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Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperature and the North Atlantic Oscillation

Abstract—Eighty years of monthly mean lake surface temperature (LST) data from eight lakes in the northern perialpine area of Austria show a high degree of coherence among lakes in all seasons and reflect much of the temporal structure of the regional air temperature. Coherence is least in winter because of the distorting effect of varying periods of ice cover. In spring, regional coherence in meteorological driving forces that are essentially uncorrelated with air temperature (e.g., geostrophic wind speed) contribute to the coherence in LST, presumably by partially determining the timing of the onset of stratification. In summer, spatial coherence in LST appears to be related directly (via the radiation balance) and/or indirectly (via air temperature) to large-scale variations in high-altitude cloud cover. Correlations of the Austrian LSTs with (1) seasonal indices of the North Atlantic Oscillation (NAO), (2) the timing of spring ice break-up in Finland, and (3) air temperatures in northern and western Europe, suggest that from autumn to spring, spatial coherence of LST in central Europe is related to the dominance of the weather by large-scale climatic processes occurring over the North Atlantic, whereas in summer the processes responsible are more regional in nature. The influence of the NAO on LST is greatest in low-lying lakes in which periods of ice cover are infrequent and short.

Lake surface temperature (LST) is one of the most important physical parameters of any lacustrine system. On the one hand, it reflects meteorological forcing more immediately and more sensitively than any other lake parameter; on the other hand, it is strongly related to the mean temperature of the photosynthetically productive zone and thus plays a major role in lake biology. Because many cellular processes are temperature dependent, epilimnetic temperature conditions are important not only for individual pelagic and littoral organisms but for entire aquatic ecosystems (e.g., Regier et al. 1990; Arnell et al. 1996 and references therein). LST is comparatively easy to measure (traditionally several cm below the lake surface). Accordingly, existing time series of LST tend to extend further back in time than those of most other lake parameters and thus comprise a valuable source of data for studying the effects of climatic forcing on lakes on long timescales.

The five main heat-exchange processes that determine the heat balance of a lake depend essentially on only four meteorological variables; viz. cloud cover, water vapor pressure, wind speed, and air temperature (Edinger et al. 1968; Sweers 1976). Of these, air temperature is of greatest interest, in view of its importance in the current climate change debate (e.g., Nicholls et al. 1996). LST tends asymptotically toward an equilibrium temperature (Edinger et al. 1968) that can be close to the ambient air temperature (Arai 1981) but can also deviate strongly from this because of radiative heat exchange and wind mixing (Dingman 1972; Arai 1981). However, despite the apparent weakness of the direct causal connection, air and surface water temperature are often highly correlated on both short and long timescales (McCombie 1959; Shuter et al. 1983; Livingstone and Lotter 1998; Livingstone et al. 1999). Long-term comparisons of LST with surface air temperature are therefore of interest to determine to what extent general conclusions that have already been drawn with respect to the manifestations of global and regional climate change on air temperature (Nicholls et al. 1996) may also be applicable to LST.

Surface air temperatures in Europe are highly correlated over distances corresponding to synoptic-scale meteorological processes (~1,000 km), especially in winter and spring (Table 1). Taken in conjunction with the fact that the LSTs of individual lakes are usually highly correlated with air temperature locally (e.g., Livingstone and Lotter 1998), this suggests that LSTs may also be correlated over similarly large distances. Various studies have shown LSTs to be correlated on a much smaller scale—e.g., several tens of km within individual lake districts (Magnuson et al. 1990; Benson et al. 2000; George et al. 2000)—but work by Benson et al. (2000) suggests that the spatial scales involved may indeed be much greater than this. The question of the geographical extent of the correlation between LSTs is essentially one of whether the LST of a given lake can be profitably considered as the local manifestation of a spatially coherent synoptic-scale response to synoptic-scale meteorological processes, as opposed to an isolated local phenomenon. This question is of particular interest in view of the fact that air temperatures over large regions of the Northern Hemisphere, including most of Europe, appear to be determined to a large degree by climatological processes occurring over the North Atlan-

Table 1. Pairwise coefficients of determination (r^2, in %) (top) between air temperatures measured at Basle, Munich, and Vienna and (bottom) between the mean air temperature at these stations (BMV) and air temperatures measured at four other stations in Europe. All calculations are based on linearly detrended time series from 1911–1990. The distances given in the bottom section are to the Munich station. The only value of r^2 not significant at the $P < 0.01$ level (i.e., $r^2 < 8.2\%$) is given in italics. See Fig. 1 for meteorological station locations. Data sources: Basle, Swiss Meteorological Institute; De Bilt, Dutch Meteorological Institute; Stockholm, Moberg and Bergström (1997); Central England, Manley (1974) and Parker et al. (1992); Munich, Vienna, and Berlin, Global Historical Climatology Network (see Vose et al. 1992).

Station pair	Winter (DJF) mean	Spring (MAM) mean	Summer (JJA) mean	Autumn (SON) mean	Annual mean
Basle & Munich (300 km)	92	88	84	90	87
Munich & Vienna (350 km)	86	79	74	85	78
Basle & Vienna (660 km)	77	57	56	80	70
BMV & Berlin (500 km)	79	79	39	75	73
BMV & De Bilt (630 km)	84	69	44	60	69
BMV & Central England (1,080 km)	64	32	26	22	48
BMV & Stockholm (1,310 km)	32	42	*5*	33	43

tic, specifically those associated with the North Atlantic Oscillation (NAO) in winter (e.g., Walker and Bliss 1932; Hurrell 1995, 1996; Hurrell and van Loon 1997). Recent work suggests that the breakup of ice on various lakes distributed around the Northern Hemisphere is related to the NAO (Livingstone 1999, in press). In view of this, it can be hypothesized that, during at least part of the year, LSTs are likely to be subjected to a similar NAO influence. Testing this hypothesis credibly, however, requires at least several decades of LST measurements.

Study lakes and historical data—In many lakes in Austria, surface temperatures (actually near-surface temperatures, measured at 50-cm depth) have been registered continuously once per day (in the early morning) since the early part of the 20th century. The monthly means of these data have been tabulated by the Austrian Hydrographic Office (Hydrographisches Büro 1964*a,b,* 1973, 1985, 1994). Here, eight LST series that cover the 80-yr period 1911–1990 without interruption are presented and compared with one another, with regional air temperatures, and with Hurrell's (1995) winter NAO indices, to estimate the degree of spatial coherence in LST in the northern perialpine area of central Europe and to determine to what extent LST in the recent past may have reflected synoptic-scale climatic forcing. Six of the eight perialpine lakes providing the LST series (Traunsee, Attersee, Mondsee, Hallstätter See, Wolfgangsee, and Fuschlsee) are located in the Salzkammergut region of Austria; the other two (Zeller See and Bodensee) lie to the west of these (Fig. 1).

Some relevant physical characteristics of the eight lakes are listed in Table 2. The most important of these is the duration of ice cover. Temperatures were measured at the same depth (50 cm) in all lakes, regardless of the presence or absence of ice cover. Therefore, because ice cover essentially decouples the water column from atmospheric forcing, the long-term frequency of occurrence of ice-cover events and their duration will affect the time series of measured water temperature and their perceived relationship to the time series of regional air temperature. All eight study lakes can freeze over during a severe winter, but not all do so during milder winters. If they freeze, they usually do so in January and thaw during March (Eckel 1955), so the presence of ice cover will directly affect seasonal mean LSTs in winter (DJF), and also to a lesser extent in spring (MAM). The occurrence and duration of ice-cover events depends to a large extent on lake elevation in the eastern Alps in general (Eckel 1955) and in the eight lakes of this study in particular (Table 2). The effect of ice cover on the LST time series can therefore be assumed to be least in the case of Bodensee (396 m above sea level [a.s.l.]) and greatest in the case of Zeller See (750 m a.s.l.).

Air temperature measurements covering the period 1911–1990 are available from the meteorological stations of Basle (316 m a.s.l.) to the west of the lakes, Munich (529 m a.s.l.) to the north, and Vienna (203 m a.s.l.) to the east (Fig. 1). The three air temperature series are highly correlated in all seasons (Table 1, top) and thus clearly reflect regional climate to a large degree. Livingstone and Lotter (1998) have shown that air temperatures are highly correlated over the entire northern perialpine area of Switzerland, which allows the use of standard composite mean air temperature series for comparison with LSTs in this area. On a slightly larger scale, the similarity of the Basle, Munich, and Vienna series also justifies the use of one composite series to represent regional air temperature for comparison with LSTs in Austria. This composite series, henceforth abbreviated "BMV," was constructed by taking the arithmetic mean of the air temperatures measured at Basle, Munich, and Vienna and correcting this from the mean altitude of the three stations (349 m a.s.l.) to the mean altitude of the eight lakes (525 m a.s.l.) by use of the mean monthly surface air temperature lapse rates calculated by Livingstone and Lotter (1998) for the north-facing slope of the Alps.

Regional coherence of lake surface temperature—As in the case of the three air temperature time series, the eight LST time series exhibit a similar temporal structure. The proportion of variance shared pairwise between each of the detrended LST series and the mean of the other seven detrended series in each season is high (r^2, Table 3, top). With the exception of Zeller See in winter, r^2 is always at least

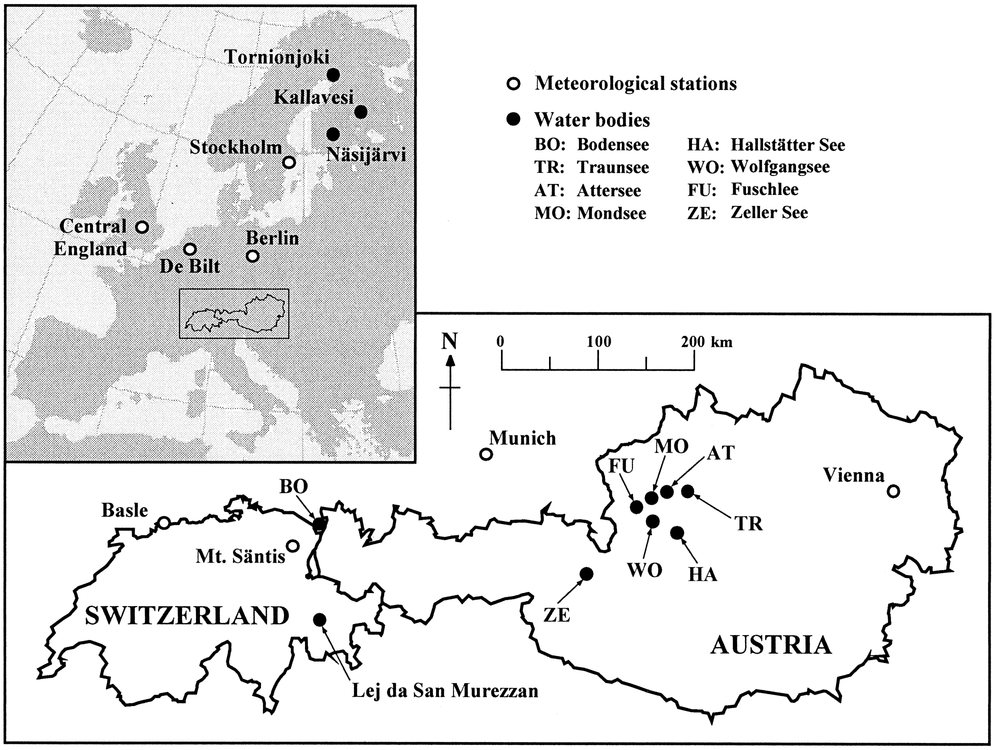

Fig. 1. Locations of water bodies and meteorological stations mentioned in the text.

30%, which implies a large degree of spatial coherence in LST within the region. The r^2 values listed in the top section of Table 3 are also a measure of the degree to which each lake can be considered representative of the entire group in each season. The most representative of the eight lakes, Traunsee, has r^2 values that range from 60% for winter to as high as 74% for spring and summer. Mean r^2 values averaged over all lakes are substantially lower for winter than for the other seasons (Table 3, top), which implies that spatial coherence is lowest for winter. This is presumably due primarily to the differences in the duration of ice cover apparent in Table 2: Bodensee, for instance, which is hardly ever ice-covered, has a winter r^2 value of 55%, whereas Zeller See, which lies substantially higher than the other lakes and is frozen over longest, has a winter r^2 value of only 11%. As in the case of air temperature, the high degree of correlation among the LST series also justifies constructing one composite mean series (henceforth denoted "MLST") to represent regional LST for comparison purposes by taking the arithmetic mean of the eight LST series.

Table 2. Elevations (E), surface areas (A_0), maximum depths (z_m), and mean duration of ice cover events from 1895–1955 (D_{ice}) of the eight study lakes, listed in order of increasing E. See Fig. 1 for lake locations. Data on E, A_0, and z_m from Sampl et al. (1989); data on D_{ice} from Eckel (1955).

Lake	E (m a.s.l.)	A_0 (km^2)	z_m (m)	D_{ice} (d)
Bodensee	396	476.0	252	0
Traunsee	422	25.6	191	44
Attersee	469	45.9	171	40
Mondsee	481	14.2	68	59
Hallstätter See	508	8.6	125	37
Wolfgangsee	538	12.8	113	75
Fuschlsee	636	2.7	66	61
Zeller See	750	4.6	68	93

Relationship between lake surface temperatures and regional air temperature—Again with the exception of Zeller See in winter, in all lakes and in all seasons, LSTs are highly correlated with the BMV regional air temperature series (Table 3, bottom). In all seasons, with respect to general variability, short-term trends, and extreme events, series MLST corresponds closely to series BMV (Fig. 2), which reflects the fact that the LST series are not only coherent among themselves but also reflect much of the temporal structure present in the regional air temperature. Obvious discrepancies between the MLST and BMV series exist only in the long-term means (because of the lag involved in heating during spring and summer and cooling during autumn and winter) and in the variance in winter (when LSTs have a lower bound that limits their variance, whereas air temperatures do not).

The proportion of variance shared between the MLST and BMV series shows only little seasonal variability, ranging from 58% to 66% (Fig. 2; Table 3, bottom). Thus, despite the fact that LST is less spatially coherent in winter than in the other seasons (Table 3, top), the mean winter LST still exhibits a strong association with regional air temperature. This implies that regional climate forcing supplies the basic structure to the LST time series but that local differences

Table 3. (Top) Pairwise coefficients of determination (r^2, in %) between the surface temperature of each of the eight study lakes and the mean surface temperature of the other seven lakes. (Bottom) Pairwise coefficients of determination (r^2, in %) between the surface temperatures of the same eight lakes and the mean regional air temperature (BMV = mean of measurements at Basle, Munich, and Vienna) and between the mean regional lake surface temperature MLST and BMV. All calculations are based on linearly detrended time series from 1911 to 1990. The only value of r^2 not significant at the $P < 0.01$ level (i.e., $r^2 < 8.2\%$) is given in italics. See Fig. 1 for lake locations. The lakes are listed in order of increasing elevation.

Lake	Winter (DJF) mean	Spring (MAM) mean	Summer (JJA) mean	Autumn (SON) mean	Annual mean
Bodensee	55	43	30	30	36
Traunsee	60	74	74	66	69
Attersee	51	66	62	73	49
Mondsee	51	67	67	62	62
Hallstätter See	53	65	55	58	53
Wolfgangsee	45	58	59	63	52
Fuschlsee	41	69	54	54	53
Zeller See	11	55	48	62	40
Mean r^2	46	62	56	59	52
Bodensee	47	32	37	15	32
Traunsee	54	49	47	52	49
Attersee	41	48	58	58	47
Mondsee	34	42	52	60	37
Hallstätter See	43	38	36	48	41
Wolfgangsee	33	40	44	54	37
Fuschlsee	49	50	35	28	43
Zeller See	*6*	42	51	42	21
MLST	64	58	66	66	60

between lakes (e.g., differences in ice cover duration) are important enough in winter to result in strong lake-specific modifications to this basic temporal structure.

In view of predictions that epilimnetic temperatures and the thermal stability of lakes are likely to increase as a result of global warming (Arnell et al. 1996), linear regressions of the seasonal MLST series on calendar year were conducted to determine whether any evidence of long-term warming could be found in the Austrian lakes. At the $P < 0.05$ level, the existence of a warming trend could be confirmed only in the autumn MLST series of Fig. 2D (1.1°C 100 yr^{-1}, with a 95% confidence interval of ±0.7°C). This trend is essentially the same as that found in the autumn BMV air temperature series (1.2°C 100 yr^{-1}, with a 95% confidence interval of ±1.0°C).

Regional air temperatures are known to influence not only LST but also the timing of thawing of lakes in Europe (Palecki and Barry 1986; Ruosteenoja 1986; Livingstone 1997). Thus the same synoptic-scale climatic signal detected in the LSTs of relatively low-lying lakes may be present in the timing of thawing of high-altitude lakes. This hypothesis was tested by comparing the Austrian LST time series with the only time series of the calendar date of breakup of a lake in the Alpine region known to cover the entire period 1911–1990, viz. Lej da San Murezzan (1,768 m a.s.l., see Fig. 1). The timing of breakup of this lake (usually during May), which previous work has shown to be strongly related to April mean air temperatures (Livingstone 1997), was indeed found to be significantly ($P < 0.01$) correlated with the April mean of the Austrian MLST series, with 20% shared variance. This suggests that the signature left by regional or supraregional climate forcing in the LSTs of low-lying lakes is likely to be paralleled by a similar signature in the timing of breakup of high-altitude lakes.

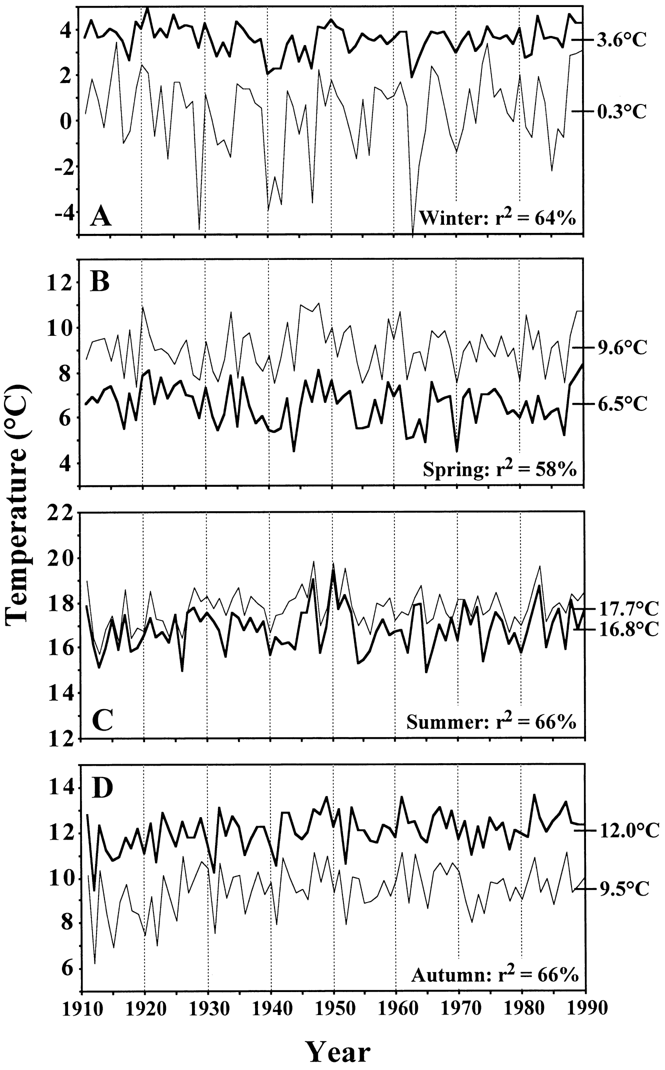

Fig. 2. Seasonal comparison of the mean lake surface temperature of eight Austrian perialpine lakes (MLST, thick solid lines) with the regional mean air temperature (BMV, thin solid lines), 1911–1990. MLST: arithmetic mean of lake surface temperatures measured at 50 cm depth in the eight lakes listed in Table 2. BMV: arithmetic mean of air temperatures measured at the meteorological stations of Basle, Munich, and Vienna, corrected to the mean elevation of the eight lakes (525 m a.s.l.) by use of the mean monthly surface air temperature lapse rates of Livingstone and Lotter (1998). The r^2 values shown represent the percentage variance shared between series MLST and series BMV for each season (see Table 3, bottom). Seasonal means (1911–1990) are listed on the right-hand side of the plots. See Fig. 1 for locations of lakes and meteorological stations.

Table 4. Pairwise coefficients of determination (r^2, in %) between the mean surface temperature of the eight study lakes (series MLST, Fig. 2) and measurements of high-altitude wind speed and cloud cover from the Mt. Säntis observatory (2,500 m a.s.l.). All calculations are based on linearly detrended time series from 1911 to 1990. Values of r^2 not significant at the $P < 0.01$ level (i.e., r^2 8.2%) are given in italics. See Fig. 1 for lake and observatory locations.

	Winter (DJF) mean	Spring (MAM) mean	Summer (JJA) mean	Autumn (SON) mean	Annual mean
Mt. Säntis wind speed	*0*	11	*4*	*0*	*4*
Mt. Säntis cloud cover	*4*	*8*	31	10	17

Influence of other climatic driving forces on lake surface temperatures—In spring, when spatial coherence of LST is highest, on average (Table 3, top), correlations with regional air temperature are lowest (Table 3, bottom). This suggests that other driving forces that are regionally coherent but are uncorrelated with regional air temperature, may be partially responsible for the spatial coherence of LST in spring. Wind speed, which can critically affect the timing of the onset of stratification during spring and therefore the mean spring LST, is one factor that may be important in this context. Although local wind speeds at ground level tend to be spatially heterogeneous because of the effect of the local terrain (Barry 1992), this is much less true of high-altitude winds measured at mountaintop stations, which more faithfully reflect the spatially homogeneous geostrophic wind. Wind speed measurements from 1911–1990 are available from the Mt. Säntis meteorological observatory, located at 2,500 m a.s.l. on a mountaintop 20 km from Bodensee (Fig. 1). In spring, the mean wind speed at the Mt. Säntis observatory is uncorrelated with the BMV mean regional air temperature series ($r^2 < 1\%$). However, it was found to be significantly ($P < 0.01$) negatively correlated with the LST not only of Bodensee but also of three of the Salzkammergut lakes (Traunsee, Attersee, and Hallstätter See) and with the MLST series (Table 4). Although the proportion of variance accounted for is not large (10%–12%), the fact that the LSTs of at least some of the Salzkammergut lakes (those with the shortest period of ice cover and hence the longest exposure to wind influence) correlate significantly with high-altitude wind speeds measured 300 km from the lakes suggests that part of the regional spatial coherence of LST in spring may be due to geostrophic wind rather than to air temperature or a factor correlated with air temperature. In seasons other than spring, correlations between the MLST series and the Mt. Säntis wind speed are low (Table 4), which implies that geostrophic wind speed is unlikely to play an important role in determining the spatial coherence of LST in summer, autumn, and winter.

High-altitude cloud cover in mountain regions tends to be more spatially coherent than low-altitude cloud and mist, which are often dependent on local orographic effects (Barry 1992). Spatial coherence in perialpine LST may therefore be due in part to the regional nature of variations in the radiation balance brought about by temporal variations in high-altitude cloud cover. This hypothesis was investigated by use of historical cloud cover data from 1911 to 1990 from the Mt. Säntis observatory (see Schüepp 1963 for the early part of this series). The MLST series is highly negatively correlated with the Mt. Säntis cloud cover series in summer, is only weakly negatively correlated in autumn, and is essentially uncorrelated otherwise (Table 4). The LSTs of each of the eight lakes taken individually are also significantly negatively correlated with the Mt. Säntis cloud cover series in summer. Thus, during summer, when solar elevation is greatest and fluctuations in incident solar radiation therefore have their greatest effect on LST, modulation of the radiation balance on a regional scale by high-altitude cloud cover is likely to be an important factor contributing to the spatial coherence of LST. This hypothesis is supported by the fact that the BMV air temperature series is also highly negatively correlated with the Mt. Säntis cloud cover series in summer ($r^2 = 46\%$) but not otherwise ($r^2 < 10\%$). During the other seasons (with the possible exception of early autumn), high-altitude cloud cover is unlikely to contribute to the spatial coherence of the LST series, either because it is masked by more spatially heterogeneous low-altitude cloud or because it is insufficiently spatially coherent itself. The effect of cloud cover on the radiation balance of a lake is to cause a decrease in incident short-wave solar radiation and a simultaneous increase in incident long-wave atmospheric radiation (Edinger et al. 1968). The negative correlation between LST and high-altitude cloud cover implies that the effect of the increase in atmospheric radiation is outweighed by that of the reduction in incident solar radiation.

Influence of the NAO—The NAO, which affects the extent to which warm, moist air is transported from the Atlantic eastward across Europe, is known to have a significant influence on air temperatures throughout much of the continent (e.g., Walker and Bliss 1932; Hurrell 1995, 1996; Hurrell and van Loon 1997). Because this influence is strongest during the winter half-year, much of the relevant climatological research is based on a broad (4-mo) index of the winter NAO (denoted here as NAO_{win}) derived from standardized differences in surface air pressure between Lisbon and Iceland from December to March (Hurrell 1995). The monthly mean BMV regional air temperature time series are significantly correlated with NAO_{win} from November to March (Fig. 3A). In view of the strong relationship between LST and regional air temperature apparent from Table 3, bottom, and Fig. 2, the Austrian LSTs might therefore also be expected to correlate with NAO_{win}. This is the case not only for the MLST series (Fig. 3B) but also for all eight lakes individually, albeit to different extents (Fig. 3C–J). Presumably because of the insulating effect of ice cover, the influence of the winter NAO on the LST of the four highest lakes (Hallstätter See, Wolfgangsee, Fuschlsee, and Zeller See) is relatively modest (Fig. 3G–J). However, a comparison of Fig. 3B–F with Fig. 3A reveals that in the mean and in each of the four lowest lakes, the NAO appears to influence the LST more strongly than it influences regional air temperature. This is presumably because the NAO will influence LST not only via air temperature but also via its effects on other relevant meteorological variables, e.g., cloud cover. As in the case of air temperature, the influence of the NAO on LST is strongest

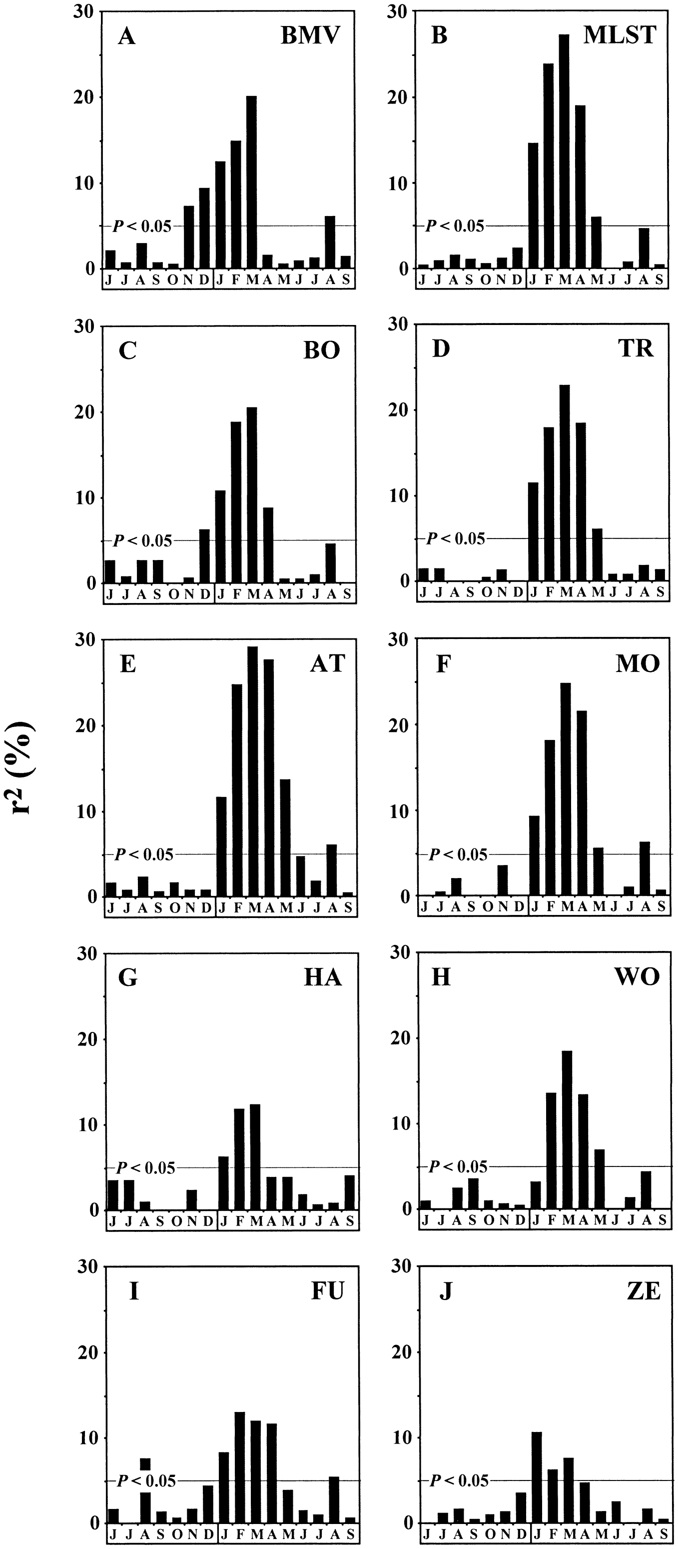

Fig. 3. Coefficients of determination (r^2) between Hurrell's (1995) winter NAO index (NAO_{win}) and air and lake surface temperatures in the northern perialpine area of central Europe. (A) r^2 between NAO_{win} and monthly mean regional air temperature (BMV). (B) r^2 between NAO_{win} and monthly mean regional lake surface temperature (MLST). (C–J) r^2 between NAO_{win} and the monthly mean regional lake surface temperatures of the eight individual lakes of Table 2 (see Fig. 1 for lake locations and abbreviations).

Table 5. Pairwise coefficients of determination (r^2, in %) (top) between the mean surface temperature of the eight study lakes (series MLST, Fig. 2) and air temperatures measured at seven meteorological stations in Europe; (middle) between Hurrell's (1995) seasonal NAO indices and the same air temperature data; and (bottom) between Hurrell's (1995) seasonal NAO indices and series MLST. All calculations are based on linearly detrended time series from 1911 to 1990. Values of r^2 not significant at the $P < 0.01$ level (i.e., $r^2 < 8.2\%$) are given in italics. Values given as 0 imply $r^2 < 0.5\%$. See Fig. 1 for lake and meteorological station locations and Table 1 for sources of data.

Meteorological station	Winter (DJF) mean	Spring (MAM) mean	Summer (JJA) mean	Autumn (SON) mean	Annual mean
Basle (Switzerland)	63	42	52	65	55
Munich (Germany)	60	55	62	64	54
Vienna (Austria)	59	60	65	58	57
Berlin (Germany)	49	50	28	54	42
De Bilt (Netherlands)	53	39	28	34	37
Central England (U.K.)	39	12	9	11	22
Stockholm (Sweden)	22	32	*4*	30	25
Basle	17	9	*0*	14	12
Munich	19	15	*0*	14	11
Vienna	23	21	*0*	13	13
Berlin	32	27	*0*	25	23
De Bilt	33	24	*0*	17	21
Central England	45	15	*0*	*7*	22
Stockholm	39	36	13	35	37
MLST	14	13	*0*	8	11

during March. In general, however, correlations are significant ($P < 0.05$) from January to April or May, which implies that the winter NAO has a more persistent effect on LST than on regional air temperature. This is likely to be largely the result of the fact that water temperatures during early spring depend not only on the heat exchange that occurs at that time but also on heat exchange that occurred during the previous winter.

Further evidence for the large-scale nature of the driving forces responsible for spring LSTs is provided by comparing the central European LSTs with historical observations of the timing of spring ice breakup in northern Europe. After linearly detrending all time series, the proportion of variance shared between the spring MLST in Austria and the timing of breakup of lakes and rivers in Finland is as much as 19% in the case of Lake Näsijärvi, 16% in the case of Lake Kallavesi, and 14% in the case of the Tornionjoki River (see Fig. 1 for locations; all correlations significant at the $P < 0.01$ level). The consistently high proportion of variance shared between time series of two different physical phenomena—LST and the timing of ice breakup—occurring ~2,000 km apart emphasizes the fact that physical lake forcing during spring cannot be considered merely as a local, or even a regional, phenomenon. Because the winter NAO is known to exert a strong influence on the timing of spring ice breakup in Finland (Livingstone in press), it can be assumed that the interregional coherence in physical lake forcing between northern and central Europe is a result of the large-scale influence of the NAO on both regions.

Although the Austrian LSTs are most highly correlated with air temperatures measured within the region (e.g., at Basle, Munich, or Vienna), the high degree of coherence exhibited by air temperature on synoptic scales (Table 1, bottom) means that the Austrian LSTs also vary coherently with air temperatures measured at stations several hundred kilometers away, e.g., in Germany, the Netherlands, the United Kingdom, and Sweden (Table 5, top). The relationship between the MLST series and the air temperatures at these distant stations, although almost always statistically significant ($P < 0.01$), is generally considerably weaker in summer than in the other seasons. This can be explained by the relative lack of influence of the NAO during summer. From autumn through spring, air temperatures throughout much of Europe are significantly ($P < 0.01$) correlated with the respective 3-mo seasonal (as opposed to 4-mo winter) NAO indices, but, in summer, this correlation is confined to northern Europe (Table 5, middle). Specifically, there is no significant correlation between the 3-mo summer NAO index and the air temperature measured at either Basle, Munich, or Vienna. In addition, although the seasonal MLST series are significantly correlated with the respective seasonal NAO indices from autumn to spring, this is not the case in summer (Table 5, bottom). Therefore, the mechanism accounting for the spatial coherence of the Austrian LSTs in summer cannot be associated with the NAO but is geographically more limited, extending perhaps from the Alps to Berlin and De Bilt but not to Stockholm, central England, or the North Atlantic.

Conclusions and implications—Climate forcing on regional scales (summer) to synoptic scales (autumn, winter, and spring) has been shown here to leave a common signature in air temperature and LST over several hundred kilometers of the northern perialpine region of central Europe. Under the assumption that LSTs in other regions of Europe are as highly correlated with their respective regional air temperatures as they are in this region, this would imply the existence of a synoptic-scale spatial coherence in LST from autumn to spring extending over much of western Europe. Support for this hypothesis, which has far-reaching biological implications, is provided by the strong NAO signals found in lake temperatures in the United Kingdom (George et al. 2000) and northern Germany (Gerten and Adrian 2001). Additionally, recent work suggests that both phytoplankton and zooplankton population dynamics in lakes across western Europe are strongly influenced by North Atlantic ocean-atmosphere dynamics, as is manifested in shifts in the position of the Gulf Stream (George and Taylor 1995) and fluctuations in the NAO (Weyhenmeyer et al. 1999; Gerten and Adrian 2000; Straile 2000; Straile and Adrian 2000).

The fact that an NAO signature is detectable in historical observations of lake ice breakup not only in northern and central Europe but also in Siberia and Wisconsin (Livingstone 1999, in press) suggests additionally that the Arctic Oscillation, of which the NAO can be considered a regional manifestation (Thompson and Wallace 1998), may play a significant role in driving the physical and biological limnology of lakes distributed over large areas of the Northern Hemisphere, possibly resulting in some degree of synchronicity and spatial coherence among lakes not only on regional and synoptic scales but also on scales corresponding to those of planetary waves.

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