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Temporal structure in the deep-water temperature of four Swiss lakes: A short-term climatic change indicator?

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Introduction

It is well known that information on past climatic conditions over a period of millenia can be obtained by the study of lacustrine sediments. Less well known, however, is the fact that climatic information on a shorter time scale, a time scale of decades, may be gleaned from the water column itself, for instance from the temperature regime. The lamentable shortness of this time scale is a consequence of the informationally destructive effect of lake turnover.

In general, the response of the temperature regime of a lake to meteorological influences is not immediate: the water temperature tends to react less to short-term fluctuations in meteorological parameters than to longer-term means. A lake can in a sense be viewed as a type of low-pass filter which filters out a substantial amount of high-frequency meteorological "noise". The deeper one looks in the water column, the lower the cut-off frequency of the filter tends to be. For example, the surface water temperature exhibits a diel response to atmospheric forcing which is usually not apparent lower down in the water column. A strong annual response to atmospheric forcing is exhibited by the water temperature of the epilimnion and metalimnion; below the thermocline, however, the water column is shielded from much (but not all) of the seasonal meteorological variability, resulting in considerable attenuation of the annual response in the hypolimnion. Since in temperate latitudes coupling between deep water and atmosphere is at its strongest during one particular time of year, viz. at spring turnover, the influence of between-year variations in atmospheric forcing on the deep-water temperature may well be greater than any seasonal influences. The deep-water temperature of many lakes is thus frequently dominated by very low-frequency fluctuations punctuated by short-term responses to atmospheric forcing during spring turnover (Fig. 1).

The data

Long-term measurements of temperature profiles are available from several Swiss lakes. With a view to establishing the general feasibility of using water temperature as a climatic change indicator over a time scale of a few decades, data from four of these lakes – Lakes Neuchâtel (NE), Geneva (GE), Zug (ZG) and Zürich (ZH) – are considered here. Assuming horizontal homogeneity, the mean (volume-weighted) deep-water temperature (100 m – bottom) and the corresponding mean lake temperature (0 m – bottom) were computed from each available profile. In addition, mean temperatures were computed for water layers 20 m thick from the surface down to 100 m depth in Lake Zürich. The available data allow the temporal evolution of the temperature regimes in the lakes to be followed continuously from 1981–91 (NE), 1957–91 (GE), 1968–91 (ZG) and 1946–91 (ZH), as well as over shorter time periods in earlier years (Fig. 1). The mean temperatures obtained were interpolated on the last day of each month with a cubic spline to give time series of representative monthly data. Since the time series are based on data from various sources (see acknowledgements) taken over long periods of time, a certain degree of incompatibility both within and among the time series is unavoidable. Nevertheless the data do allow a broad assessment of the similarities and dissimilarities of the response of the deep-water temperature of the four lakes to their common mesoscale climatic environment.

The lakes

The four lakes lie within 200 km of one another on the northern side of the Alps, their surfaces all lie within ± 30 m of 400 m a.s.l. and they are exposed to the same mesoscale weather conditions. One might thus expect their temperature regimes to exhibit a high degree of common response to atmospheric forcing. In order to ascertain whether this is the case (apart from the obvious seasonal cycle), the heat content of Lake Zürich was correlated with that of the other three lakes for each month of the year separately (Fig. 2). During the period of stratification from April to October, when the radiation balance dominates the heat exchange process, the degree of common response is low. During the rest of the year, and especially in February and March, i.e. during spring turnover, it is considerably higher. At this time of year lake stability is at its lowest and lakes therefore

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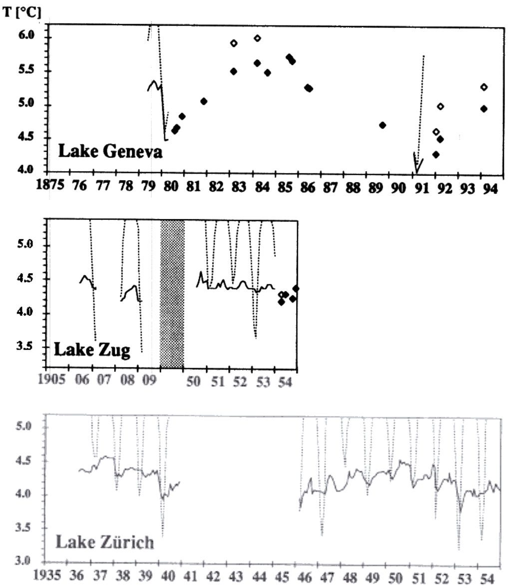

react most sensitively to anomalous meteorological conditions. Since deep-water formation occurs at this time, the deep-water temperature might be expected to evolve similarly in the four lakes. Looking at Fig. 1, however, it is immediately apparent that this is not the case.

Lake Neuchâtel (154 m deep) is exposed to higher wind speeds than are the other three lakes, mixes rapidly, and consequently exhibits a fast, short-term response to meteorological influences. Spring turnover begins early (usually in January), is consequently of long duration, and allows the lake to cool down to 4 °C or lower during a cold spring. In spite of the fact that Lake Neuchâtel attains equilibrium with the atmosphere rapidly, long-term structures can still be observed. For instance, although the lake circulated fully in all years shown in Fig. 1, the deep-water temperature underwent an increase from 4 °C in March 1987

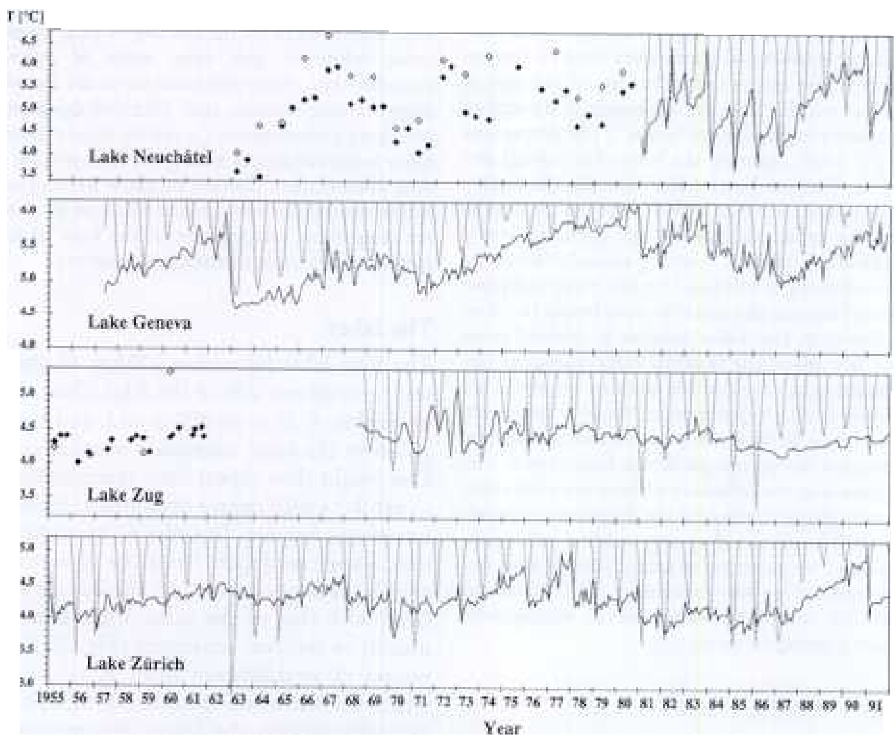

Fig. 1. Time series (lines) and occasional individual measurements (◆, ◇) of deep-water temperatures (below 100 m: solid lines, ◆) and mean lake temperatures (dotted lines, ◇) in four deep Swiss lakes, showing the effect of lake turnover on the deep-water temperature. The temperature scales (T) are the same for Lakes Geneva, Zug and Zürich; the scale for Lake Neuchâtel is ⅓ smaller. Based on data from various sources (see acknowledgements).

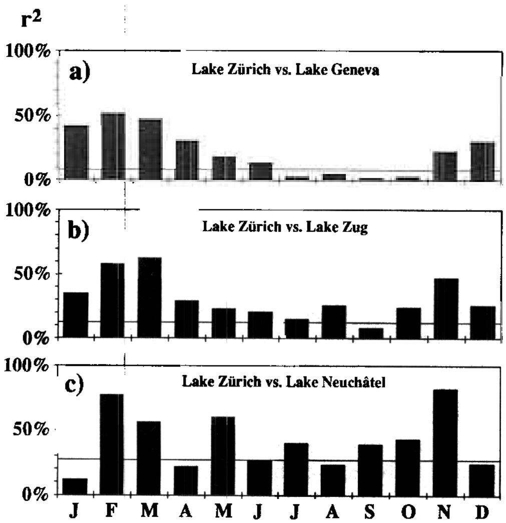

Fig. 2. Coefficients of determination (r^2) for the correlation of the heat content of Lake Zürich with that of Lake Geneva, 1957–91 (a), Lake Zug, 1969–91 (b) and Lake Neuchâtel, 1981–91 (c) for all months of the year. The horizontal solid lines indicate 99 % significance levels.

to 5.9 °C in March 1990 (spring turnover) and further to 6.9 °C in December 1990.

Lake Geneva (310 m deep) does not circulate fully in all years. Long-term, persistent structures dominate. The deep-water temperature undergoes a continual increase over a period of several years, only to fall rapidly during a cold winter, as was the case for instance in 1963 and 1981. Although Lake Geneva circulated fully during these two unusually cold winters, the deep water did not cool down to 4 °C. Earlier temperature data (Forel 1895) show, however, that deep-water temperatures of 4 °C did occur in the past (Fig. 1 a).

Lake Zug (197 m deep) has a chemically stratified hypolimnion, which results in a stable density stratification and slight inverse temperature gradients near the bottom (Imboden et al. 1988). The deep-water temperature varies little about a long-term mean of 4.4 °C (st. dev. = 0.1 °C), even when the mean lake temperature falls considerably below 4 °C. Thus the deep-water temperature does not exhibit a strong response to atmospheric forcing.

Lake Zürich (136 m deep) experiences both long-term and short-term temperature variations. As in Lake Geneva, the deep-water temperature frequently undergoes a long-term increase which is brought to a sudden end by deep mixing during a cold winter. For example, between October 1987 and January 1991 the deep-water temperature increased by 1 °C from 4.0 °C to 5.0 °C, only to fall back down to 4.1 °C within a period of two weeks during February 1991.

Differences in the temporal evolution of the deep-water temperatures of the four lakes are likely to result primarily from differences in local weather conditions and in the response of the lakes to atmospheric forcing, although differences in other factors (e.g. degree of meromixis, thickness of the deep-water layer, river inflow rates) may also play a role. Differences in local weather conditions are confined mainly to the wind. Mean annual wind speeds (1978–91) of 2.4 $m \cdot s^{-1}$ (NE), 2.1 $m \cdot s^{-1}$ (ZH) and 1.8 $m \cdot s^{-1}$ (GE) were recorded at meteorological stations situated close to the shore of three of the lakes, suggesting that the degree of short-term response may be associated with the local wind regime.

Fig. 1 illustrates not only the temporal evolution of the deep-water temperature, but also the degree to which the deep-water temperature is influenced by spring turnover. If the mean lake temperature remains higher than the deep-water temperature from December to March (e.g. ZG, 1987–90), it can be assumed that spring turnover did not significantly influence the deep water. Coincidence of the two temperatures, on the other hand, implies homothermic conditions, during which the deep water can undergo either cooling (e.g. GE, 1981; ZH, 1981), warming (e.g. GE, 1967) or both cooling and subsequent warming (e.g. NE, 1982, 1985). Homothermic cooling phases are often preceded by phases of abrupt, non-homothermic deep-water warming in early winter (e.g. NE, 1983/84; ZG, 1972/73), so that overall deep-water cooling during the winter/spring season is usually much less than might at first glance appear to be the case. A mean lake temperature substantially lower than the deep-water temperature implies the existence of an inverse temperature gradient. This may be associated with deep-water cooling (e.g. ZH, 1956), but more often it is not (e.g. ZH, 1954). An extreme example of this latter situation is encountered during very cold winters, when the lake freezes over completely, eliminating wind influence and inhibiting vertical mixing. Thus the extremely cold winter of 1962/63, the coldest since that of 1829/30 (von Rudloff 1967), did not result in any deep-water cooling in Lake Zürich. In contrast, Lake Geneva, which did not freeze over, experienced the greatest drop in its deep-water temperature over the entire period for which data are available.

It is also apparent from Fig. 1 that in all four lakes, deep-water warming occurs during summer. Thus downward heat transport within the hypolimnion, presumably as a result of internal wave action, occurs in all lakes to a certain extent. This is at its most obvious between 1987 and 1990, when, as the result of a series of unusually warm winters, almost no deep-water cooling took place in any of the lakes. Mean rates of deep-water temperature increase during this period were $0.5\,K \cdot yr^{-1}$ (NE), $0.2\,K \cdot yr^{-1}$ (GE), $0.1\,K \cdot yr^{-1}$ (ZG) and $0.25\,K \cdot yr^{-1}$ (ZH), corresponding to heat transport rates into the deep water of $1.7\,W \cdot m^{-2}$ (NE), $3.3\,W \cdot m^{-2}$ (GE), $0.8\,W \cdot m^{-2}$ (ZG) and $0.7\,W \cdot m^{-2}$ (ZH). Similar occurrences in previous years resulted in the same rates of deep-water warming (e.g. GE, 1959–61, 1964–66, 1971–75; ZH, 1973–75). The deep-water warming rate may therefore be a long-term property specific to the lake concerned. One further point deserves mention here: the longer such a period of deep-water warming lasts, the higher becomes the temperature at which full turnover is possible. This increases the likelihood of occurrence of a full turnover and, consequently, of a fall in the deep-water temperature.

Lake Zürich

The longest continuous temperature time series available, that from Lake Zürich (540 values from January 1947 to December 1991), was subjected to further analysis in order to detect structure which would not otherwise be apparent. A detailed statistical analysis of this data set up to 1963 has been conducted by KUTSCHKE (1966).

Influence of spring turnover on the deep-water temperature

Since Lake Zürich undergoes deep circulation in most years (Fig. 1), one would expect spring turnover to exert an important determining influence on the deep-water temperature during the subsequent summer stratification period. In Fig. 3, the coefficient of determination (r^2) is employed to compare the between-year variance of the deep-water temperature at the end of March (i.e. at the end of spring turnover) with that at the end of each of the following 24 months. From March to June, r^2 falls to ~ 70 % and remains at this value until the end of December. During January and February, r^2 declines abruptly to ~ 25 %, again remaining at this value until the end of the following December. The next abrupt decline during January and February brings r^2 to a value below the 99 % significance level. The between-year variance in the deep-water temperature at the end of spring turnover therefore accounts for most of the between-year variance in the deep-water temperature not only during the summer stratification period, but also during autumn and early winter. Not until January do vertical mixing processes begin to cause an appreciable deterioration of the signal left in the deep water by the previous spring turnover, but even the occurrence of the next spring turnover does not eliminate the signal entirely.

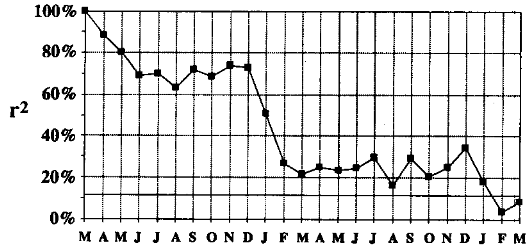

Fig. 3. Coefficients of determination (r^2) for the correlation of the deep-water temperature of Lake Zürich at the end of March with that at the end of the following 24 months. The horizontal solid line indicates the 99 % significance level.

The importance of spring turnover for the deep-water temperature might lead one to expect a strong statistical relationship between deep-water temperature and air temperature (viewed as an empirical indicator of atmospheric forcing: see JONES 1988, ROBERTSON & RAGOZKIE 1990) during spring turnover. This is however not the case. Although almost 50 % of the variance in the mean lake temperature in March can be "explained" in terms of a linear dependence on air temperature, a significant correlation between air temperature and deep-water temperature cannot be demonstrated during spring turnover (or at any other time). This is presumably because the lake does not always circulate completely, so that air temperature and related meteorological parameters cannot influence the deep-water temperature in all years.

Fluctuations and trends

Autocorrelation functions of Lake Zürich monthly temperature anomalies (Fig. 4) show two dominant periodicities, 5–6 yr in the upper hypolimnion (20 m–60 m) and 12–16 yr in the lower hypolimnion (below 80 m). Values of the autocor-

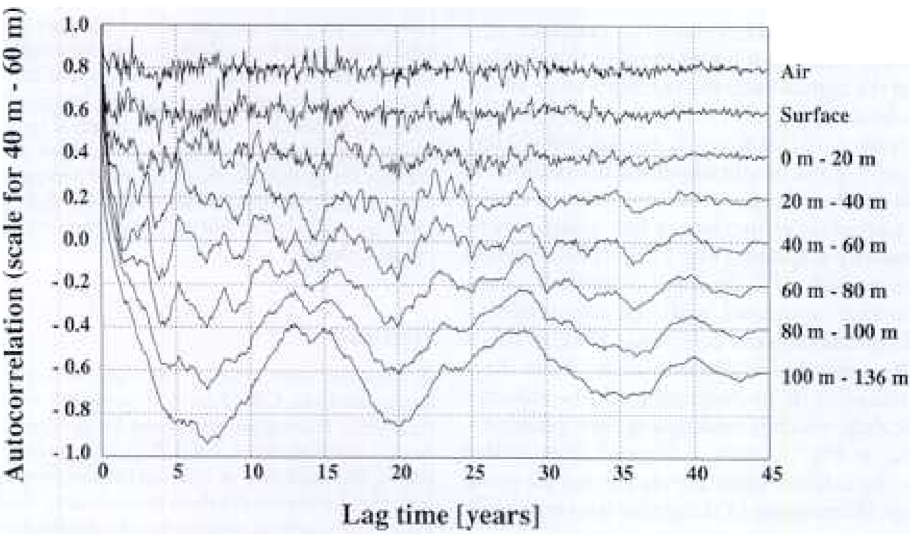

Fig. 4. Autocorrelation functions of the monthly anomalies of air temperature at Zürich and of the monthly anomalies of the temperature of various water layers in Lake Zürich (based on data from 1947 – 91). For the sake of simplicity, the scale on the vertical axis refers only to the 40 – 60 m layer; the other autocorrelation functions are offset from this scale at intervals of 0.2.

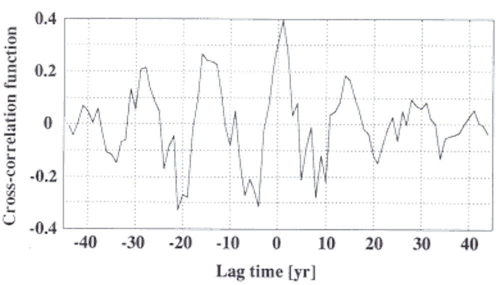

Fig. 5. Cross-correlation function of the surface temperature at the end of March with the deep-water temperature at the end of October for Lake Zürich.

relation functions in the neighbourhood of the peaks exceed the 99 % significance level. Both periodicities are detectable in the intermediate hypolimnion (60 m – 80 m). The 12 – 16 yr periodicity is present not only in the deep-water temperature throughout the year, but also in the entire temperature profile in spring. Fig. 5 illustrates this well: the cross-correlation function of the surface temperature anomalies in March with the deep-water temperature anomalies in any month (the example shown in Fig. 5 is October) shows a pronounced 12 – 16 yr periodicity. The fact that the linear coupling between air temperature and deep-water temperature is slight suggests that the 12 –

$r = 0.09$; $p > 0.05$). However, the existence of a statistically significant linear trend in the absolute value of the annual deep-water temperature anomaly can be shown (1937–40, 1947–91; $n = 49$; rate of increase = $0.002\,K \cdot yr^{-1}$; $r = 0.30$; $p < 0.05$), implying that the amplitude of the fluctuations in the deep-water temperature anomaly is undergoing a progressive increase, a fact which can be confirmed by inspecting Fig. 1. This phenomenon may be a result of a decrease in stability in the hypolimnion associated with the oligotrophication of the lake (Schanz & Thomas 1981). If this is the case, a decrease in the amplitude of the deep-water temperature fluctuations might be expected in Lake Zug, which is undergoing eutrophication. Looking at Fig. 1, such a decrease does indeed seem to have taken place during the last 20 years, although fluctuations in the earlier data are small.

Conclusions

Time series of deep-water temperature exhibit both short-term and long-term structure. The conditions obtaining during spring turnover are of paramount importance for the deep-water temperature during most of the year, and are thus responsible to a large extent for this structure. Although lake heat content at the end of spring turnover is significantly correlated with air temperature, and although a high degree of common response to atmospheric forcing appears to exist among the four lakes studied here, the structure of the deep-water time series is still to a large degree specific to the particular lake under consideration. It is therefore difficult to separate effects due to mesoscale climate from those due to local meteorology or to the specific response characteristics of the lake concerned. One lake-specific factor which deserves special mention here is trophic status, a progressive change in which will affect the stability of the lower hypolimnion, progressively altering the response of the deep-water temperature to atmospheric forcing.

In the specific case of Lake Zürich, the deep-water temperature shows a periodicity of about 12–16 yr. This same 12–16 yr periodicity is apparent in the water temperature at all depths during spring turnover, while a periodicity of 5–6 yr can be detected in the upper hypolimnion during the rest of the year. Neither of these periodicities can be detected in any of the meteorological parameters relevant to air-water heat exchange during spring turnover or during any other time of year. Thus, if physically real, these periodicities must be the result of factors specific to Lake Zürich. It follows that the employment of deep-water temperature data as integrative indicators of climate change must be based on models capable of accounting for the individual response characteristics of the lakes chosen. Even if these periodicities are considered to be artefacts of the data, however, they still give an idea of the time scales over which data must be available in order to detect climatically dependent trends, since the distinction between fluctuation and trend depends on the length of the data series upon which the analysis is based. If long-term lake-specific fluctuations with a time scale of one or two decades are present in the deep-water temperature, superficial analyses of time series shorter than about 50 years are unlikely to yield much information relevant to climatic change.

Summary

A fifty-year time series of historical monthly temperature data from Lake Zürich is compared with shorter time series from three other deep Swiss lakes (Lake Geneva, Lake Neuchâtel, Lake Zug) with a view to establishing the feasibility of utilising the temperature of the lower hypolimnion as a short-term climatic change indicator. The temporal structure of the deep-water temperature depends not only on the meteorological conditions prevailing during spring turnover, but is also to a large degree specific to the lake concerned. Fluctuations in the deep-water temperature anomaly in Lake Zürich appear to exhibit a periodicity of 12 to 16 years and a progressively increasing amplitude. The time scale of the fluctuations suggests that time series shorter than about fifty years are unlikely to yield much information relevant to climatic change.

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