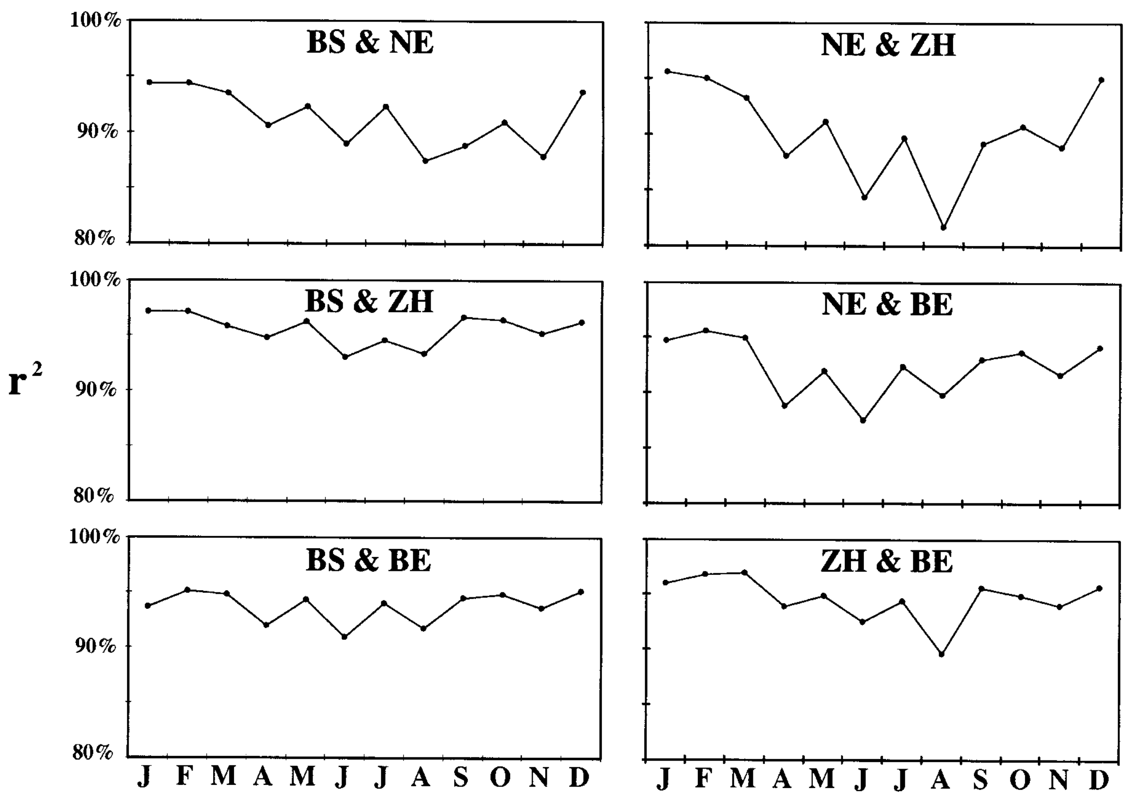

Figure 3. Pairwise coefficients of determination (r^2) between monthly mean air temperatures measured at Basel-Binningen (BS), Neuchâtel (NE), Zürich-MZA (ZH) and Bern-Liebefeld (BE) from 1901–95.

Table 3. a) Mean monthly surface air temperature lapse rates for the Swiss Plateau based on linear regressions of monthly mean air temperature from the 15 stations listed in Table 1a against station altitude (1981–95). All regressions were significant at at least the $p < 0.05$ level. b) Mean monthly surface air temperature lapse rates for the north slope of the Swiss Alps according to Maurer et al. (1909)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
a)	0.368	0.446	0.529	0.552	0.520	0.543	0.529	0.523	0.465	0.394	0.373	0.382
b)	0.400	0.485	0.583	0.625	0.610	0.602	0.545	0.514	0.485	0.458	0.442	0.397

The high degree of uniformity in temporal structure present on both short and long time scales allows a composite air temperature time series to be constructed to represent the whole Swiss Plateau. Two such composite series will be referred to in the following: Series I is based on the mean air temperature of the four stations BS, NE, ZH and BE; while Series II is based on the mean air temperature of all 15 stations listed in Table 1a. Because air temperatures generally decrease with increasing altitude, it is necessary to specify a standard altitude for such composite series and to correct the series to this altitude using appropriate lapse rates. For the present study, 500 m a.s.l. was chosen as the standard altitude. Based on the monthly mean air temperatures computed for all 15 stations from 1981–95, surface air temperature lapse rates for the Swiss Plateau were computed by linear regression for each month (Table 3a). These lapse rates, which range from 0.37–0.54 $K \cdot m^{-1}$, are very similar to, although slightly smaller than, those applicable over a greater altitude range for the whole of the north slope of the Swiss Alps (Table 3b). For both composite series, the altitude corrections were minimal, since the mean altitudes of the four stations of Series I (482.5 m a.s.l.) and of the 15 stations of Series II (494.5 m a.s.l.) are both very close to the chosen 500 m a.s.l. standard altitude. Series II is more representative spatially and hence more reliable than Series I, but is limited in use since it extends back only to 1981. Although there is a seasonally-dependent offset of 0.2–0.5 K (Series I being the warmer), the two series are very highly correlated, with monthly coefficients of determination (r^2) always exceeding 0.97, implying that the interannual temperature signal is essentially the same in both series (Table 4).

Surface water temperatures of lakes on the Swiss Plateau

In very shallow lakes in which the epilimnion accounts for a large proportion of the total lake volume, the volume-weighted mean lake temperature often follows the surface air temperature closely during a large part of the year. Livingstone & Schanz (1994) showed that the mean lake temperature of Lützelsee (maximum depth = 6.2 m) faithfully mirrors the air temperature measured at the nearby Zürich-MZA meteorological station from spring to autumn (Figure 4a). Especially in summer, the influence of cold outbreaks on the mean lake temperature can be very marked (e.g. June–

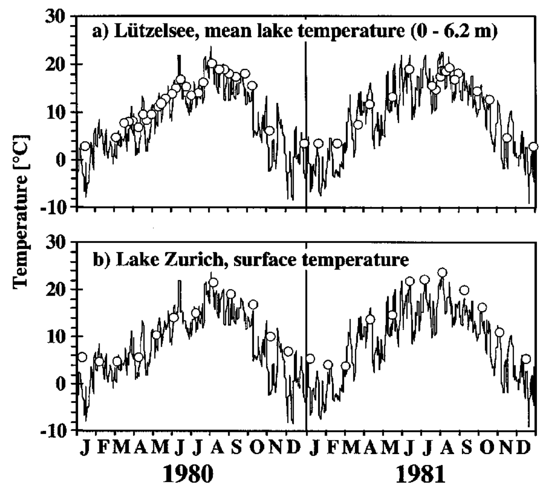

Figure 4. Comparison of air temperature measured at station Zürich-MZA (solid line) with (a) the mean lake temperature of Lützelsee (open circles; after Livingstone and Schanz, 1994) and (b) the surface temperature of Zürichsee (open circles).

July 1980), such outbreaks being followed immediately by a drop in the temperature of the uppermost 3 m of the lake (Livingstone & Schanz, 1994). In deeper lakes, however, short-term variations in air temperature are reflected only in the temperature of the uppermost water column, and then only in spring and summer when the epilimnion is comparatively thin and mixing with underlying colder water layers is minimal. This is illustrated in Figure 4b, where the same Zürich-MZA air temperature data are compared with surface water temperature measurements from Zürichsee (maximum depth = 136 m). Despite the comparative coarseness of sampling in the case of Zürichsee (about 1 month), there is an obvious similarity in the deviations from the seasonal cycle exhibited by the local air temperature and those exhibited by the water temperatures of these two unequal neighbouring (∼ 3 km apart) lakes.

It is clear from Figure 4b that much shorter sampling intervals are essential if the relationship between lake surface temperature and air temperature is to be investigated in any detail. Automatic temperature measurements from thermistor chains are ideal for this purpose. Such measurements (generally at half-hour intervals) are available from within the uppermost 6 m of six lakes situated on the Swiss Plateau (Figure 1b) during the period 1990–95. The measured data were averaged to yield daily means. To allow comparisons to be made with the composite air temperature series, the daily mean water temperature data were also corrected

Table 4. Monthly mean air temperature differences (ΔT) and coefficients of determination (r^2) between the 4-station (Series I) and 15-station (Series II) Swiss Plateau composite air temperature time series (corrected to 500 m a.s.l. using the lapse rates of Table 3a). The comparison is based on 15 yr of data (1981-95). Despite the existence of a seasonally-dependent offset (Series I being the warmer), the extremely high r^2 values imply that the interannual temperature signal in both series is essentially the same

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
ΔT [K]	0.48	0.53	0.43	0.35	0.23	0.28	0.36	0.43	0.35	0.34	0.38	0.40
r^2	0.999	0.998	0.998	0.977	0.994	0.994	0.992	0.987	0.988	0.986	0.995	0.994

to 500 m a.s.l. using the same lapse rates applied to the air temperature data (this is justifiable if it is assumed that the relationship between lake surface water temperature and surface air temperature does not vary with altitude). These comparisons are illustrated in Figure 5.

In addition to the thermistor chain measurements, some water temperature data were obtained from lakes with officially designated bathing areas in which surface temperatures are measured once or twice daily with a hand thermometer during the bathing season. Because such measurements are made only during daylight hours, they are bound to be biased and will exceed daily mean values. While these data may not be of the same quality as those obtained as part of a scientific monitoring programme, they do provide some information on surface water temperatures in lakes for which no other data exist. These data are illustrated in Figures 6 and 7.

Temperatures in the upper water column are unlikely to exhibit any significant short-term correspondence with air temperature during the winter half-year (October–March) because of the damping effect the thickness of the mixed layer has on meteorological forcing (also, the smaller lakes are often frozen over during part of the winter). In addition, statistical model calibrations and temperature reconstructions in temperate or higher latitudes based on biological sediment remains refer principally to the productive summer months (e.g. Walker et al., 1991a, b, 1997; Pienitz et al., 1995; Wunsam et al., 1995; Lotter et al., 1997; Olander et al., 1997; Weckström et al., 1997), to which the following remarks will therefore be confined.

Those water temperature measurements taken within 1 m of the lake surface (Figures 5, 6, 7) generally follow the composite air temperature series quite closely, although in most cases with an offset in the mean which may vary from month to month. The lake surface water is usually, but not always, warmer than the overlying air. Table 5 shows that in July of the same year, differences between lake surface water temperature and air temperature can vary from lake to lake by more than 5 K. However, correlations between lake surface water temperature and air temperature are, with some exceptions, generally high in July, with r^2 values of over 0.5 being not uncommon. The highest r^2 value attained was 0.84 (July 1992 in Greifensee).

Table 5. Mean differences (ΔT) and coefficients of determination (r^2) between various water temperature measurements conducted during July in the years 1992–95 and the 15-station composite air temperature time series (Series II) (see Figures 5–7). For the computation of ΔT, all series were corrected to a standard altitude of 500 m a.s.l. using the surface air temperature lapse rates of Table 3a. See Table 1b for an explanation of the lake abbreviations. Significant correlations are denoted by ∗∗∗ ($p < 0.001$), ∗∗ ($p < 0.01$) or ∗ ($p < 0.05$)

	Lake	n	ΔT [K]	r^2	p
July 1992	GR (0.2 m)	30	4.5	0.838	∗∗∗
	GR (5.0 m)	29	0.1	0.191	∗∗
July 1993	GR (0.5 m)	31	4.4	0.234	∗∗
	GR (5.0 m)	31	1.0	0.016	
July 1994	LS	31	4.1	0.568	∗∗∗
	BR	30	−1.6	0.563	∗∗∗
	BG	31	3.0	0.454	∗∗∗
	MO	22	2.8	0.370	∗∗
	TH	30	−2.5	0.222	∗∗
July 1995	LS	31	4.3	0.553	∗∗∗
	KA	31	4.1	0.524	∗∗∗
	BA (1.0 m)	31	3.6	0.505	∗∗∗
	BA (5.5 m)	31	−5.5	0.001	
	GR	31	2.1	0.365	∗∗∗
	ZH	31	2.2	0.287	∗∗∗
	RO	31	3.6	0.227	∗∗
	SE	31	−0.9	0.137	∗
	VW	30	0.1	0.106	∗
	BU	26	5.2	0.058	

In general, lake water temperatures do not respond immediately to short-term changes in meteorological forcing. A lake acts in a sense like a low-pass filter, filtering out more and more high-frequency meteorological ‘noise’ with increasing depth (Livingstone, 1993b),

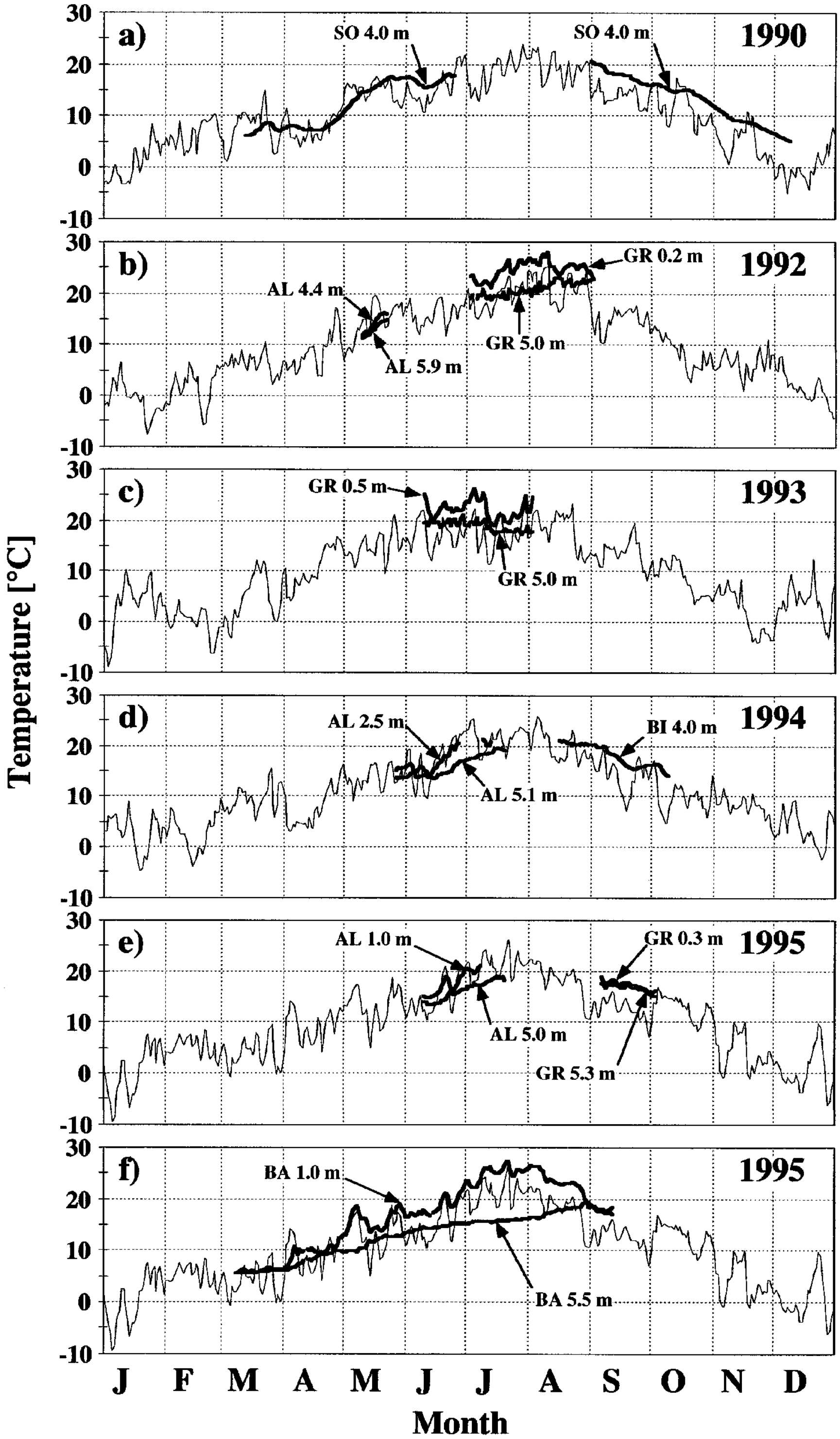

Figure 5. Comparison of lake water temperature data (thick lines) with composite air temperature data Series II (thin lines) for the Swiss Plateau. Series II is based on data from 15 meteorological stations (Figure 1a; Table 1a) corrected to 500 m a.s.l. using the lapse rates of Table 3a. Water temperature data from Soppensee (SO), Greifensee (GR), Alpnachersee (AL), Bielersee (BI) and Baldeggersee (BA) were measured using thermistor chains and corrected to 500 m a.s.l. using the same lapse rates.

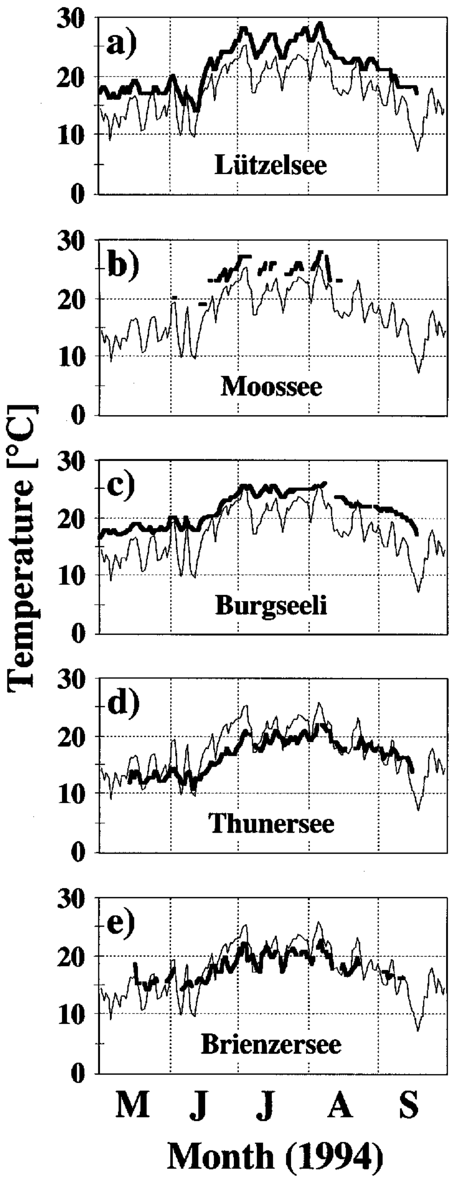

Figure 6. Comparison of lake water temperature data (thick lines) with composite air temperature data Series II (thin lines) for the Swiss Plateau during the summer months of 1994. Series II is based on data from 15 meteorological stations (Figure 1a; Table 1a) corrected to 500 m a.s.l. using the lapse rates of Table 3a. Lake surface water temperatures were measured at lake bathing areas with hand thermometers and corrected to 500 m a.s.l. using the same lapse rates. All values plotted refer to measurements made once per day at one bathing area except for Thunersee (d) and Brienzersee (e), for which the means of measurements made at two bathing areas in each lake are plotted.

so that the degree of correspondence between air and lake water temperatures decreases considerably with depth. While lake surface water exhibits essentially the same temperature signature as the overlying air (see Figure 6a for a good example of this), this is not true of water temperatures measured only a few metres below the surface. The six-month series of thermistor measurements from Baldeggersee in 1995 (Figure 5f) clearly illustrate the dependence of the water temperature signal on depth. While the temperature signal at 1 m follows the air temperature signal from May to July, the water temperature at 5.5 m increases almost monotonically from April to August. Similar differences can be noted in Alpnachersee (Figures 5d, e), although in Greifensee (Figures 5b, c, e) differences generally seem to be less pronounced. The water temperature at 4.0 m in Soppensee (Figure 5a) reflects longer-term variations in air temperature, although with a lag of about a week, from April to June.

In general, increases in air temperature are mirrored better in surface water temperature than are equivalent decreases. This is because a temperature increase is associated with an increase in thermal stability in the epilimnion. This decouples the upper epilimnion from the lower epilimnion to a certain extent, essentially reducing the thickness of the mixed layer and causing it to react more sensitively to fluctuations in the net heat flux through the lake surface. In contrast, a decrease in surface temperature is associated with a decrease in thermal stability in the epilimnion, and consequently with an increase in turbulent mixing and a deepening of the mixed layer, reducing the sensitivity of its response to fluctuations in the net heat flux.

On the Swiss Plateau, annual maximum air and lake surface water temperatures usually occur in July, or, at the latest, at the beginning of August (Figures 4–7). During August, and even more so during September, surface cooling, coupled with increased wind action, predominates, causing a general deepening of the mixed layer. Thus surface water temperatures in August and September tend to follow air temperatures less closely than in the preceding three to four months, and also tend to exceed the corresponding air temperatures (Figures 5b, e, f; Figures 6a, c; Figures 7a, b, c, d, h). There are some exceptions to this, however (Figures 6d, e; Figures 7e, g), where the surface water temperature corresponds well to air temperature throughout the summer.

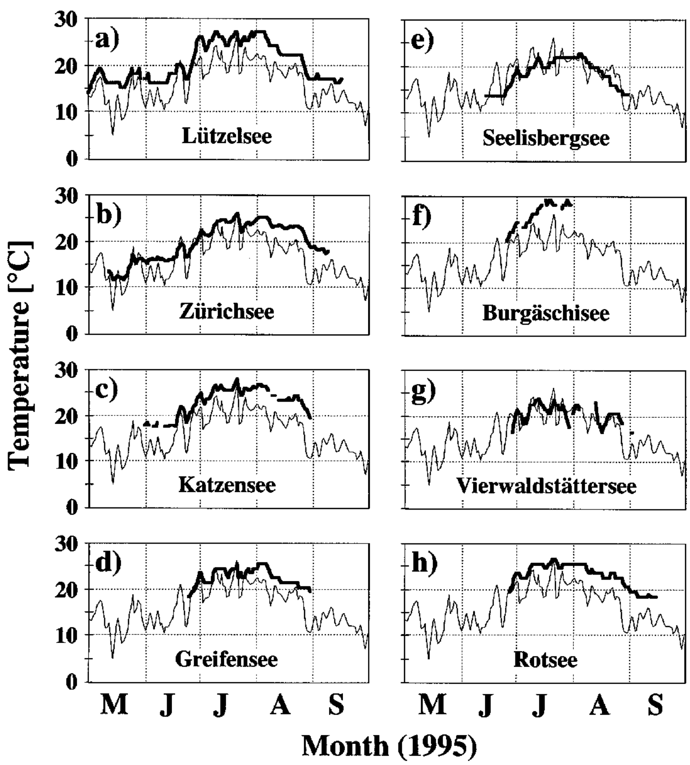

Figure 7. As Figure 6, but for the summer of 1995. All values plotted refer to measurements made once per day at one bathing area except for Zürichsee (b), for which the means of twice-daily (morning and afternoon) measurements made at five separate bathing areas around the lake are plotted, and for Katzensee (c), for which the means of twice-daily measurements at one bathing area are plotted.

Interannual variations

Water temperature profiles have been measured in Zürichsee at approximately monthly intervals since 1936 with the exception of 1941–45 (Kutschke, 1966; Livingstone, 1993b). Temporal interpolation of these temperatures using cubic splines yielded smoothed temperature estimates at daily intervals which were then averaged to produce estimates of monthly mean temperatures. The surface of Zürichsee lies at 406 m a.s.l.; after correction to 500 m a.s.l., the monthly mean water temperature estimates could be compared with air temperature Series I. Figure 8 illustrates the seasonal progression of air temperature and water temperature at 0 m and at 5 m (cf. Figure 15 of Kutschke, 1966). During most of the year (June–February), surface water temperatures usually exceed the corresponding air temperatures, with temperature differences greater than 2 K during at least half the year (August–January). From December to March, the lack of stratification means that the surface water temperature responds only sluggishly to meteorological forcing, and so interannual variations in water temperature (horizontal bars in Figure 8a) are much less than interannual variations in air temperature (vertical bars in Figure 8a). From April to August, however, when stratification is strongest and the thin epilimnion can respond rapidly to changes in the surface heat flux, the opposite is the case (only during this period is there a significant difference between the water temperatures at 0 m and 5 m, the former being about 1.5–2 K higher than the latter). The surface water temperature in summer is therefore a more sensitive indicator of interannual variability in meteorological forcing than is air temperature, which may be of great relevance to the use of lacustrine biota as indicators of climate change. Deepening of the mixed layer successively reduces this sensitivity from August to December.

Palæolimnologically, the correspondence between air and lake surface water temperatures in summer is of most interest, because the rates of production of fossilisable organisms are highest during this season. Figure 9 illustrates the monthly mean air temperature and surface water temperature (0–5 m) in the three

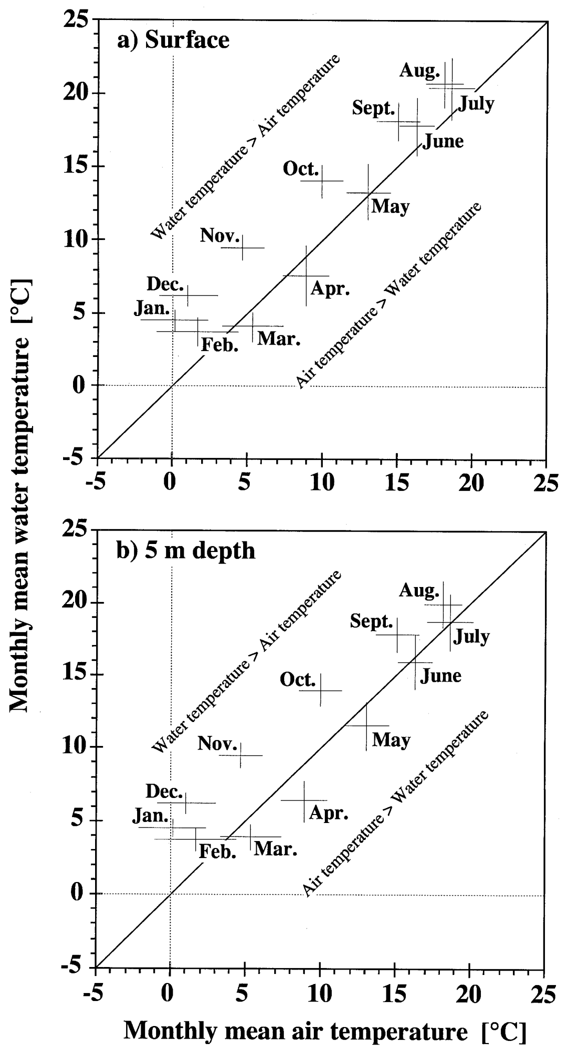

Figure 8. Relationship of monthly mean water temperatures in Zürichsee (a) at the surface and (b) at 5 m depth to monthly mean air temperatures on the Swiss Plateau. The air temperatures illustrated are from the 4-station composite series (Series I). Both air and water temperatures have been reduced to 500 m a.s.l. using the lapse rates of Table 3a (see text for an explanation of the method of estimating monthly mean lake water temperatures). Illustrated are both the monthly means and their standard deviations, based on 54 yr of data (1937–40 and 1946–95). On the diagonal line, air and water temperatures are equal.

summer months, and Figure 10 the correlation coefficients between air temperature and the corresponding water temperatures measured at various depths in the upper 20 m of Zürichsee. On average, the air temperature lies between the water temperatures at 0 and 5 m in June and July, but is considerably lower than both in August. The absolute values of air and water temperature, however, are of less importance than the amount of shared interannual variance (r^2), which is a measure of the extent to which both carry a common interannual signal. In all three summer months, the monthly mean air temperature is significantly ($p<0.001$) correlated with the corresponding mean water temperatures measured in the uppermost 5 m of the lake (Figure 10). The proportion of interannual variance shared between air temperature and water temperature at 0 m is 36% (June), 45% (July) and 36% (August); corresponding values for air temperature and water temperature at 5 m are slightly smaller, viz. 29%, 38% and 36%. At 10 m, there is no significant correlation ($p>0.5$). However, going deeper in the lake, an interesting phenomenon emerges: water temperatures from 10–20 m show a significant negative correlation with air temperature in late summer (e.g. for 15 m: $r = -0.28$; $p<0.05$ in July; $r = -0.33$, $p<0.01$ in August, see Figure 10). This is presumably because warm periods are likely to be associated with stable stratification and little downward mixing of heat, whereas cold periods are likely to enhance such mixing.

Discussion

With few exceptions (e.g. light intensity), the influence of terrestrial climatic variables on aquatic organisms is mediated by internal lake processes. Consequently, except for palynological and palæoentomological studies in which a lake functions as a convenient trap for potential terrestrial fossils, most quantitative palæolimnological studies can only deliver information on aquatic climate – i.e. on the physical lake environment – rather than on terrestrial climate.

However, the physical lake environment is determined to a large extent by meteorological forcing (e.g., Hostetler, 1995). Since the reaction of individual species to their physical environment is an important factor in shaping lake ecology, this implies the existence of an indirect link between terrestrial climate and aquatic ecology. This link can be exploited to make indirect inferences about terrestrial palæoclimates based on the species composition of assemblages of subfossil aquatic organisms found in lake sediments. Such an approach requires knowledge of species optima and tolerances with respect to a particular lacustrine environmental variable that is strongly related to the terrestrial climate (see Birks, 1995).

One important example of such a climate-dependent lacustrine environmental variable is the tem-

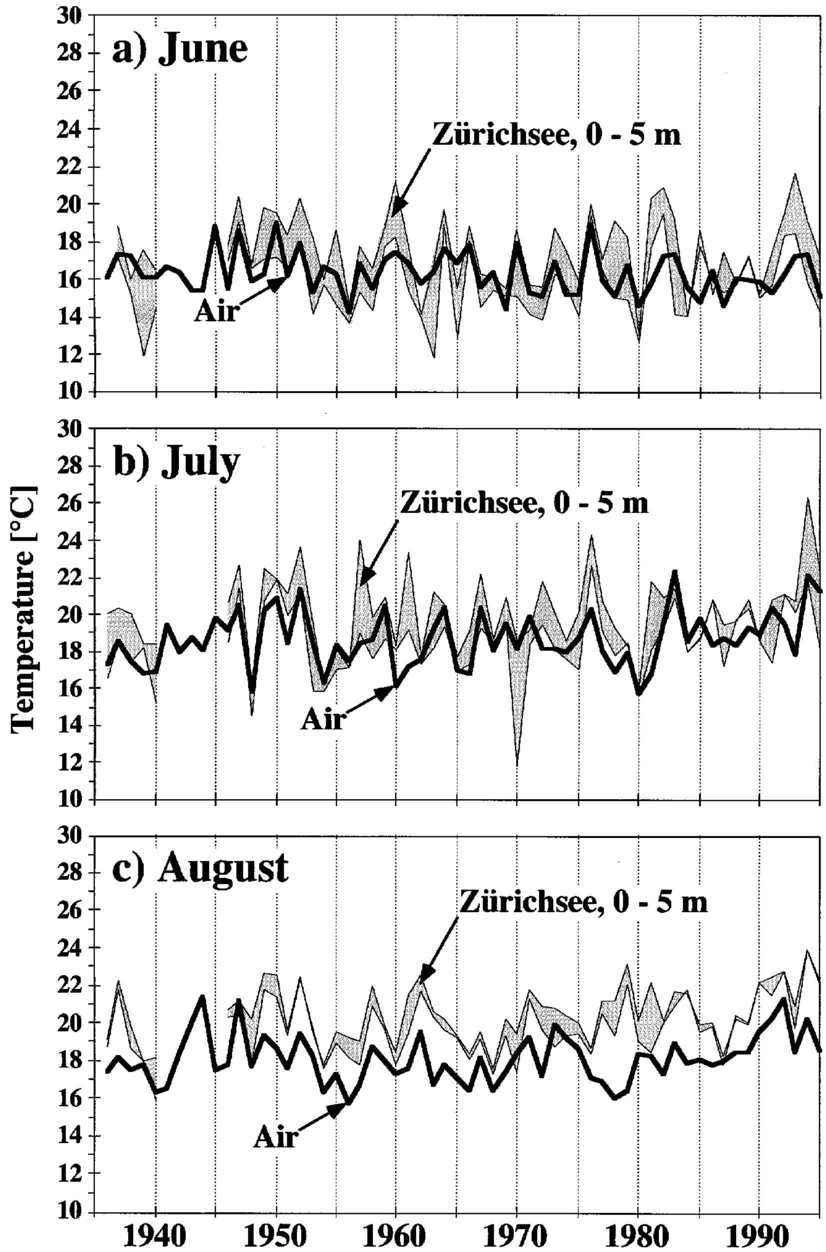

Figure 9. Interannual comparison of monthly mean air temperatures on the Swiss Plateau (thick solid lines) with monthly mean water temperatures from 0–5 m in Zürichsee (shaded) in (a) June, (b) July and (c) August. For further information on the data, see Figure 8.

perature of the epilimnion. Most microfossil assemblages found in lake sediments were originally produced in the epilimnion or in the littoral zone, where rates of biological assimilation are also generally highest. Because primary and secondary production in these zones is partially dependent on water temperature, fossilisable phytoplankton and zooplankton assemblages are potentially of use in inferring epilimnetic palæotemperatures. In contrast, benthic organisms inhabiting the profundal zone are exposed to the more or less constant, relatively cold temperatures prevailing in the hypolimnion; many benthic chironomids, ostracods and molluscs are cold-stenothermal (see, e.g., Hofmann, 1986; von Grafenstein et al.,

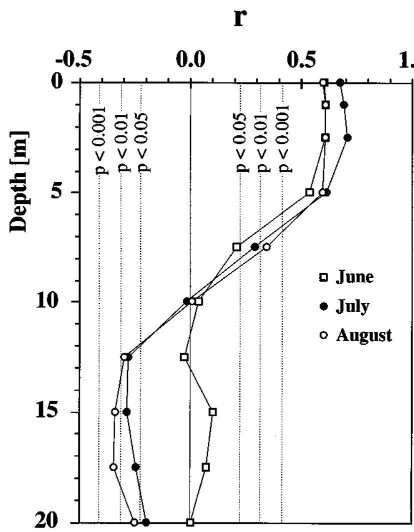

Figure 10. Correlation coefficients (*r*) between the summer monthly mean air temperatures illustrated in Figure 9 and the corresponding water temperatures measured at various depths in the upper 20 m of Zürichsee. Correlations are based on 54 yr of data (1937–40 and 1946–95); significance levels are shown as dotted lines.

1992) and are therefore of comparatively little use for palæoclimate reconstruction. An important basic assumption of quantitative inference models is that in stratified lakes, the aquatic organisms of interest occur optimally in the uppermost epilimnion, and the water temperature to be reconstructed is therefore that of the uppermost epilimnion during the productive season, i.e. the 'summer lake surface water temperature' (e.g. Walker et al., 1991a, 1997; Pienitz et al., 1995; Wunsam et al., 1995; Olander et al., 1997; Weckström et al., 1997), a term which is unfortunately not particularly well defined.

Walker et al. (1991a, 1997) have shown that variations in the species composition of chironomid assemblages along a latitudinal climate gradient in Labrador are statistically related to the summer lake surface water temperature. In a similar study in the Yukon and the Northwest Territories, Pienitz et al. (1995) showed the same to be true of diatom assemblages. Along an altitudinal gradient in Papua New Guinea, Vyverman & Sabbe (1995) showed that shifts in diatom assemblages were related to altitude, and hence lake surface water temperature. In the lakes of subarctic Fennoscandia, both chironomids and diatoms have been shown to reflect summer surface water temperatures well (Olander et al., 1997; Weckström et al., 1997). It would thus appear that both chironomid head-capsules and diatom frustules are potentially useful indicators of past climatic change. These studies are principally calibration studies, i.e. they attempt to calibrate modern biotic data against modern lake surface water temperatures as a first step in reconstructing palæotemperatures. One great drawback of such studies, however, as pointed out by Hann et al. (1992), is the unrepresentative nature of the physical (and chemical) lake data, which are generally sampled only once in each lake. This is particularly serious in the case of lake surface water temperature, the main environmental variable of interest. Responding to the criticism of Hann et al. (1992), Walker et al. (1992) admitted that relying on single measurements of lake surface water temperature is unsatisfactory, but made the point that obtaining high-resolution temperature data for each of 20 or 30 lakes over several years would be prohibitively expensive. This suggests that for calibration purposes, a method of relating lake surface water temperature to air temperature (and perhaps also to other meteorological variables), routinely measured automatically by a network of stations, might provide acceptable estimates of lake surface water temperatures. In the case study described here, air temperatures reduced to a standard altitude have been shown to be highly uniform over an area of at least 20 000 km^2. The local air temperature prevailing at any particular lake site on the Swiss Plateau can be easily and accurately estimated from either the Series I or Series II data solely as a function of altitude. Thus, if lake surface water temperature can be convincingly related to air temperature, the problem of calibrating biota-based inference models of lake surface water temperature using insufficient lake water temperature data may be alleviated somewhat, improving the reliability of the calibration procedure. Causally, lake surface water temperature is not determined primarily by air temperature. However, this study has shown that in summer in the lakes of the Swiss Plateau, variations in air temperature on time scales of less than about a month are reflected well in the temperature of the uppermost 0.5–1 m of the water column, although not at lower depths (Figures 5, 6, 7). At longer (interannual) time scales, air temperature is still well correlated with the temperature of the uppermost 5 m of the water column, although shared interannual variance is unlikely to exceed 50% (Figure 10). Absolute values of air and water temperatures are likely to coincide well in June and July, but the deepening of the epilimnion which sets in during August results in a progressively increasing discrepancy between the two. Thus, the usefulness of air temperature for calibrating models of lake surface water temperature is likely to be confined to the months of June and, especially, July.

Going in the reverse direction, if it is desired not only to use changes in inferred lake surface water temperatures as indicators of palæoclimatic change, but also the inferred lake surface water temperatures themselves as proxy air temperature data, then the results of this study suggest that July temperatures are probably the most appropriate for reconstruction purposes in Northern Hemisphere temperate regions. Empirical models based on species optima and tolerances are normally calibrated against, and attempt to reconstruct, rather broadly defined 'summer lake surface water temperatures'. The results presented here suggest that it might be advantageous to limit the definition of 'summer lake surface water temperatures' in the Northern Hemisphere to those measured in July. Reconstructing air temperatures, however, at least in temperate regions, is probably best carried out using a model calibrated directly against air temperature without going through the intermediate stage of calibrating July lake surface water temperatures (Lotter et al., 1997). In unstratified high-latitude lakes, the correspondence between air and surface water temperature as described here may no longer apply. In this case, a better alternative might be to calibrate the model against a surface water temperature predicted from air temperature modified by some function of lake depth; air temperature reconstruction would then involve modifying the inferred surface water temperature to account for the lake depth at the time the fossils were deposited (I. R. Walker, pers. comm.). In high-altitude lakes, the relationship between air and surface water temperatures may be additionally distorted by complications such as topographic shading and the altitude-dependence of the incident solar radiation.

Finally, the question of scale should not be forgotten. Because of the nature of the data-base, this study has focused on the relationship between relatively short-term fluctuations in lake water temperature and air temperature. Palæoclimate reconstructions, however, may focus on either short-term processes (e.g. interannual variability) or long-term processes (e.g. decadal to century-long trends), depending on the time-scale of interest. Limits are imposed on the temporal resolution of any quantitative palæoclimate reconstruction based on sediment data by the sampling methods employed and by the nature of the sediment (e.g. whether laminated or not). Individual core samples commonly integrate sedimentation over a period which can cover several years to several decades, thus smoothing out interannual variability. If variability on interannual or even intra-annual time-scales is of interest, high-resolution sampling, confined to annually laminated sediments, is necessary (e.g. Lotter, 1989b; Simola et al., 1990; Peglar, 1993; Lotter & Birks, 1997). The usefulness and palæoclimatological relevance of the present study is probably greatest in the case of such high-resolution reconstructions; however, the result that air temperature during the summer months generally lies between the water temperatures measured at 0 m and 5 m depth in Zürichsee, and therefore corresponds quite well with the average epilimnetic temperature, also supports the use of air temperature for both calibration and reconstruction purposes in sedimentological studies of long-term palæoclimatic processes.

Summary and conclusions

This study has shown that altitude-corrected air temperatures are highly uniform over the entire Swiss Plateau, implying that local air temperatures at any particular lake site can be estimated well based on standard composite air temperature series. Short-term variability in air temperature in summer is reflected extremely well in the temperature of the uppermost metre of the water column, but not necessarily in temperatures at depths lower than this. Lake surface water temperature mirrors air temperature more faithfully during periods of increasing air temperature (when the epilimnion is thin and thermal stability suppresses mixing) than during periods of decreasing air temperature (when convective mixing is deepening the epilimnion). This implies that the relationship between lake surface water temperature and air temperature is generally stronger during early summer (June, July) than during late summer (August). Lake surface water temperature during the summer months appears to react more sensitively to interannual variability in meteorological forcing than does air temperature, supporting the use of temperature-sensitive lacustrine biota as indicators of climatic change.

In Zürichsee during the summer months, the air temperature generally lies between the water temperatures measured at 0 m and 5 m depth, and therefore corresponds quite well with the average epilimnetic temperature. Again, absolute values of air and water temperatures are likely to coincide best in early summer, especially in July. Interannual variations in air temperature are reflected quite well in the water temperature of the uppermost 5 m of the water column, but shared interannual variance between air and water temperatures is unlikely to exceed 50%. Interannual variations in air temperature are negatively correlated with interannual variations in the water temperature below 10 m, presumably because the downward mixing of heat tends to be inhibited during warm periods with stable thermal stratification.

This study suggests that standardised altitude-corrected air temperature series may be a useful alternative to sparse measurements of summer lake surface temperatures for the purposes of calibrating palæotemperature models based on aquatic biota. In Northern Hemisphere temperate regions, air temperatures and mean lake surface water temperatures are likely to correspond most closely in July, and so temperatures from this month are probably most suitable for both calibration and reconstruction purposes. This may not be the case, however, for unstratified high-latitude lakes, in which any correspondence between air and water temperatures will be additionally dependent on lake depth.

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