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Twenty years of spatially coherent deepwater warming in lakes across Europe related to the North Atlantic Oscillation

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Abstract

Twenty to fifty years of annual mean deepwater (hypolimnetic) temperature data from twelve deep lakes spaced across Europe (2°95′W to 14°0′E, 46°27′ to 59°00′N) show a high degree of coherence among lakes, particularly within geographic regions. Hypolimnetic temperatures vary between years but increased consistently in all lakes by about 0.1–0.2°C per decade. The observed increase was related to the weather generated by large-scale climatic processes over the Atlantic. To be effective, the climatic signal from the North Atlantic Oscillation (NAO) must affect deep lakes in spring before the onset of thermal stratification. The most consistent predictor of hypolimnetic temperature is the mean NAO index for January–May ($\mathrm{NAO}_{\mathrm{J-M}}$), which explains 22–63% of the interannual variation in deepwater temperature in 10 of the 12 lakes. The two exceptions are remote, less wind-exposed alpine valley lakes. In four of the deepest lakes, the climate signal fades with depth. The projected hypolimnetic temperature increase of approximately 1°C in 100 yr, obtained using a conservative approach, seems small. Effects on mixing conditions, thermal stability, or the replenishment of oxygen to deep waters result in accumulation of nutrients, which in turn will affect the trophic status and the food web.

Acknowledgments

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Deep lakes are widely regarded as sensitive monitors of the changing climate (George et al. 1998). Analyses are typically based on long-term studies of ice cover, surface temperature, and mixing regimes (Robertson 1989; Livingstone and Dokulil 2001; Salmaso et al. 2003) in temperate lakes, glacial, and high-latitude systems (Magnuson et al. 2000; Quayle et al. 2002). More recently, temperature increase in deep, hypolimnetic water has been detected as an indicator for climate warming in both freshwaters (Ambrosetti and Barbanti 1999; Straile et al. 2003*a*) and oceanic systems (Fukasawa et al. 2004) with strong ecological consequences.

Lakes in the Northern Hemisphere, particularly in Europe, are strongly influenced by the North Atlantic Oscillation (NAO) (Blenckner and Chen 2003). The NAO is an index describing patterns of atmospheric pressure gradients that develop over the North Atlantic, especially during boreal winter (Hurrell et al. 2001). Effects of weather conditions generated by the NAO are well established for surface water temperature and mixing (Gerten and Adrian 2003). Effects on hypolimnetic temperatures have been reported from Switzerland, Italy, France (Livingstone 1993; Guilbaud 2003; Salmaso et al. 2003), and Africa (Verburg et al. 2003). Deep, hypolimnetic lake waters are particularly good places to look for effects of climate signals because the deep strata are homogenous and should maintain a more or less constant temperature. It can be hypothesized that positive deviations of deepwater temperature (DWT) are likely to be the result of influences by the NAO. Testing this hypothesis requires long-term data from DWT measurements.

Study lakes, data, and statistics

The analyses are based on deepwater, hypolimnetic temperatures acquired over the last two to five decades from twelve deep lakes distributed throughout Europe from 2°95′W to 14°0′E and 46°27′ to 59°00′N (Fig. 1). Nine of the twelve lakes are located in the perialpine region. The lakes cover a wide range of size, depth, and water volume (Table 1). Temperature observations dating back to 1848 are analyzed for three lakes in Austria by Dokulil et al. (2006).

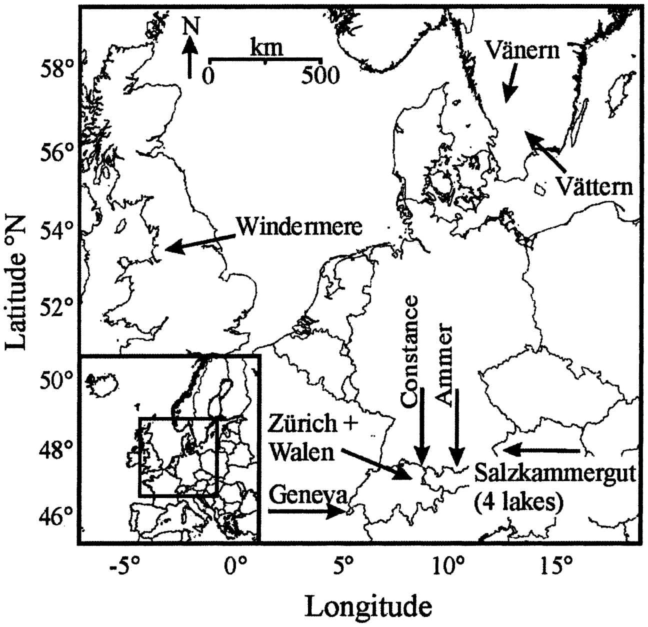

Fig. 1. Map of Europe with the geographical position of the lakes investigated.

Data are extracted from temperature profiles taken either by conventional sampling strategies using water samplers with built-in thermometers calibrated in °C or from thermistor readings. Information for the Swedish lakes Vänern and Vättern originates from http://www.ma.slu.se. All other data were supplied by the authors. Data sets differ in observational length, the longest beginning in 1947 (Windermere, UK), the shortest starting in 1984 (Ammersee, Germany). Sampling intervals among the 12 lakes varied between weekly (Windermere, UK) and monthly (Swedish lakes), but were in general biweekly. All data were quality controlled by calculating first the annual average plus standard deviation from the raw data and then removing values outside two standard deviations.

Table 1. Name, abbreviation, country, position, and morphometry of the 12 European deep lakes arranged by their geographical position from west to east keeping countries together. $z_{\max}$ = maximum depth, z_{avg} = average depth, T_w = retention time.

Lake	Country	Geographical position	Altitude (m)	Area (km^2)	$z_{\max}$ (m)	z_{avg} (m)	Volume (106 m^3)	T_w (yr)	Catchement area (km^2)
Windermere, WNB	GB	54°35′ N 02°95′ W	39.0	14.76	64.0	21.3	315	0.8	230.50
L. Geneva, LL	CH/F	46°27′ N 06°32′ E	372.0	582.0	309.0	152	89,000	1.4	7395.00
Zürichsee, LZ	CH/F	47°20′ N 08°35′ E	406.0	67.0	140.0	49	29	1.2	1740.00
Walensee, WS	CH/F	47°10′ N 09°15′ E	419.0	24.0	151.0	105	25	1.4	1061.00
L. Constance, LC	A/CH/D	47°39′ N 09°18′ E	395.0	472.0	253.0	101	47,600	4.2	11890.00
Ammersee; AM	D	48°00′ N 11°20′ E	523.9	46.61	81.1	37.6	1,750	2.7	993.90
Vänern, LVN	S	59°00′ N 13°00′ E	44.55	5,650.00	106.0	27	153,000	9.0	46830.00
Vättern, LVT	S	58°50′ N 14°00′ E	88.51	1,890.00	120.0	40	77,600	8.0	6359.00
Mondsee, MO	A	47°48′ N 13°24′ E	481.0	14.21	68.3	36	510	1.7	247.00
Attersee, AS	A	47°48′ N 13°30′ E	469.2	45.9	170.6	84.2	3,945	7.0	463.50
Hallstättersee, HS	A	47°36′ N 13°42′ E	508.0	8.58	125.2	64.9	557	0.5	646.50
Traunsee, TS	A	47°53′ N 13°48′ E	422.0	25.6	191.0	89.7	2,302	1.0	1417.00

Annual volume-weighted averages were then calculated depthwise from the corrected data sets. To show and test that trends in DWT are consistent within each lake, three depths are analyzed, except for Lake Vänern and Windermere, where measurements from only one depth (60 m) were available.

Weekly data for Windermere were grouped into five 10-week periods that provided the best measures of seasonal change. Trend analysis of these five periods indicates the greatest slope of data regression versus time for period one (Q1), the first 10 weeks of the year.

All data are tested for normality (Kolmogorov–Smirnov), constant variance, and power when performing regression analysis of DWT against time. Robustness is tested using Mann–Kendall's tau (SPSS 10) and calculation of median trend lines. Slopes and intercepts thus obtained did not significantly deviate from conventional analysis. Following suggestions by Yue and Wang (2002), prewhitening to eliminate influences of serial correlation on the Mann–Kendall test has not been applied.

Coherence (synchrony) between lakes (Baines et al. 2000) is calculated from the corrected data sets for the period 1980–2003 using Pearson product moment correlation as suggested by Magnuson (SigmaStat 3.1). Calculation of coherence and correlation to the NAO is based on data from 100 m or the greatest depth available when lakes are less than 100 m deep.

Values for the simple NAO index are obtained from http://www.cru.uea.ac.uk. This index is based on the difference of normalized sea level pressure between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland. Besides the traditional NAO winter index (December–February), several monthly indices and combinations of them were tested including November, December of the previous year, and January to June. DWT correlates with the winter index in a few lakes only (e.g., Lake Geneva). The most consistent and robust relation was obtained using an averaged index for January to May $NAO_{J–M}$, which was therefore applied to all lakes. Repeated calculations using multistation NAO indices based on principal component analysis (PC-based NAO, http://www.cgd.ucar.edu/cas/jhurrell/indices.info.html) gave identical results with smaller r^2 values. As a further test, temperature data were standardized, linearly detrended over time, and the residuals related to the detrended NAO residuals. Results deviate marginally from those obtained with the raw data.

Time sequence

Annual mean DWT data for the 12 lakes are plotted against time in Fig. 2, covering periods between 20 and 55 yr. Considerable interannual and site-specific variability is observed in these time series. Regression lines show a consistent trend of increasing DWT at all sites, which is significant in lakes deeper than 120 m (Table 2). Slopes vary from 0.004 to 0.044, indicating differences in magnitude of warming. In Windermere, the slope is 0.015 and significant during Q1, showing the importance of the winter period for the temperature increase (Table 2). A rise of 0.1°C to 0.2°C per decade can be deduced from the majority of the temperature gradients, closely resembling the warming rate of 0.15°C per decade in Lake Tahoe and 0.2°C per decade in Lake Washington in North America (Arhonditsis et al. 2004; Coats et al. 2006).

Regional coherence

Correlation between sites (Table 3) indicates considerable coherence among time series with a higher degree of synchrony within geographic regions such as the two lakes in Sweden, the lakes in the Austrian Salzkammergut district, and the Alpine lakes in Germany and Switzerland (Table 3). The prealpine Ammersee (AM) is more closely related to lakes in the western Alps than to lakes elsewhere. Lakes with maximum depth greater than 100 m (Table 1) are spatially coherent over longer distances (Table 3), e.g., Zürichsee (LZ) with the two lakes in Sweden (LVN, LVT) and the two deepest lakes in Austria, Attersee (AS) and Traunsee (TS). Similarly, the moderately deep Windermere (WNB) is synchronized across Europe among other lakes with Mondsee (MO), a lake similar in size and depth.

Influence of the NAO

Macroscale atmospheric phenomena such as the NAO, the Pacific Decadal Oscillation, or the El Nino Southern Oscillation are increasingly recognized as regulating forces in aquatic and terrestrial ecosystems (Marshall et al. 2001; Arhonditsis et al. 2004). The spatial coherence of DWT across Europe suggests teleconnection to large-scale climatic processes that seem to be more important than regional weather conditions (Hallett et al. 2004). To affect DWT, the climate signal must penetrate into deeper layers before the onset of temperature stratification in summer. This aspect is supported by the significant increase in DWT for the first 10-week period in Windermere (WNB Q1, Fig. 2 and Table 2). The optimal time window obviously is then the phase of spring overturn when lakes mix completely, but the timing of the influential signal might vary depending on the geographic location, size, depth, and presence or absence of ice cover. Applying a number of different NAO indices to the 12 European lakes for the time window 1984–2003, the mean NAO index for January to May ($NAO_{J–M}$) proved as the best and most robust signal for the entire data set. As indicated by the coefficient of determination (Fig. 3; Table 4), the $NAO_{J–M}$ explains 22–63% of the interannual variation of DWT in 10 of the 12 lakes. Exceptions are Walensee and Hallstättersee, which show no statistically significant relation. The timing and the mixing conditions are different in these two remote, less wind-exposed alpine valley lakes. Hallstättersee, a N-S-orientated fjord-type lake, receives on average 5 h less sunshine than other lakes in the region. Water temperatures, mixing conditions, and ice duration vary because of the short, erratic retention time (Dokulil 2004). These conditions are also reflected in the weak relation of lake surface temperature to winter NAO (Livingstone and Dokulil 2001) and a low inter-regional coherence (Table 3). Other factors such as oligotrophication seem to override

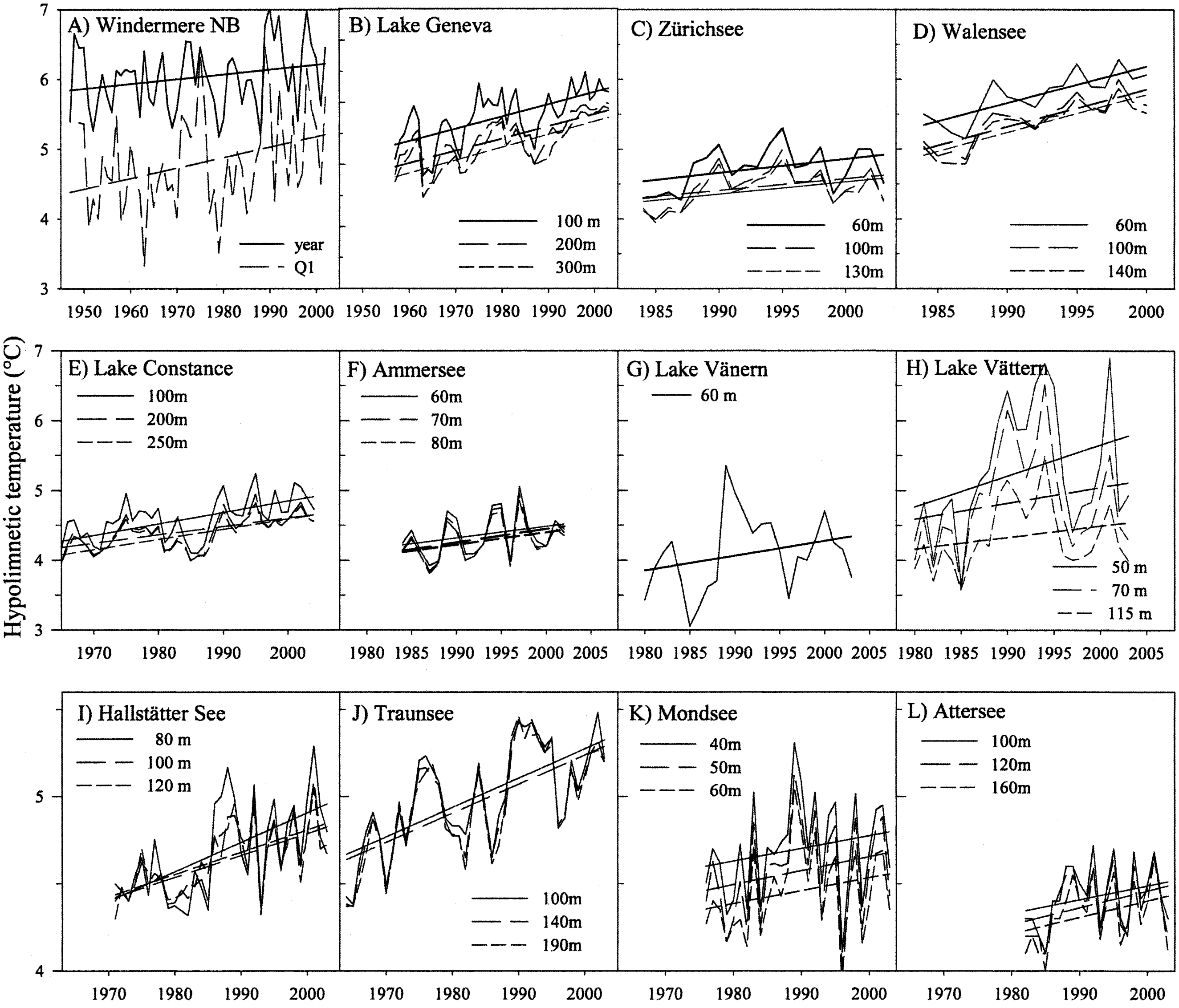

Fig. 2. Time series and regression lines for annual average deepwater temperatures. (A) Windermere North Basin 60 m and the first 10-week period (Q1), (B) Lake Geneva, (C) Zürichsee, (D) Walensee, (E) Lake Constance, (F) Ammersee, (G) Lake Vänern, (H) Lake Vättern, (I) Hallstättersee, (J) Traunsee, (K) Mondsee, and (L) Attersee for the depths indicated.

climate signals in Walensee, similar to what has been concluded in a phytoplankton study (Anneville et al. 2004).

All available information supports the conclusion that climate variability has a statistically significant effect on DWT and can explain the observed increase over the time window analyzed. Milder and warmer-than-usual spring periods associated with positive NAO_{J-M} increase DWT, whereas cold weather during spring expressed as negative NAO_{J-M} index depresses temperatures in the hypolimnion. The primary mechanism transmitting the signal of spring NAO to DWT are the conditions during spring turnover. Mixing of the water column during this period is of paramount importance for the hypolimnetic temperatures during the rest of the year. Atmospheric coupling of the lake heat content via air temperature to the mesoscale climate (Livingstone 1993) is largely responsible for the correlation of DWT to the NAO. Mixing conditions, landscape topography, and lake morphometry determine the persistence of the climate signal with time and depth. As a result, the strength of the signal decreases with depth in several of the lakes investigated, especially in the two deepest lakes, Lake Geneva and Lake Constance, but it is also noticeable in Traunsee and Mondsee (Fig. 4). Similar observations have been made in the oceans (Barnett et al. 2005). Parts of the structure of the deepwater time series, however, remains specific to the particular lake under consideration and can not be directly related to atmospheric forcing. Changes in trophic status influencing stability or time lag in reaction deserve mentioning (Livingstone 1993; Straile et al. 2003*a*,*b*).

In 12 lakes across Europe, we have shown that DWT increased by 0.1–0.2°C per decade mediated by mesoscale atmospheric forcing. Although the temperature increase might be considered small (approx. 1°C in 100 yr using

Table 2. Regression parameters, coefficient of variance, *F* and *p* statistics for the trend lines in Fig. 2. Bold letters indicate significant positive trends versus time. All data are tested for normality (Kolmogorov–Smirnov), constant variance, and power.

Lake	Period	Depth (m)	Intercept	Slope	R^2	*F*	*P*	*n*
WNB Ann	1947–2002	60	−7.57	0.007	0.06	3.308	0.075	56
WNB Q1		60	−24.84	0.015	**0.12**	7.157	0.010	
LL	1960–2003	100	−33.34	0.020	**0.43**	33.267	<0.001	47
		200	−33.63	0.020	**0.54**	53.372	<0.001	
		300	−36.13	0.021	**0.58**	61.063	<0.001	
LZ	1944–2002	60	−8.92	0.007	**0.19**	13.030	<0.001	59
		100	−5.64	0.005	**0.17**	11.825	0.001	
		130	−4.27	0.004	**0.16**	10.419	0.002	
WS	1974–2002	60	−18.72	0.017	**0.19**	5.771	0.024	27
		100	−29.98	0.018	**0.22**	7.037	0.014	
		140	−34.00	0.020	**0.23**	6.784	0.016	
LC	1963–2002	100	−28.18	0.017	**0.39**	25.587	<0.001	42
		200	−19.44	0.012	**0.34**	20.837	<0.001	
		250	−24.49	0.014	**0.49**	39.096	<0.001	
AM	1984–2002	60	−28.90	0.017	0.09	1.622	0.220	19
		70	−34.24	0.019	0.13	2.432	0.137	
		80	−30.87	0.017	0.12	2.330	0.145	
LVN	1980–2003	30	−24.57	0.016	0.02	0.390	0.539	24
		70	−24.13	0.015	0.02	0.476	0.497	
LVT	1980–2004	50	−83.00	0.044	0.12	3.043	0.095	24
		70	−40.938	0.023	0.05	1.175	0.290	
		115	−28.420	0.017	0.06	1.376	0.253	
MO	1978–2003	40	−9.99	0.007	0.07	1.289	0.267	28
		50	−11.41	0.008	0.06	1.617	0.215	
		60	−10.23	0.007	0.06	0.888	0.355	
AS	1968–2003	100	−20.63	0.013	**0.37**	14.168	<0.001	26
		120	−15.86	0.010	**0.29**	9.774	0.005	
		160	−17.73	0.011	**0.37**	14.066	<0.001	
HS	1971–2003	80	−28.91	0.017	**0.35**	16.945	<0.001	33
		100	−20.46	0.013	**0.38**	18.994	<0.001	
		120	−20.79	0.013	**0.41**	21.924	<0.001	
TS	1964–2003	100	−28.44	0.017	**0.47**	28.025	<0.001	39
		140	−28.15	0.017	**0.47**	27.970	<0.001	
		190	−28.64	0.017	**0.44**	24.824	<0.001	

a conservative approach), mixing conditions, thermal stability, or oxygen concentration will be affected. Reduced winter cooling in Lake Constance during high NAO winters resulted in incomplete mixing, lack of oxygen replenishment, and accumulation of nutrients in the hypolimnion (Straile et al. 2003). Similar effects were observed in Zürichsee and Lake Bourget (Livingstone 1993; Guilbaud 2003). Sharper density gradients and slowed

Table 3. Coherence (synchrony) between deepwater lake temperatures expressed as Pearson product moment correlation. Lakes abbreviated as in Table 1. Bold numbers indicate significant correlation at $p < 0.05$, underlined numbers are significant at $p < 0.10$. All data (n =24, 1980–2003) were tested for normality (Kolmogorov–Smirnov) and robustness (Mann–Kendall Test).

	LL	LZ	WS	LC	AM	LVN	LVT	MO	AS	HS	TS
WNB	0.21	0.38	0.31	0.27	0.35	**0.63**	**0.44**	**0.44**	0.36	0.24	**0.45**
LL		**0.60***	**0.85***	**0.79***	**0.58***	0.31	0.21	−0.01	0.33	0.15	0.35
LZ			**0.79***	**0.86***	**0.56***	**0.52**	**0.54**	0.29	**0.58**	0.38	**0.72**
WS				**0.89***	**0.49***	**0.45**	0.23	0.07	**0.50**	0.28	**0.54**
LC					**0.51***	**0.53**	**0.46**	0.12	**0.49**	0.30	**0.71**
AM						0.38†	0.28	0.30	0.35	0.17	0.38
LVN							**0.66**†	**0.44**	**0.49**	0.29	**0.69**
LVT								0.37	**0.64**	0.14	**0.50**
MO									**0.74**‡	**0.67**‡	**0.42**‡
AS										**0.85**‡	**0.55**‡
HS											**0.44**‡

Coherent lake regions are: * Switzerland/Germany, † Sweden, ‡ Austria.

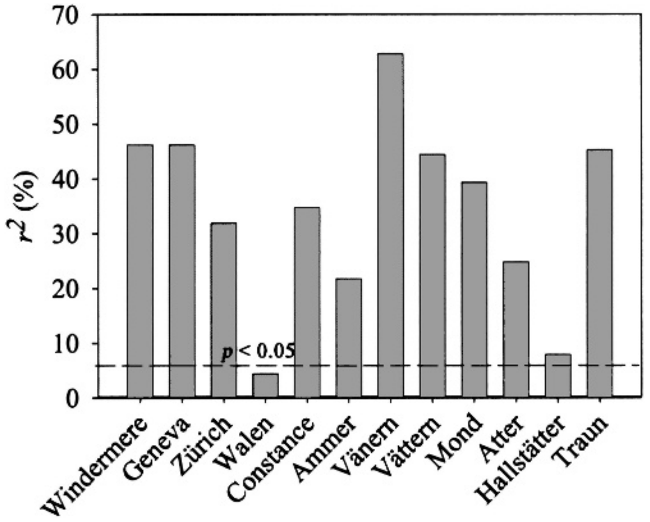

Fig. 3. Coefficients of determination (r^2) between the mean NAO index for January–May ($NAO_{J–M}$) and the deepwater temperatures of the 12 European lakes, depths, and the period given in Table 4.

Table 4. Dependence of annual average deepwater temperatures (°C) on the North Atlantic Oscillation (NAO) as mean index for January to May ($NAO_{J–M}$) of each year for the period 1984–2003 ($n = 20$). Significant correlation is indicated in bold.

Lake	Depth (m)	r^2	F	p
WNB	60	**0.46**	15.458	**<0.001**
LL	100	**0.46**	15.458	**<0.001**
LZ	100	**0.32**	8.428	**0.009**
WS	100	0.04	0.830	0.374
LC	100	**0.35**	9.551	**0.006**
AM	80	**0.22**	5.003	**0.038**
LVN	70	**0.63**	30.334	**<0.001**
LVT	115	**0.44**	14.389	**0.001**
MO	60	**0.39**	11.649	**0.003**
AS	100	**0.25**	5.922	**0.026**
HS	100	0.08	1.552	0.229
TS	100	**0.45**	14.829	**0.001**

vertical mixing influenced the trophic status and the food web in two Italian prealpine lakes south of the Alps (Salmaso et al. 2003). In Lake Tanganijka reduced primary productivity was observed as a consequence of reduced mixing (Verburg et al. 2003). In North America, greater resistance against mixing and increased stability during stratification including biological responses was reported from Lake Washington and Lake Tahoe (Arhonditsis et al. 2004; Coats et al. 2006). The extent to which lakes are affected largely depends on the lake type. Frequently circulating polymictic lakes are least influenced, whereas deep dimictic lakes with stable summer stratification preserve the NAO signal (Gerten and Adrian 2003). The implication of this study suggests that society has seriously to consider warming of freshwater ecosystems and must develop strategies against water quality impairment.

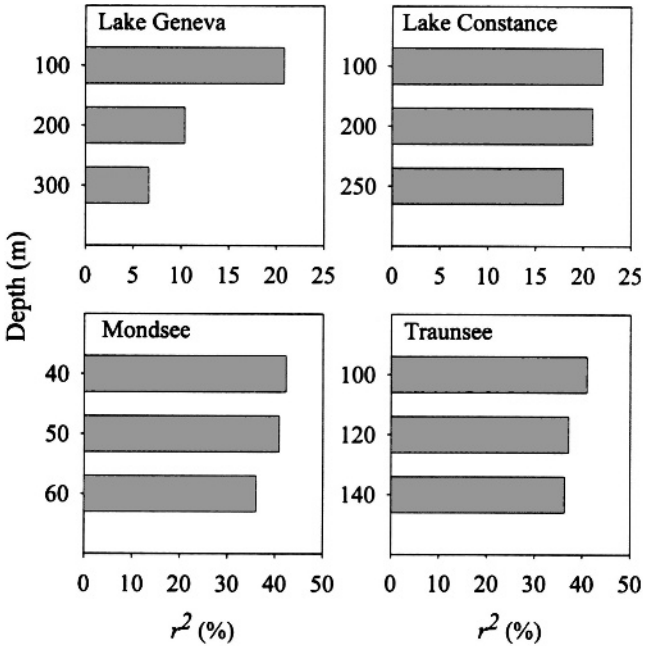

Fig. 4. Coefficient of determination (r^2) between $NAO_{J–M}$ and deepwater temperatures at different depths for four European lakes.

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