Limnol. Oceanogr., 46(2), 2001, 448–455

Differences in the persistency of the North Atlantic Oscillation signal among lakes

Abstract—Large-scale climatic fluctuations, such as the El Niño Southern Oscillation and the North Atlantic Oscillation (NAO), are known to influence variability in abiotic site conditions and organism population dynamics in both terrestrial and aquatic ecosystems. Here we demonstrate that the influence of the NAO on lake water temperatures—one of the major factors controlling ecological processes in lakes—differs substantially among lake types of different thermal structures and mixing regimes, even under identical climatic forcing. A frequently circulating polymictic lake was found to be least influenced by the winter effects of the NAO, with an effect lasting only into early spring. In contrast, in a deep dimictic lake with stable summer stratification, the NAO signal persisted in the hypolimnion until the following winter. A shallow dimictic lake revealed an intermediate response, as weather conditions both in April and midsummer probably modified the strength and persistency of the NAO signal in the hypolimnion of that lake. Based on these results, it is to be expected that NAO effects on ecological processes vary significantly among lakes. Because the study period (1979–1998) includes a series of uncommonly warm winter and spring seasons, our findings also suggest that the influence of anticipated climate warming will vary substantially among lake types.

Ecologists are becoming increasingly aware that large-scale oceanic and climatic fluctuations affect interannual and interdecadal variability in ecological processes for both terrestrial (e.g., Post et al. 1999) and aquatic systems (e.g., Beamish et al. 1999) around the world. In general, aquatic environments may be more responsive to these broad-scale phenomena than terrestrial environments, because the thermal characteristics of most water bodies are well suited to store such climate information. As a consequence, effects on water temperature may shape responses down to the level of individual organisms. In fact, population dynamics on various trophic levels, in both marine and lacustrine ecosystems, have been found to be influenced by the El Niño Southern Oscillation (e.g., Barber and Chavez 1983), displacements of the Gulf Stream (George and Taylor 1995), or the Pacific Interdecadal Oscillation (Mantua et al. 1997).

Here, we focus on the North Atlantic Oscillation (NAO), a prime source of weather variability in winter, in particular over vast regions of Eurasia and parts of North America (Hurrell and van Loon 1997). This natural decadal-scale climatic oscillation usually is expressed in terms of the NAO index—a measure of the differences of sea level pressures between the subtropic Azores high and the subpolar Icelandic low. A positive winter NAO index indicates predominating zonal circulation over the Atlantic leading to mild and rainy winters, particularly in western and northern Europe. The reverse situation is associated with low-pressure gradients over the Atlantic, usually bringing cold winters over Europe (Hurrell 1995). It has been demonstrated that the NAO influences surface-water temperatures (Hurrell 1995; George et al. 2000) and ice conditions (Livingstone in press) as well as abundances and population dynamics of phytoplankton (Weyhenmeyer et al. 1999; Gerten and Adrian 2000), zooplankton (Straile 2000), and fish (Fromentin et al. 1998) in aquatic environments.

It is to be expected that the persistency of the NAO signal varies among lake types differing in their morphological properties and mixing regimes (Shuter et al. 1983). Comparative studies concerning such differences in NAO responsiveness would add to the understanding of the extent to which this macroscale climate signal potentially contributes to year-round water temperatures and, as a consequence, to successional ecological processes in various aquatic systems. In the present study, we assessed the potential of the NAO as a predictor of depth-dependent water temperatures in three lakes in the temperate zone, based on the analysis of a 20-yr time series of climatic and water temperature data. Although our perspective is a regional one, the lakes selected for the study represent an empirical suite of thermal responses to the NAO for numerous lake types in temperate latitudes.

Study sites—The three medium-sized lakes are situated in the lowlands of northern Germany and span a wide range of lake depths, stratification behaviors, and trophic states (Table 1). Regional climate is temperate and humid, characterized by high inter- and intraannual variation of temperature conditions, in particular. Accordingly, there is high interannual variation in water temperatures and in the ice development of all lakes. Ice duration is highly synchronous in the three lakes, ranging from 0 d in very mild winters (1988/1989 and 1989/1990) to almost 4 months in severe winters (1996). A detailed description of the ice development of the Müggelsee is given in Adrian et al. (1999).

Data and analysis—Air temperature and wind velocity data were available as daily means for Berlin-Schönefeld (52°23′N, 13°31′E); daily sums of global radiation were available for Potsdam (52°23′N, 13°4′E). Spatial differences in climatic conditions are relatively subtle within the study region, so we assumed these data to be representative for all lake sites. Recent temperature conditions were rated using an unbroken series of historical (since 1756) air temperatures from Berlin-Tempelhof (52°29′N, 13°24′E), which are available at http://www.wetterzentrale.de/klima/tberlintem.html. We used the winter NAO index (means of December–March) as provided by the National Center of Atmospheric Research, Boulder (http://goldhill.cgd.ucar.edu/cas/climind/). Monthly indices (available at the same site) were employed for a more detailed analysis of correlations in winter and to check for correlations in the other seasons. The NAO indices express the difference of sea level pressures between Lisbon/Portugal (monthly indices: Ponta Delgada/Azores) and Stykkishólmur/Iceland, normalized relative to the period 1864 to 1983.

Table 1. Physiographical features of the lakes under examination. The Secchi depths are given as annual arithmetic means for 1979–1998 based on weekly to monthly recordings. For further details, *see* Driescher et al. (1993), Adrian et al. (1995), and Casper (1985), respectively.

	Müggelsee	Heiligensee	Stechlinsee
Location	52°26′N, 13°39′E	52°36′N, 13°13′E	53°10′N, 13°02′E
Area (km^2)	7.30	0.32	4.25
Mean depth (m)	4.9	5.9	22.8
Maximum depth (m)	8.0	9.5	68.0
Mixing regime	Polymictic	Dimictic	Dimictic
Trophic state	Hypereutrophic	Hypereutrophic	Oligotrophic
Secchi depth (m)	1.8	1.8	8.6

Water temperatures were recorded at the deepest sections of the lakes from the surface to the bottom at 1-m intervals in the Müggelsee and the Heiligensee and at 2-m intervals (10-m intervals below 20 m deep) in the Stechlinsee, respectively. Water temperature in the Müggelsee was recorded weekly or biweekly, whereas temperatures of the Heiligensee and the Stechlinsee usually were recorded once a month. There were no recordings for the Heiligensee in 1979 and 1985. A nuclear power plant, which discharged cooling water into the Stechlinsee, ceased operation during the study period in 1990 (Casper and Koschel 1995). Intervention analysis (Wei 1990) based on monthly differences between air temperature and water temperature at different depths before and after the stoppage suggested that the emissions did not considerably affect the water temperature profile ($P < 0.05$). This profile was measured at a site located in the most distant part of the Stechlinsee from the emission source. At times of thin ice cover, when water temperature recordings were impossible, surface temperatures of all lakes were assumed to be 0°C (Müggelsee and Heiligensee, $n = 8$; Stechlinsee, $n = 16$ data points).

The location of the thermoclines was defined as the depth with a temperature difference of $>1°\text{C m}^{-1}$. Unfortunately, because of the rather coarse temporal resolution of the temperature recordings, we were not able to determine exactly the dates of stratification onset and termination. Therefore, possible relationships between the timing of these events and climatic conditions could not be examined in detail.

Prior to statistical analysis, water temperatures of all lakes were interpolated onto the first day of each month with a cubic spline in order to get comparable and equispaced time series. This temporal resolution was chosen because water temperature was sampled at lowest frequency in the Stechlinsee, where recordings were performed regularly at the beginning of a month. Thus, monthly water temperatures given herein actually refer to the interpolated value of the first day of the respective following month. Climatic data were taken as arithmetic monthly means. All climatic and water temperature series were checked for significant trends with the nonparametric Mann–Kendall trend test (Sneyers 1975) for each month separately. Series for which a significant trend was identified were linearly detrended prior to correlation analysis in order to avoid spurious relationships, which might occur only because of the presence of these trends. Comparisons with correlation coefficients of the non-detrended series, however, showed that differences were minor.

To quantify the spatiotemporal pattern of the NAO influence on the three lake types, monthly series of water temperatures at all depths were correlated with the NAO index of the preceding winter. Correlation analyses with the monthly NAO indices were performed as well but will only be reported in cases where they differed substantially from the correlation pattern with the winter index. Fortunately, water temperature series of the Stechlinsee date back to 1960, which allowed us to assess the longer term validity of the correlation pattern found for the period 1979–1998. In addition, correlations between water temperatures and climatic conditions (air temperature, global radiation, wind speed) during the concurrent and the preceding months were calculated to check for further, possibly time-lagged, relationships.

Observed trends in climatic conditions and water temperatures—Significant rising trends within the investigation period were detected for monthly mean air temperatures in April (Mann–Kendall, $P < 0.05$) and August ($P < 0.1$). Some seasons in the second half of the investigation period (winter 1989/1990 and 1990/1991; spring 1990 and 1993; summer 1992) can even be interpreted as extreme climatic events, as they appeared to be within the warmest 2% of the respective seasons on record since 1756. The NAO remained in a highly positive phase since the 1980s (Fig. 1a) compared to the preceding decades (Hurrell 1995), and the winter NAO indices of 1989, 1990, and 1995 were among the highest on record since 1864. Note, however, that there was a very low NAO index in 1996, which was one of the lowest ever recorded. This may be why the winter index did not show a significant rising trend within the investigation period ($P > 0.1$). Wind and radiation conditions did not reveal significant trends in any month, except for an upward trend of wind speed in February ($P < 0.05$).

Water temperatures of the three lakes generally exhibited a pronounced seasonal pattern with relatively high interannual variation (Fig. 1, Fig. 2 *top*). These short-term fluctuations were superimposed by increasing trends in epilimnetic temperatures from January to August, yet these trends mostly were nonsignificant (Fig. 2 *bottom*). This warming tendency was reflected in anomalously high surface-water temperatures during some years of the past decade, including the highest annual means ever recorded since 1946 in the Müggelsee (Behrendt et al. 1987) and since 1960 in the Stechlinsee. Temperatures of the deep-water layers increased in the polymictic Müggelsee in particular, especially in the

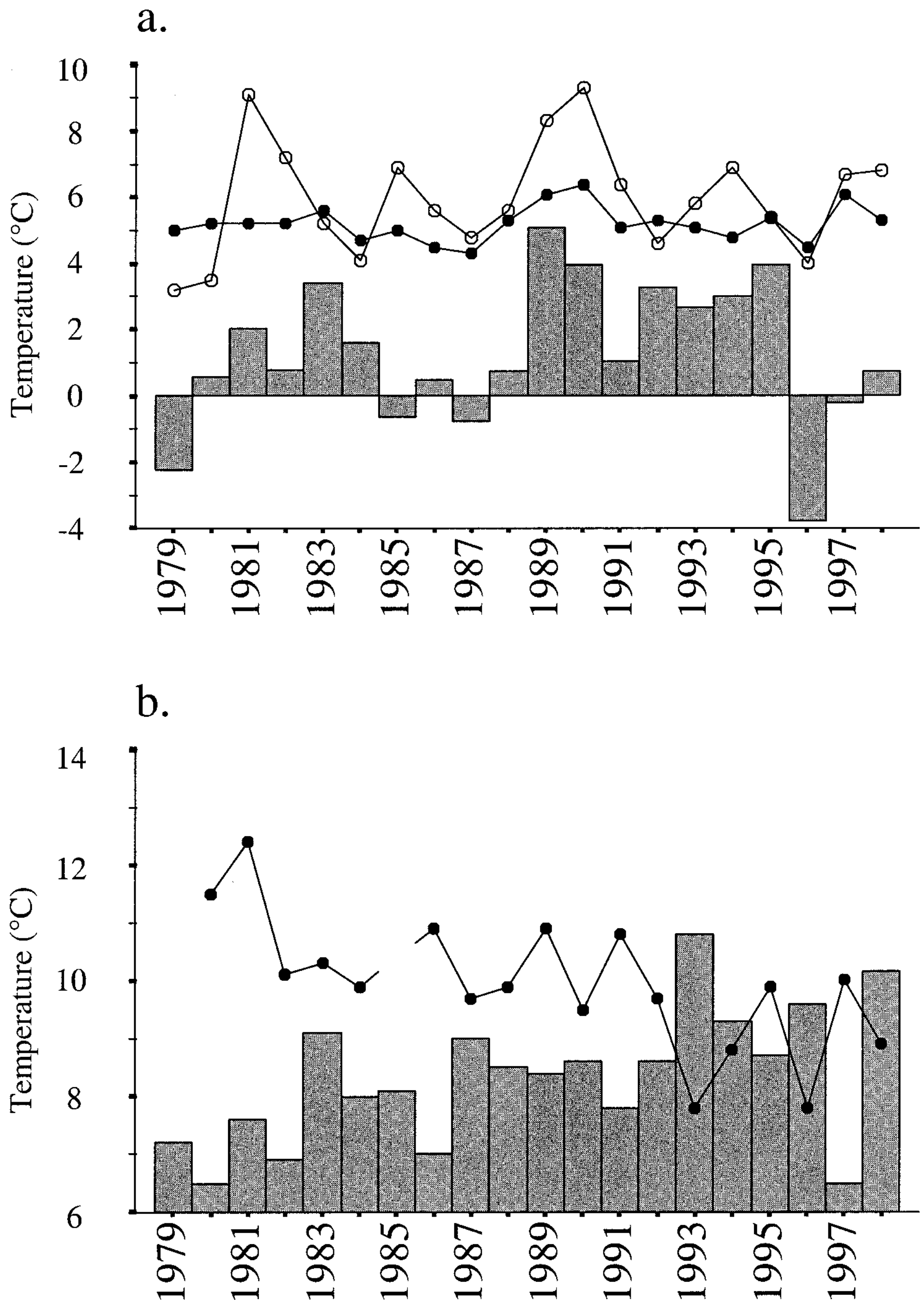

Fig. 1. Time series (1979–1998) of (a) the winter NAO index (bars) and water temperatures of the Müggelsee at a depth of 2 m in March (line with open circles) and of the Stechlinsee at a depth of 60 m in August (line with filled circles); (b) mean air temperature at Berlin-Schönefeld in April (bars) and water temperature in the Heiligensee at a depth of 7 m in August (line). Temperatures are in °C; the NAO index is dimensionless. There were no recordings of water temperature in the Heiligensee in 1979 and 1985.

first months of the year and in July (Fig. 2a *bottom*). In contrast, hypolimnetic temperatures in the Heiligensee decreased during the last two decades ($0.001 < P < 0.12$; Fig. 1b, Fig. 2b *bottom*). In the Stechlinsee, no significant trends of hypolimnetic temperatures occurred, yet there was a tendency toward warmer conditions, particularly in summer and autumn (Fig. 2c *bottom*).

Relationships between the NAO and climatic conditions—During the investigation period, monthly means of regional air temperature from December to March were significantly related to the winter NAO index and the respective monthly indices ($r > 0.52$, $P < 0.05$). Moreover, wind speed in the winter months was significantly correlated with the NAO indices ($r > 0.45$, $P < 0.05$), but global radiation was not

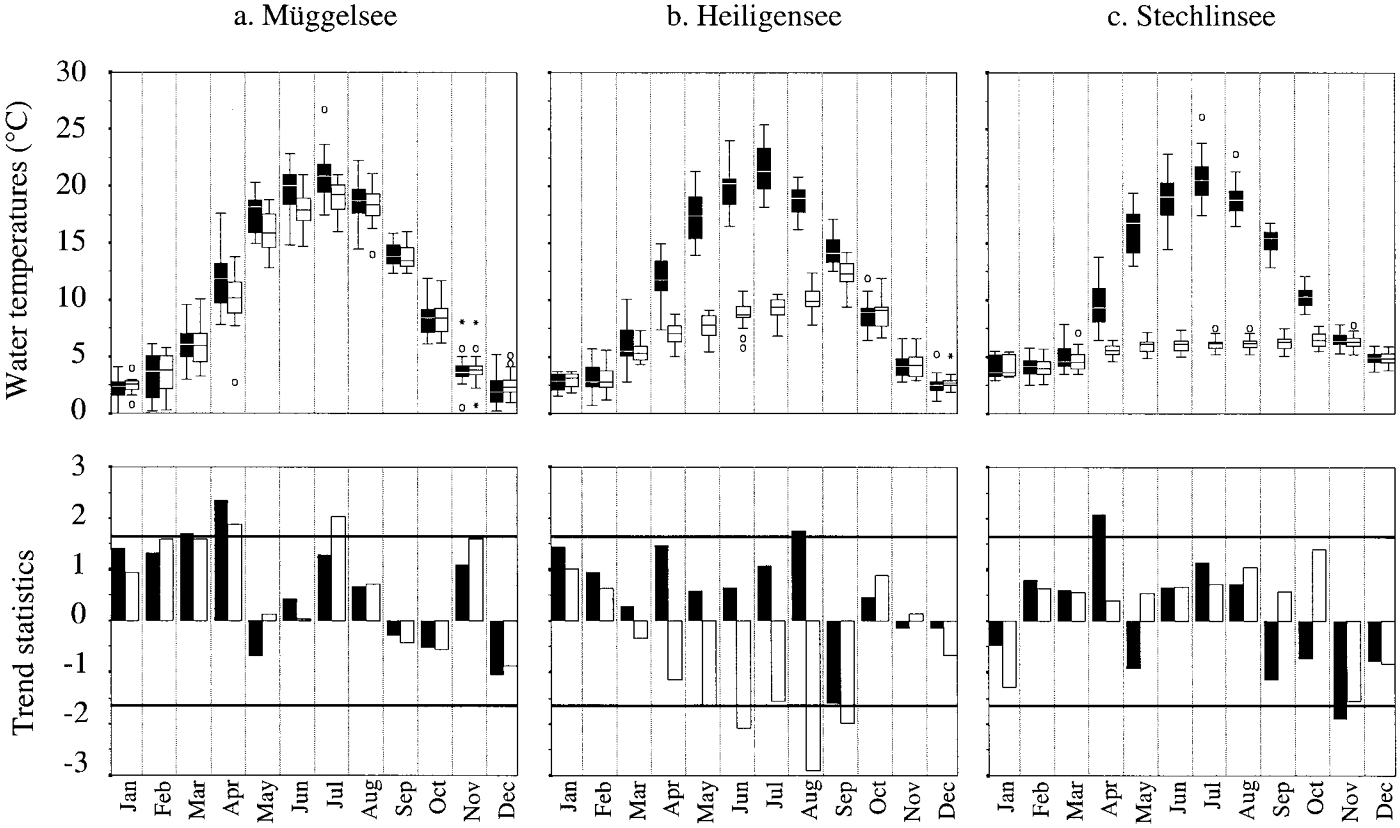

Fig. 2. Temporal characteristics of epilimnetic (black symbols) and hypolimnetic (white symbols) water temperatures of (a) Müggelsee, (b) Heiligensee, and (c) Stechlinsee, 1979–1998. The epilimnion refers herein to a depth of 2 m and the hypolimnion to a depth of 7 m (Stechlinsee: 60 m). *Upper panels:* Box-and-whisker plots of monthly temperatures (°C). *Lower panels:* Monthly test statistics of the Mann–Kendall trend test (standardized values). Thick horizontal lines represent the 90% significance levels.

($r < 0.23$, $P > 0.1$). Thus, the NAO index can be regarded as a surrogate for air temperature (and wind speed) in winter; therefore, we will not report correlations between water temperatures and winter air temperature here. No significant relationships existed between any NAO index and climatic conditions from April to November ($r < 0.3$, $P > 0.1$). Analogously, the warming tendency in spring and summer was also largely unrelated to the NAO ($P > 0.1$).

Relationships between the NAO and profile water temperatures—Year-round patterns in water temperature profiles showed substantial differences in their relationship with the winter NAO depending upon the lake type under examination. Monthly NAO indices from April to November generally did not significantly influence water temperatures at any time and will not be discussed further. Moreover, temperatures of the epilimnia (Müggelsee: of the entire water column) during the summer season (May–October) generally were not related to the NAO ($P > 0.1$) but to concurrent air temperature and solar radiation ($r > 0.45$, $P < 0.05$). Epilimnetic temperatures of the Stechlinsee were furthermore influenced by weather conditions of the preceding month, yet less significantly so ($P < 0.1$).

Müggelsee: The shallow, polymictic Müggelsee (Table 1; Fig. 2a *top*) exhibited only a short-term response to the winter NAO, as we observed significant correlations ($r > 0.46$, $P < 0.05$) between the NAO index and water temperature only from January to March (Figs. 1, 3a). Because of its low heat storage capacity, water temperature of the Müggelsee is strongly influenced by ambient weather conditions, and consequently, the NAO signal is soon masked by prevailing weather.

Heiligensee: In the shallow, dimictic Heiligensee (Table 1; Fig. 2b *top*), the situation was similar to the Müggelsee during the first months of the year, except that significant correlations with the winter NAO index occurred only in the uppermost 2 m of the water column ($r > 0.4$, $P < 0.1$; Fig. 3b). It is worth noting that the February NAO index, which was only marginally correlated with the winter index in 1979–1998 ($r = 0.38$, $P = 0.09$), explained much of the variance in water temperature at all depths in February/March ($r > 0.6$, $P < 0.01$). The significant winter NAO correlation persisted until April, including the period of spring turnover.

In spring, prevailing weather, which was largely unrelated to the NAO (Table 2), came into play as an additional factor

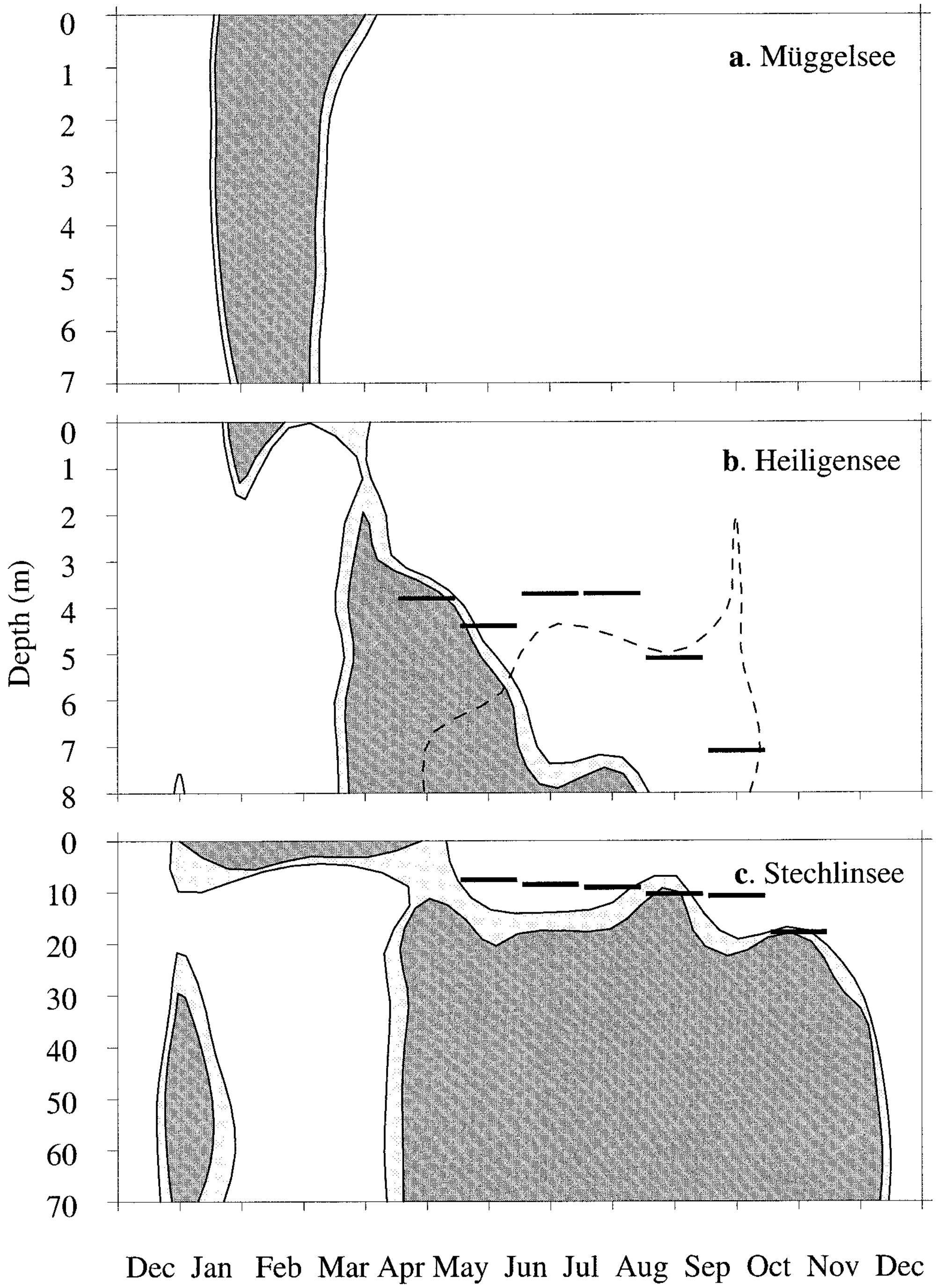

Fig. 3. Contour plots of significant positive Pearson correlations between the winter NAO index and monthly water temperatures of (a) shallow polymictic Müggelsee, (b) shallow dimictic Heiligensee, and (c) deep dimictic Stechlinsee, 1979–1998 ($P < 0.05$, dark shading; $0.05 < P < 0.1$, light shading). The dashed outline (Fig. 3b) additionally indicates significant negative correlations ($P < 0.05$) between mean air temperature in April and water temperatures of the Heiligensee. The thick horizontal lines represent the average locations of the thermoclines. The contour plots are drawn based on linear interpolation of the monthly correlation coefficients between the NAO (and April air temperature in Fig. 3b) and water temperatures at the first day of a month.

Table 2. Pearson correlation coefficients between the winter (December–March) NAO index, mean air temperature (AT_{Apr}), wind velocity (v_{Apr}), and global radiation (Rad_{Apr}) in April and mean hypolimnetic water temperature of the Heiligensee in May–September (WT_{sum}), based on the period 1980–1998 (exclusive of 1985). Asterisks denote correlations significant at $P < 0.05$. Series with a significant trend ($P < 0.05$, Mann–Kendall) are indicated by arrows (positive trend: ↑, negative trend: ↓) and were linearly detrended prior to correlation analysis.

	AT_{Apr} (°C)↑	v_{Apr} (m s^{-1})	Rad_{Apr} (J cm^{-2} d^{-1})	WT_{sum} (°C)↓
NAO index	0.04	0.42	−0.23	0.34
AT_{Apr}		−0.33	0.56*	−0.77*
v_{Apr}			−0.39	0.47*
Rad_{Apr}				−0.65*

determining temperatures in the deep-water layers in the Heiligensee. Specifically, hypolimnetic water temperatures throughout summer were significantly correlated with air temperature, wind speed, and solar radiation in April (Table 2; Fig. 3b). The influence of April weather coexisted with a significant effect of the NAO in the hypolimnion, though the latter successively diminished during summer (Fig. 3b). The short-term enhancement of the correlation with April conditions in October probably reflects the upward mixing of hypolimnetic water at times of the initiation of fall turnover.

To determine the relative importance of both the NAO and weather conditions in April, we split the investigation period into years with NAO indices and April air temperatures above or below their 18-yr means (NAO index ≤ 1.59, > 1.59; April temperature ≤ 8.4°C, > 8.4°C, respectively), and then checked the correlation pattern for these four subsets of years. As a result, we found that only for the subset of years with a warm April ($n = 11$) were hypolimnetic temperatures significantly correlated with the NAO index ($r > 0.6$, $P < 0.05$), whereas there was no such relationship for years with a cold April ($n = 7$, $P > 0.1$). The most probable explanation for this phenomenon is that in years with a cold month of April, the lake presumably stratified late in the season (around early May, *see* Adrian et al. 1995), when terminal lake temperature of spring turnover most likely was already independent of the NAO. In contrast, in years with fair weather in April (high solar income, high air temperature, low wind stress), stratification most likely established early (around mid-April) (i.e., at times when lake temperatures were still rather low and were probably influenced by the NAO [Fig. 3b; *see also* Hondzo and Stefan 1993]). Accordingly, as air temperature in April exhibited a pronounced rising trend during the investigation period, there was an associated cooling trend in the hypolimnion throughout summer (Table 2; Figs. 1, 2b, 3b). The NAO may have amplified this cooling in years with a cold winter (e.g., in 1987 and 1996, Fig. 1), but may have dampened it after mild winters (possibly in 1983 and 1994).

An explanation for the extinction of the NAO signal during summer (Fig. 3b) may be its absence in the hypolimnion in years with a cold April (*see above*), resulting in a dampening of the long-term correlation with water temperature. In addition, summer seasons (July/August) in the years with a warm April—when the NAO signal probably was present in the hypolimnion—often were rather windy and cool (e.g., in 1987, 1993, and 1998), possibly enhancing turbulent conduction of heat from the epilimnion into the hypolimnion (Wetzel 1983). Thus, the persistency of the NAO signal in the shallow dimictic Heiligensee seemed to be influenced by the superposition of weather conditions in April and midsummer, albeit our time series are not sufficiently long to clearly separate such effects.

Stechlinsee: The deep, dimictic Stechlinsee (Table 1; Fig. 2c *top*) was most responsive to the NAO. We observed a significant impact throughout the year, although it varied with depth (Fig. 3c). The NAO had an influence on water temperatures in the upper layers in winter and early spring and on the entire water column at times of spring turnover (April, early May). Similarly to the Heiligensee, the lack of significant correlations for the deeper water layers of the Stechlinsee in February/March can be attributed to the rather weak correlation between the February NAO index and the winter index. However, when we considered the longer time period, 1960–1998, there was a significant NAO signal (winter index) in the deep-water layers throughout most of the winter.

The warming in April had no significant effect on hypolimnetic water temperatures ($r < 0.19$, $P > 0.1$), most likely because the Stechlinsee generally does not stratify permanently before early May (Casper 1985), probably independently of the NAO. Due to the high heat-storage capacity, water temperature still was strongly related to the NAO at times of stratification onset (particularly in the lower water layers), leading to the transmission of the NAO signal into the hypolimnion (Fig. 3c). The NAO influence persisted within the hypolimnion until complete mixing had occurred by the end of the year. Accordingly, in high NAO years (e.g., 1989, 1990), hypolimnetic temperatures were up to 2°C higher than in low NAO years (e.g., 1996; Fig. 1a). Water temperatures in the hypolimnion throughout summer were also correlated with solar radiation in May ($r > 0.48$, $P < 0.05$), which thus may have modulated the NAO effect. The correlation pattern between the NAO and hypolimnetic water temperatures during summer was essentially the same as compared to the period 1960–1998.

Varying NAO responsiveness and its ecological implications—Our results are the first to demonstrate the broad range of lake responses to the NAO that occur among different lake types, even under identical climatic forcing. These pronounced differences in the response patterns became clear despite the rather coarse temporal resolution of the water temperature recordings. In addition to geographical position and regional climatic conditions, the influence of the NAO on lakes is no doubt coupled to morphological lake features and to the associated mixing regimes. Other factors (e.g., discharge of tributaries and transparency) may also play a role (Wetzel 1983). For example, the occurrence of high phytoplankton biomass in the upper water layers of eutrophic lakes (such as the Heiligensee) after mild winters (Adrian et al. 1995) may delay the onset of the stratification period because of reduced transparency. In dimictic lakes, the combination of these factors ultimately determines whether or not well-mixed lake temperatures just prior to the onset of stratification are influenced by the NAO and thus dictates whether this influence can persist in the hypolimnion. Consequently, the effect of the NAO is least pronounced in polymictic lakes and is most pronounced in deep dimictic lakes that are characterized by temporally coherent thermal structures. Lakes categorized between deep dimictic and shallow polymictic types may reveal intermediate responses, ranging from a persistent NAO influence in the hypolimnion to its immediate suppression by meteorological conditions in spring (Fig. 3). In very deep lakes that do not circulate fully each winter, one could even expect a positive NAO phase to contribute to multiannual deep-water warming (Livingstone 1993; Ambrosetti and Barbanti 1999; D. M. Livingstone pers. comm.).

Such pronounced differences in the responsiveness of seasonal water temperatures to the NAO, which in turn are of paramount importance to biological processes, have numerous implications for the ecology and water quality of freshwater ecosystems. Overall effects of the NAO on ice and temperature conditions in winter and early spring and on associated vernal algal development in small eutrophic lakes are already documented (Adrian et al. 1999; Weyhenmeyer et al. 1999; Straile and Adrian 2000). Effects on zooplankton in late spring (development of *Daphnia* and associated timing of the clearwater phase), however, seem to be restricted to large deep lakes (Straile 2000), whereas in polymictic systems, the NAO effect is soon overtaken by spring weather conditions (Gerten and Adrian 2000). Effects on growth, reproduction, and survival of organisms on higher trophic levels are likely as well (Magnuson et al. 1990), though explicit NAO impact studies on freshwater fish are lacking. As hypolimnetic temperatures of dimictic lakes are likely to respond to the NAO (Fig. 3b,c), indirect NAO effects on deep chlorophyll maxima (Gervais et al. 1997), on bacterial activity in deep water and sediments, and on hypolimnetic dissolved oxygen concentrations are also to be expected (Blumberg and Di Toro 1990).

Possible connections to climate change—Although the role of the NAO in the context of the overall climate change debate remains unclear (Paeth et al. 1999), our results suggest the nature of responses by a variety of lake types in a vast geographical region to greenhouse warming. The water temperature trends we observed (warming of all lakes in winter and early spring, cooling of the hypolimnion in the Heiligensee in summer; Fig. 1, Fig. 2 *bottom*) principally agree with projected epi- and hypolimnetic water temperatures in lakes of the temperate zone under climate-warming scenarios (Hondzo and Stefan 1993; Fang and Stefan 1999). However, the NAO-induced slight tendency toward a warmer hypolimnion in the deep Stechlinsee (Fig. 3c) was rather unexpected, as there is, to our knowledge, no such effect of a winter warming documented in the literature. Our results also suggest that a synchronous warming in both winter and spring might produce antagonistic responses of spring water temperatures in shallow dimictic lakes (Fig. 3b), and processes associated with hypolimnetic water temperature might thus not be affected by climate warming at all.

The fact that the NAO was in a quasi-persistent positive state during the investigation period (Hurrell 1995) may limit the overall validity of our findings, as the documented correlations may be different in a predominantly low NAO period. For the Stechlinsee, the correlation pattern between water temperatures and the NAO, including a low NAO phase in the 1960s (Hurrell and van Loon 1997), was basically the same for the past four decades compared to the period presented here, 1979–1998. However, this unchanging nature of the NAO–water temperature relationship does not necessarily apply to the Müggelsee or to the rather sensitive Heiligensee, in particular. Furthermore, it should be noted that the relationship between the NAO and regional air temperatures was nonstationary during the past 130 yr. For example, in the first half of the 20th century, the NAO influence on winter climate in Sweden was much weaker than during the following decades (Chen and Hellström 1999), whereas there may have been an opposite change in North America (Livingstone in press). Accordingly, NAO effects on water temperatures may have differed in these time periods compared to our findings for the two most recent decades.

Overall, the effects of the NAO on different lakes vary substantially within years, and these differences are coupled with interdecadal variability of the NAO–air temperature relationship. Projections of observed NAO effects for other lakes, or for future conditions, might thus lead to substantial misinterpretations of long-term climate–ecosystem linkages. Our findings contribute to a reduction of these uncertainties, and we would like to emphasize that aquatic ecologists should certainly be aware of the NAO as a possible control mechanism that influences the variability of ecological processes. Developing actual predictions, however, will depend upon understanding relationships among the NAO, local meteorological conditions, and the physical setting of an ecosystem under examination. Comparative, as well as hydrophysical modeling studies, for a larger geographical area are necessary to validate such expectations and would considerably improve the understanding of effects of large-scale climatic patterns and climate warming on aquatic ecosystems.

Dieter Gerten[1] *and Rita Adrian*

Institut für Gewässerökologie und Binnenfischerei
Müggelseedamm 260
D-12587 Berlin
Germany

---

[1] Corresponding author (gerten@igb-berlin.de).

Acknowledgments

This paper is dedicated to the late T. M. Frost. We thank Rüdiger Biskupek, Wolfgang Dohle, Thomas Hintze, Peter Lederer, Günter Schellenberger, and Bernd Schütze for water temperature recordings in the Müggelsee and the Heiligensee. Secchi depth readings from the Stechlinsee were kindly provided by Rainer Koschel. Climatic data and water temperatures of the Stechlinsee were provided by the Deutscher Wetterdienst. The manuscript benefited from critical readings by Tom Frost, Georgi Kirillin, Norbert Walz, and two

References

Adrian, R., R. Deneke, U. Mischke, R. Stellmacher, and P. Lederer. 1995. A long-term study of the Heiligensee (1975–1992). Evidence for effects of climatic change on the dynamics of eutrophied lake ecosystems. Arch. Hydrobiol. **133:** 315–337.

———, N. Walz, T. Hintze, S. Hoeg, and R. Rusche. 1999. Effects of ice duration on the plankton succession during spring in a shallow polymictic lake. Freshw. Biol. **41:** 621–632.

Ambrosetti, W., and L. Barbanti. 1999. Deep water warming in lakes: An indicator of climatic change. J. Limnol. **58:** 1–9.

Barber, R. T., and F. P. Chavez. 1983. Biological consequences of El Niño. Science **222:** 1203–1210.

Beamish, R. J., D. J. Noakes, G. A. McFarlane, L. Klyashtorin, V. V. Ivanov, and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. Can. J. Fish. Aquat. Sci. **56:** 516–526.

Behrendt, H., R. Stellmacher, and M. Olberg. 1987. Long-term changes in water quality parameters of a shallow eutrophic lake and their relations to meteorologic and hydrologic elements, p. 535–544. *In* S. I. Solomon, M. Beran, and W. Hogg [eds.], The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS Publication 168.

Blumberg, A. F., and D. M. Di Toro. 1990. Effects of climate warming on dissolved oxygen concentrations in Lake Erie. Trans. Am. Fish. Soc. **119:** 210–223.

Casper, P., and R. Koschel. 1995. Description of Lake Stechlin. Limnologica **25:** 281–284.

Casper, S. J. [ed.]. 1985. Lake Stechlin—a temperate oligotrophic lake. Monographiae Biologiae 58.

Chen, D., and C. Hellström. 1999. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: Spatial and temporal variations. Tellus **51A:** 505–516.

Driescher, E., H. Behrendt, G. Schellenberger, and R. Stellmacher. 1993. Lake Müggelsee and its environment—natural conditions and anthropogenic impacts. Int. Rev. Gesamten Hydrobiol. **78:** 327–343.

Fang, X., and H. G. Stefan. 1999. Projections of climate change effects on water temperature characteristics of small lakes in the contiguous U.S. Clim. Chang. **42:** 377–412.

Fromentin, J.-M., N. C. Stenseth, J. Gjøsæter, T. Johannessen, and B. Planque. 1998. Long-term fluctuations in cod and pollack along the Norwegian Skagerrak coast. Mar. Ecol. Prog. Ser. **162:** 265–278.

George, D. G., and A. H. Taylor. 1995. UK lake plankton and the Gulf Stream. Nature **378:** 139.

———, J. F. Talling, and E. Rigg. 2000. Factors influencing the temporal coherence of five lakes in the English Lake District. Freshw. Biol. **43:** 449–461.

Gerten, D., and R. Adrian. 2000. Climate-driven changes of spring phytoplankton dynamics and the sensitivity of shallow polymictic lakes to the North Atlantic Oscillation. Limnol. Oceanogr. **45:** 1058–1066.

Gervais, F., J. Padisák, and R. Koschel. 1997. Do light quality and low nutrient concentration favour picocyanobacteria below the thermocline of the oligotrophic Lake Stechlin? J. Plankton Res. **19:** 771–781.

Hondzo, M., and H. G. Stefan. 1993. Regional water temperature characteristics of lakes subjected to climate change. Clim. Chang. **24:** 187–211.

Hurrell, J. W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science **269:** 676–679.

———, and H. van Loon. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. Clim. Chang. **36:** 301–326.

Livingstone, D. M. 1993. Temporal structure in the deep-water temperature of four Swiss lakes: A short-term climatic change indicator? Verh. Int. Ver. Limnol. **25:** 75–81.

———. In press. Large-scale climatic forcing detected in historical observations of lake ice break-up. Verh. Int. Ver. Limnol.

Magnuson, J. J., J. D. Meisner, and D. K. Hill. 1990. Potential changes in the thermal habitat of Great Lakes fish after global climate warming. Trans. Am. Fish. Soc. **119:** 254–264.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteorol. Soc. **78:** 1069–1079.

Paeth, H., A. Hense, R. Glowienka-Hense, R. Voss, and U. Cubasch. 1999. The North Atlantic Oscillation as an indicator for greenhouse-gas induced regional climate change. Clim. Dyn. **15:** 953–960.

Post, E., R. O. Peterson, N. C. Stenseth, and B. E. McLaren. 1999. Ecosystem consequences of wolf behavioural response to climate. Nature **401:** 905–907.

Shuter, B. J., D. A. Schlesinger, and A. P. Zimmerman. 1983. Empirical predictors of annual surface water temperature cycles in North American lakes. Can. J. Fish. Aquat. Sci. **40:** 1838–1845.

Sneyers, R. 1975. Sur l’analyse statistique des séries d’observations. WMO Note Technique 143, Geneva.

Straile, D. 2000. Meteorological forcing of plankton dynamics in a large and deep continental European lake. Oecologia **122:** 44–50.

———, and R. Adrian. 2000. The North Atlantic Oscillation and plankton dynamics in two European lakes—two variations on a general theme. Glob. Chang. Biol. **6:** 663–670.

Wei, W. W. S. 1990. Time series analysis. Addison-Wesley.

Wetzel, R. G. 1983. Limnology, 2nd ed. Harcourt Brace College Publ.

Weyhenmeyer, G., T. Blenckner, and K. Pettersson. 1999. Changes of the plankton spring outburst related to the North Atlantic Oscillation. Limnol. Oceanogr. **44:** 1788–1792.

Received: 24 July 2000
Accepted: 6 November 2000
Amended: 14 November 2000

---

anonymous reviewers. The study was funded by the Deutsche Forschungsgemeinschaft and benefited from cooperation with the European Union project REFLECT.