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Large-scale coherence in the response of lake surface-water temperatures to synoptic-scale climate forcing during summer

Abstract—Daily mean lake surface-water temperatures (LSWTs) measured in Swiss Alpine lakes in summer and early autumn 2000 were compared with LSWTs measured simultaneously in Lake Balaton, Hungary, 750 km to the east. The Swiss lakes are small (0.0043–0.46 km^2), predominantly oligotrophic, and are located in a mountainous environment, some at altitudes >2,000 m above sea level, whereas Lake Balaton is a large (593 km^2), shallow, mesotrophic lake situated in the much lower-lying Carpathian Basin. Despite the large distance separating the two regions and the extreme differences in character between the lakes, the LSWTs in Switzerland and Hungary exhibited a coherent response to synoptic-scale meteorological forcing, expressed in terms of exponentially smoothed air temperature, which can be viewed as a causal forcing variable in its own right and as a proxy for other forcing variables with which it is correlated. The coherent response of LSWT in very dissimilar lakes in two different geographical regions of Europe demonstrates that large-scale climatic forcing on synoptic timescales is much more important for lakes than previously thought. This appears to be particularly true for low-altitude lakes, whereas lakes at higher altitudes exhibit more heterogeneity in their response.

Lake surface-water temperature (LSWT) is a key variable in any lacustrine system. It represents the primary physical response of a lake to climatic forcing (Livingstone et al. 2005*a*) and can be used as an external boundary condition in physical lake modeling to summarize the effects of the major meteorological forcing variables (Goudsmit et al. 2002). Recent analyses of LSWT have shown that in the long term (from year to year), it can respond coherently to climatic forcing on scales of several hundred kilometers (e.g., Benson et al. 2000; Straile and Adrian 2000; Livingstone and Dokulil 2001). In the short term (from day to day), Matuszek and Shuter (1996) showed that water temperatures in the littoral zone of lakes in Ontario can be modeled empirically on the basis of air temperatures measured as far as 300 km away, which they attributed to the lack of physical relief in the region. In mountainous regions, a coherent response of day-to-day variations in LSWT to meteorological forcing on smaller spatial scales has been demonstrated, specifically for the lakes of the Swiss Plateau (Livingstone and Lotter 1998) and the Swiss Alps (Livingstone et al. 1999, 2005*a,b*). Here, we look at day-to-day fluctuations in LSWT on a spatial scale that encompasses a large area of central Europe, extending from the mountains of Switzerland to the plains of Hungary.

Study lakes and data, Switzerland—LSWTs were measured at high temporal resolution in a suite of lakes in Switzerland during summer and autumn 2000. From 29 of these lakes, usable simultaneous data were available covering the period 19 June to 01 October, which will henceforth be referred to as the study period. All 29 lakes are located in central Switzerland, in or close to the Bernese Alps, between 465 and 2,470 m above sea level (a.s.l.) (Fig. 1). They are all small, with surface areas ranging 0.0043–0.46 km^2; 24 of the 29 lakes have surface areas <0.1 km^2. Maximum depths range 2–43 m. Detailed information on the lakes and the LSWT data has been given by Livingstone et al. (2005*a*); further information on the lakes is available in a publication by Guthruf et al. (1999).

The LSWTs (actually, near-surface water temperatures) were measured ~5 cm below the surface by thermistors with integrated data loggers. The sampling interval was 1 h, and daily means were calculated from the hourly values. The LSWT measurement method has been described in detail by Livingstone et al. (1999) and summarized by Livingstone et al. (2005*a*). Although we do not claim here that the Swiss LSWT data are representative of the epilimnion as a whole, previous water temperature measurements in Swiss mountain lakes in summer have shown that even on a subdaily timescale, temperature fluctuations ~5 cm below the surface are representative of fluctuations occurring throughout at least the upper 20 cm of the epilimnion (Livingstone et al. 1999).

The Swiss LSWT series fluctuate with a very high degree of coherence across the region, reflecting regional climatic forcing (Livingstone et al. 2005*a*). This allowed a mean Swiss LSWT data series (computed as the arithmetic mean of the 29 individual Swiss LSWT data series) to be constructed that averages out local effects, facilitating comparison with the Hungarian LSWT data.

Daily mean air temperature data measured during the entire study period were available from 40 meteorological stations covering most of Switzerland (Fig. 1) and spanning altitudes of 316–3,580 m a.s.l. (Livingstone et al. 2005*a*). In summer, air temperatures measured near the land surface in mountain regions are known to decrease linearly with increasing altitude (Tabony 1985; Barry 1992), and examples demonstrating this linear decrease in the Swiss Alps during the summer and autumn of 2000 are given by Livingstone et al. (2005*a*). The rate of decrease of surface air temperature with altitude—the surface air temperature lapse rate—is quantitatively similar to the adiabatic lapse

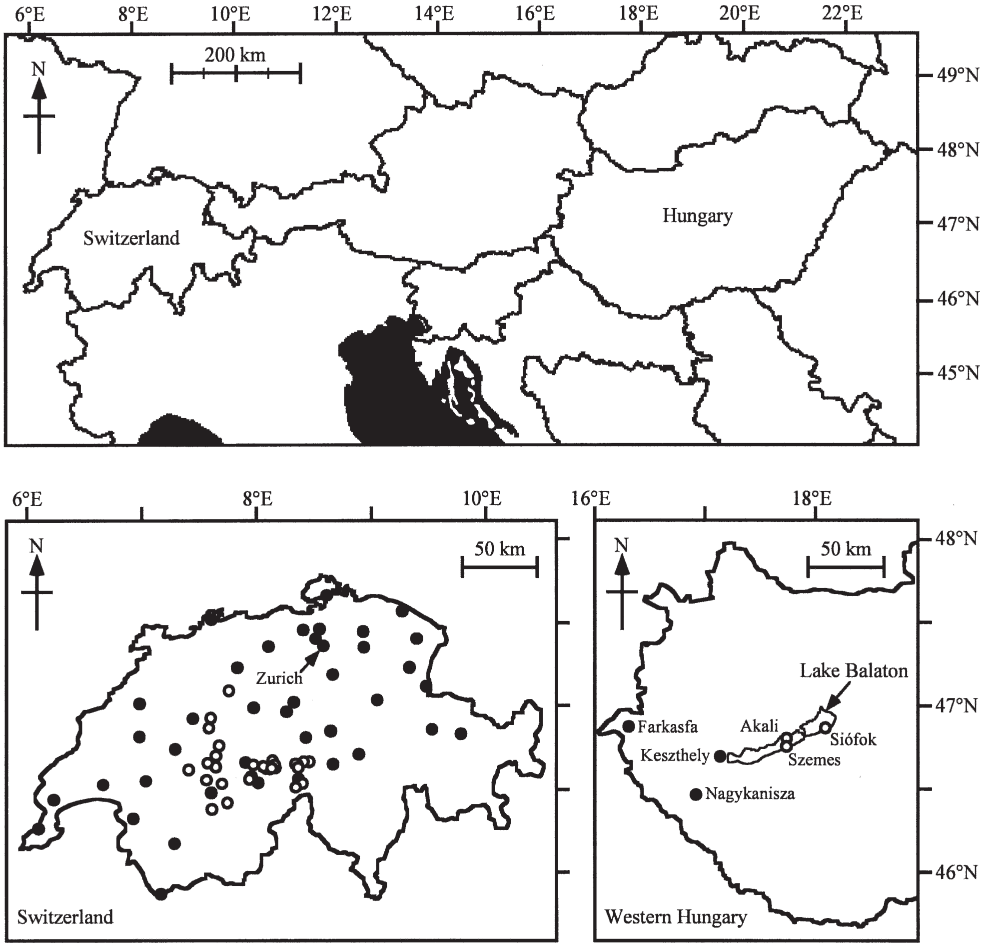

Fig. 1. Locations of lakes and measuring stations mentioned in the text. The 29 Alpine lakes (Switzerland) and the 3 Lake Balaton measuring stations (Hungary) are shown as open circles; the 40 Swiss and 3 Hungarian meteorological stations at which air temperatures were measured are shown as solid circles. At the Zurich station, wind speed, cloud cover, and relative humidity were also measured.

rate of moist air in the free atmosphere, i.e., ~6 K km^{-1} (Tabony 1985). However, the surface air temperature lapse rate can vary with time as weather conditions change. The density of available data allowed reliable surface air temperature lapse rates for each day to be computed by linear regression of the measured daily mean air temperature on the altitude of the measuring station, thus allowing air temperature time series to be computed for any given altitude, as described in detail by Livingstone et al. (2005*a*). Two such time series are used here. Series I was computed for the altitude of Lake Balaton (104 m a.s.l.) and was used to compare air temperatures in Hungary with the theoretical air temperature at the same altitude in Switzerland. (Note that Series I is a purely theoretical extrapolated series because there is no point in Switzerland as low as 104 m a.s.l.) Series II was computed for the mean altitude of the 29 Swiss lakes (1,726 m a.s.l.) and was used for modeling the mean LSWT of these lakes. Because the lapse rate used for the altitude corrections is not constant in time, Series I and II are not merely linear functions of one another, and both differ somewhat from the mean air temperature series of Livingstone et al. (2005*a*). In addition to the air temperature data from the 40 stations, daily mean data on wind speed, cloud cover, and relative humidity, which were based on three observations per day (at 07 : 00 h, 13 : 00 h, and 21 : 00 h) at the Zurich meteorological station (Fig. 1), were used.

In Switzerland, the summer of 2000 was the 25th warmest of the period 1901–2004, and the mean air temperature lay within one standard deviation of the long-term summer mean (Livingstone et al. 2005*a*). Therefore, although the summer of 2000 was somewhat warmer than average, it was not excessively so, and the results described here are not based on unrepresentatively extreme climatic conditions.

Study lakes and data, Hungary—Lake Balaton, located at an altitude of 104 m a.s.l. in western Hungary, within the Carpathian Basin (Fig. 1), is a large but shallow lake, with a surface area of 593 km^2—exceeding that of the Swiss lakes by a factor of 10^3 to 10^5—but with a mean depth of only 3.2 m and a maximum depth of 11 m (Padisák 1992). LSWT measurements covering the entire study period were available from three stations in this lake, 80 m from the lake shore at Szemes, and 20 m from the lake shore at Siófok and Akali (Fig. 1). These data were measured at 07 : 00 h each day by using thermistors fixed at a constant vertical distance from the lake bottom. Variations in the water level of the lake meant that the depth below the lake surface at which the temperature was measured varied from 0.5 to 1.1 m. However, Lake Balaton never stratifies, so the measured temperatures are not affected by the water level variations (and in fact are representative of the water column as a whole). In Lake Balaton, the LSWT data from the three stations were extremely highly correlated during the study period ($r^2 > 0.9$, $p << 0.0001$), allowing a composite arithmetic mean LSWT data series to be constructed that was representative of the entire lake.

Daily air temperature data were available during the study period from the stations of Nagykanizsa (139 m a.s.l.), Keszthely (115 m a.s.l.), and Farkasfa (312 m a.s.l.) to the west of Lake Balaton (Fig. 1). As in the case of the LSWT data, the Hungarian air temperature data were extremely highly correlated during the study period ($r^2 > 0.9$, $p << 0.0001$), allowing the creation of a composite air temperature data series representative of the western part of the Carpathian Basin. This composite series was created by taking the mean air temperature measured at the three stations and correcting it to the altitude of Lake Balaton by using surface air temperature lapse rates that were assumed to be constant with altitude. The lapse rates were calculated from the measured air temperatures by subtracting the air temperature at Farkasfa from the mean of the two air temperatures at Nagykanizsa and Keszthely and dividing by the corresponding altitude difference.

Comparison of Swiss and Hungarian lake surface-water temperature data—Despite the large distance separating the two regions and the extreme differences in morphometry, character, and geographical setting, the LSWT time series in Switzerland and Hungary exhibited a surprisingly high degree of similarity in their temporal structure (Fig. 2a). The proportion of variance shared by the two LSWT time series (r^2) as they stand is 52.2% (Table 1). However, the Lake Balaton LSWT time series shows a cooling trend during the study period (0.041 K d^{-1}) that is insignificant in the mean Swiss LSWT time series (0.001 K d^{-1}) although it is present in the LSWTs of the six lowest Swiss lakes. Linear detrending of both the Swiss and Hungarian LSWT time series to ensure stationarity removed this difference, resulting in an increase in the proportion of shared variance to 67.3% (Table 1).

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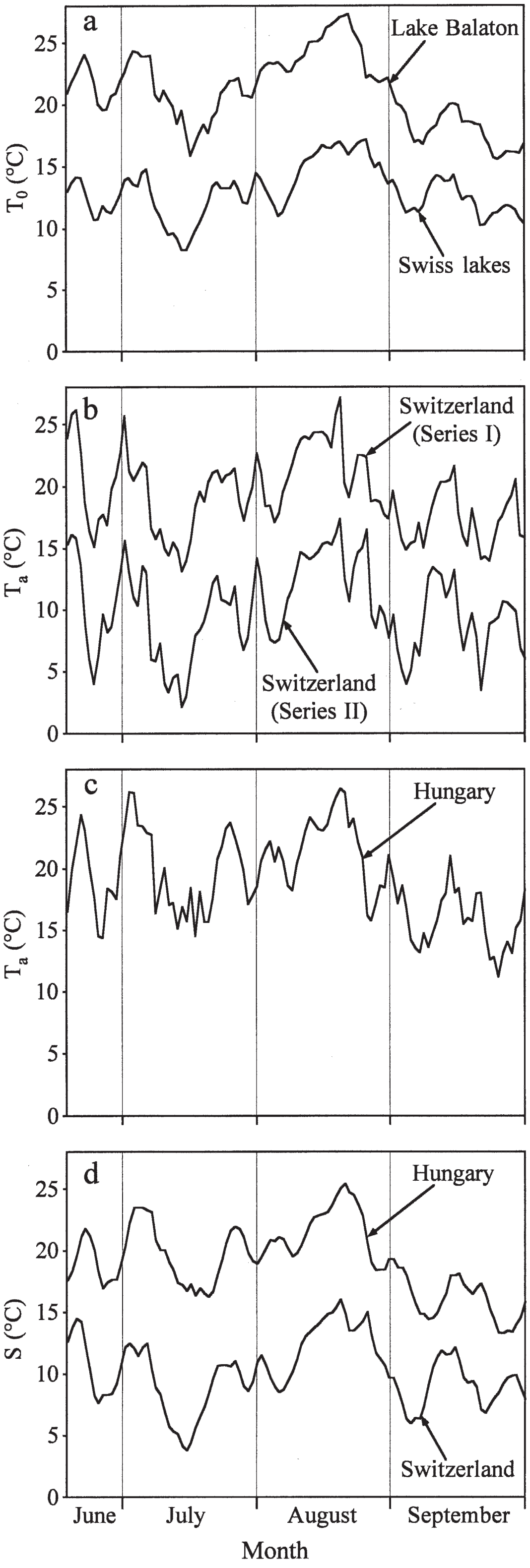

Fig. 2. Comparison of daily lake surface-water temperatures (LSWTs) and air temperatures in the Swiss Alps and in the western Carpathian Basin from 19 June to 01 October 2000. (a) The mean LSWT of 29 small lakes in the Bernese Alps and of three stations in Lake Balaton. (b) Mean air temperature measured at 40 meteorological stations in Switzerland, corrected to the altitude of Lake Balaton (104 m a.s.l., Series I) and to the mean altitude of the 29 Swiss lakes (1,726 m a.s.l., Series II). (c) Mean air temperature measured at three meteorological stations in Hungary, corrected to the altitude of Lake Balaton. (d) Mean air temperatures in Switzerland (Series II) and Hungary, smoothed with an exponential filter (Eq. 1). Altitudinal corrections to air temperature were made by using daily lapse rates. Locations of the measuring stations are shown in Fig. 1.

Table 1. Proportion of variance (r^2) shared between various time series of lake surface-water temperature (LSWT) and air temperature (AT) in Hungary and Switzerland. Positive lag is defined as Hungary lagging Switzerland. Smoothing was performed by Eq. 1 with $\alpha=0.33$, and detrending was by subtraction of the relevant linear least squares regression line. All correlations are significant at the $p<0.0001$ level at least. All calculations are based on the period 19 June to 01 October 2000.

Characteristic	Lag (d)	Smoothing	r^2 before detrending (%)	r^2 after detrending (%)
LSWT: Switzerland and Hungary	0	Unsmoothed	52.2	67.3
	1	Unsmoothed	56.6	75.1
AT: Switzerland (Series I) and Hungary	0	Unsmoothed	37.7	34.4
	1	Unsmoothed	56.8	55.8
	2	Unsmoothed	59.9	59.6
	0	Smoothed	58.9	60.6
	1	Smoothed	71.0	73.7
	2	Smoothed	75.5	78.2
Hungary: LSWT and AT	0	Unsmoothed	75.5	71.9
	0	Smoothed	89.1	88.6
Switzerland: LSWT and AT (Series II)	0	Unsmoothed	67.9	68.9
	0	Smoothed	87.5	89.3

Comparison of Swiss and Hungarian air temperature data—Air temperature is an important determinant of LSWT and is often used to model LSWT empirically when a comprehensive set of meteorological data is lacking (e.g., McCombie 1959; Shuter et al. 1983; Kettle et al. 2004). The similarity in the surface temperatures of lakes in Switzerland and Hungary may therefore reflect a large-scale similarity in air temperature across central Europe. During the study period, the air temperatures in Switzerland (Fig. 2b) and Hungary (Fig. 2c) did indeed exhibit a similar temporal structure. The proportion of variance shared by the detrended Swiss and Hungarian air temperature data (34.4%) was, however, substantially lower than that shared by the corresponding LSWT data (67.3%) (Table 1).

Because weather systems generally tend to track from west to east across western and central Europe, air temperatures in Hungary might be expected to lag those in Switzerland. Comparing Figs. 2b and 2c, this does indeed appear to be the case. The existence of a lag was confirmed by computing the cross-correlation function of the Swiss and Hungarian air temperature time series, which revealed that the Hungarian air temperatures lagged the Swiss air temperatures by 1–2 d. Taking this lag into account, the proportion of variance shared by the air temperature time series increased by >20% to reach almost 60% (Table 1). Computation of the cross-correlation function of the detrended LSWT time series also revealed a time lag, with the Hungarian LSWT lagging the Swiss LSWT by ~1 d. Although the effect of this lag was less than in the case of air temperature, it was still large enough to result in an increase in the proportion of shared variance from 67.3% to 75.1% (Table 1).

Modeling lake surface-water temperature from air temperature—Comparison of the LSWT data of Fig. 2a with the air temperature data of Figs. 2b and 2c reveals a high degree of correlation between LSWT and air temperature both in Switzerland and in Hungary, with fluctuations in LSWT closely reflecting fluctuations in air temperature, particularly at lower frequencies. In both countries, the proportion of variance shared between LSWT and air temperature during the study period was ~70% (Table 1).

By use of an exponential filter as described by Kettle et al. (2004), Livingstone et al. (2005*a*) were able to show that the mean LSWT of the 29 Swiss lakes can be modeled well on the basis of ambient air temperature alone. The exponential filter, which is easily derivable from a sensible heat exchange model (Kettle et al. 2004) and is not merely empirical, is expressed by the following difference equation:

$$S_i = (1 - \alpha)S_{i-1} + \alpha T_i \qquad (1)$$

where S_{i-1} and S_i are the smoothed daily mean air temperatures on days $i - 1$ and i, respectively; T_i is the measured daily mean air temperature on day i; and α is an exponential smoothing coefficient lying between 0 and 1. From Eq. 1, the degree of smoothing increases as α decreases from 1 to 0. For the same sampling interval (1 d), Livingstone et al. (2005*a*) found that the highest proportion of shared variance between LSWT and S_i was obtained for $\alpha = 0.33$, but that $r^2 > 85\%$ for $0.23 \leq \alpha \leq 0.5$, so that the exact value of α was not critical. Applying the same method to relate the LSWT of Lake Balaton to ambient air temperature in Hungary revealed that the highest correlation between LSWT and S_i was obtained for $\alpha = 0.30$ ($r^2 = 89.3\%$). Again, however, the value of α was not critical; for the sake of consistency, therefore, a value of $\alpha = 0.33$ was also used for Lake Balaton.

Figure 2d illustrates the resulting exponentially smoothed air temperatures for Switzerland (Series II) and Hungary. The similarity of these curves to the LSWT curves of Fig. 2a is immediately apparent. After detrending the air temperature and LSWT time series, the exponential smoothing approach explains 88.6% of the variance in the LSWT of Lake Balaton and 89.3% of the variance in the mean LSWT of the Swiss lakes in terms of air temperature alone (Table 1).

The exponentially smoothed air temperatures in Switzerland and Hungary are much more highly correlated with each other than are the original unsmoothed series.

Comparing the Hungarian air temperature time series with Swiss air temperature Series I (Table 1), exponential smoothing (with $\alpha = 0.33$) increases the proportion of shared variance (r^2) from 37.7% to 58.9% before detrending. Introducing lags of 1 d and 2 d increases the r^2 value further, to 71.0% and 75.5%, respectively. Detrending the smoothed series—although not really necessary for the air temperature data in this case—results in even higher r^2 values of up to 78.2% when a 2-d lag is included. Because smoothing decreases the relative contribution of high-frequency fluctuations to the variance of the time series, it follows that coherence between the Hungarian and Swiss air temperatures is higher at low frequencies than at high frequencies.

Effect of altitude on large-scale regional coherence—The availability of air temperature and LSWT data spanning a range of altitudes in the Swiss Alps allowed the effect of altitude on the degree of large-scale regional coherence in LSWT to be investigated. The strength of the relationship between the LSWT of Lake Balaton and the smoothed air temperature in the Swiss Alps (Fig. 3a), and between the LSWT of Lake Balaton and the Swiss LSWTs (Fig. 3b), is quantified in terms of the proportion of variance (r^2) shared between the relevant detrended time series. (The results illustrated in Fig. 3 are based on the assumption of a 1-d lag between Switzerland and Hungary, but assuming a lag of 0 or 2 d yielded qualitatively similar results.) Comparing Figs. 3a and 3b, on average, the r^2 values are seen to decrease with increasing altitude in both cases. Despite this, however, the r^2 pattern derived from the Swiss LSWT data (Fig. 3b) is distinctly different from that derived from the Swiss air temperature data (Fig. 3a). In the case of the Swiss air temperature data, the variability in the r^2 values about the mean is essentially the same at low and high altitudes. In the case of the Swiss LSWT data, however, the degree of variability in r^2 at low altitudes is comparable to that found for the air temperature data, but at high altitudes, it is substantially greater. Thus, whereas local (station to station) variability in the large-scale coherence of smoothed air temperature is essentially independent of altitude, this is not true of local (lake to lake) variability in the large-scale coherence of LSWT. At low altitudes, local variability in the large-scale coherence of LSWT is comparable to local variability in the large-scale coherence of smoothed air temperature, but at high altitudes, it substantially exceeds that of smoothed air temperature.

Discussion—The results presented above indicate clearly that in the summer of 2000, daily LSWTs in Switzerland and Hungary responded coherently to synoptic-scale meteorological forcing, with over 75% shared variance after detrending to remove seasonal variability, and lagging to take rough account of the time taken for weather systems to travel from Switzerland to Hungary. This is unexpected for the following reasons: (1) the lakes concerned are ~750 km apart; (2) Lake Balaton is larger than the Swiss lakes by a factor of 10^2 to 10^5 with respect to surface area, so internal heat distribution mechanisms are likely to differ in their relative importance; (3) the Swiss

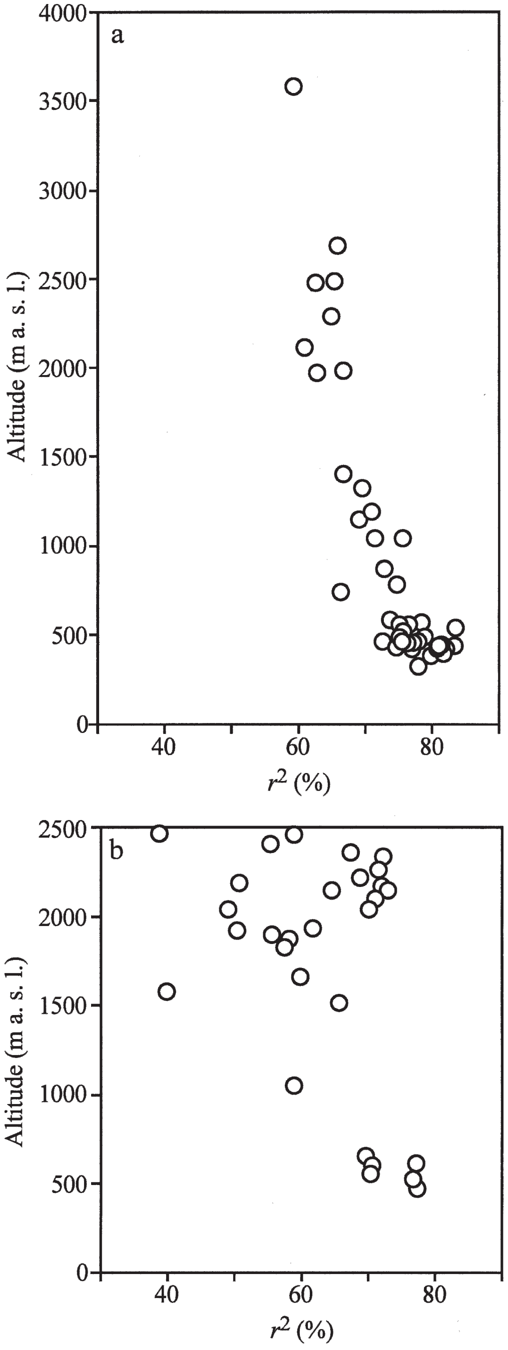

Fig. 3. Proportion of shared variance (r^2) between (a) the exponentially smoothed air temperatures measured at 40 meteorological stations in Switzerland and the lake surface-water temperature (LSWT) of Lake Balaton, Hungary; and (b) the LSWTs of 29 Swiss lakes and the LSWT of Lake Balaton. All r^2 values are shown as a function of the altitude of the Swiss lakes. All time series were linearly detrended before computing r^2, and all calculations are based on the period 19 June to 01 October 2000. The r^2 values shown incorporate an assumed lag of 1 d between the Swiss and Hungarian time series. Locations of the lakes and meteorological stations are shown in Fig. 1.

lakes span a range of altitudes extending up to >2,500 m above the altitude of low-lying Lake Balaton; and (4) unlike Lake Balaton, the Swiss lakes are located in a mountainous setting and are subject to locally heterogeneous weather.

Both in the case of the Swiss lakes and in the case of Lake Balaton, a large proportion of the variance in LSWT can be explained statistically solely in terms of exponentially smoothed air temperature. This is partly because air temperature is one of the four major meteorological driving variables that are involved explicitly in many of the processes that determine the lake heat balance, the other variables being wind speed, cloud cover, and relative humidity (e.g., Edinger et al. 1968; Sweers 1976; Livingstone and Imboden 1989). However, air temperature is not only a causal variable, it is also a correlative variable; i.e., air temperature is often significantly correlated with the other three meteorological variables. In Switzerland during the study period, the detrended time series of all four of the major meteorological driving variables measured in Zurich were significantly ($p < 0.01$) correlated with one another, with air temperature explaining 16.7% of the variance in wind speed, 28.7% of the variance in cloud cover, and 27.1% of the variance in relative humidity. Therefore, in the modeling of LSWT, air temperature can be perceived to have a dual function: on the one hand, it is an important causal variable in its own right; on the other, it acts as a proxy for the other meteorological driving variables with which it is correlated. It is causally related to these other variables via atmospheric processes, but these processes do not appear explicitly in the lake heat balance equations. The current study supplies further confirmation of the importance of air temperature, in the role of both a causal and a correlative (proxy) variable, in determining LSWTs, and demonstrates that lakes in effect act as low-pass filters, smoothing the air temperature signal.

Because air temperature generally shows a much higher degree of spatial coherence than the other meteorological variables that codetermine LSWT, and because it is correlated with them to some extent, it is eminently suitable as an anchor variable for estimating LSWTs over large areas when more extensive sets of detailed meteorological measurements are lacking. Smoothing—i.e., the removal of high-frequency variability—results in increased coherence between the Hungarian and Swiss air temperatures (Table 1). In view of the marked dependence of LSWT on smoothed air temperature, the high coherence of air temperatures at low frequencies is likely to be the primary cause of the high degree of coherence in LSWT between Hungary and Switzerland apparent in Fig. 2a.

However, as noted by Livingstone et al. (2005*a*), the LSWTs of high-altitude lakes in the Swiss Alps are less strongly dependent on air temperature than those of low-altitude lakes. This difference is manifested here first in the fact that the relationship between the LSWTs of individual Swiss lakes and the LSWT of Lake Balaton is generally weaker for high-altitude Swiss lakes than for low-altitude Swiss lakes, and second in the fact that the heterogeneity in the strength of the relationship is greater in the case of high-altitude Swiss lakes than in the case of low-altitude Swiss lakes (Fig. 3b). These differences are unlikely to result from an altitudinal difference in the climatic forcing itself, but rather from an altitudinal difference in the importance of local effects on the individual LSWTs of the Swiss lakes. Thus, the heterogenizing influence of local, disturbing factors that reduce large-scale coherence in LSWT by introducing local noise into the time series is much more important at high altitudes than at low altitudes.

It follows that the effects of large-scale climatic forcing are in general likely to be more obvious in low-altitude lakes than in high-altitude mountain lakes, in which they are more likely to be masked or overlain by local heterogeneity. The reasons for this may be lake-internal (e.g., unstable stratification at temperatures close to 4°C), or lake-external (e.g., effects of meltwater from the catchment). The similarity in the physical behavior of high-altitude and high-latitude lakes suggests that the response of the latter to large-scale climatic forcing may also be more heterogeneous and less clear-cut than that of lower latitude lakes.

This study has shown that the surface temperatures of lakes can fluctuate with a high degree of coherence over many hundreds of kilometers not only interannually, as previously documented, but also from day to day. This large-scale spatial coherence in LSWT reflects a similar coherence in smoothed air temperature, which can be viewed both as a causal forcing variable in its own right, and as a proxy for other important meteorological forcing variables, with which it is to some extent correlated. Coherence in the response of a very important internal physical boundary condition in very dissimilar lakes located in two different geographical regions of Europe implies that large-scale climatic forcing on daily timescales is important for the physics of lakes, and hence, potentially, for the lake ecosystem as a whole. Although the large-scale coherence in LSWT revealed in this study is very pronounced in the case of low-altitude lakes, this is not always the case in high-altitude lakes, implying that the effects of large-scale climate forcing on some, but not all, high-altitude lakes are likely to be outweighed by the effects of heterogeneous local factors. Thus, the effects of climate change on mountain lakes are likely to be more complex and less easy to unravel than its effects on lowland lakes.

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