Limnol. Oceanogr., 49(4), 2004, 1191–1201

Synchrony in relationships between the North Atlantic Oscillation and water chemistry among Sweden's largest lakes

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Abstract

The North Atlantic Oscillation (NAO) is commonly presented as an easy and reliable index that can be used to study climatic effects on aquatic ecosystems. Here, the NAO winter index (NAO_W) was applied to determine effects of winter climate changes on 13 water chemical variables measured monthly at 16 sites in Sweden's three largest lakes (Vänern, Vättern, and Mälaren). The NAO_W strongly affected meteorological, physical, and consequently also chemical conditions. Significant relationships were numerous in Sweden's three largest lakes, but they exhibited little agreement among lakes and even across a lake. Synchronous relationships between the NAO_W and water chemistry among lake sites were restricted to variables closely linked to surface-water temperature (i.e., reactive silica and pH in May). The weaker the association of a lake variable with water temperature, the weaker the mean NAO_W signal on the variable over the 16 lake sites. The results of this study might facilitate the prediction of lake ecosystem responses to future changes in the weather over a large region.

Aquatic ecosystems are essential contributors to biodiversity and ecological productivity, and they provide a variety of services for human populations. They are exposed to land-use changes, environmental pollution, water diversion, and, as has been much discussed lately, climatic changes. Climatic changes are expected to increasingly stress aquatic ecosystems (e.g., De Stasio et al. 1996; Schindler 2001). In many European countries, it has been observed that especially the winter climate is subjected to changes (IPCC 2001). Milder European winters have been associated with anomalies in the North Atlantic Oscillation (NAO) (Hurrell 1995). The NAO represents a large-scale fluctuation in the air pressure difference between the subtropical Azores High and the subpolar Icelandic Low, the two dominant centers of meteorological activity over the North Atlantic. The NAO is usually expressed as an index based on the air pressure differences between the two centers of meteorological activity. Over the last three decades, the phase of the NAO has been shifting from mostly negative to mostly positive index values (Visbeck et al. 2001), resulting in mild, rainy, and windy winters in West and Northern Europe. Compared to common meteorological variables, the NAO has the advantage that it is presented as an easy, reliable, and to some extent predictable index that can be used to identify simultaneous changes in the water quality of a variety of aquatic ecosystems as a response to variations in a large-scale climatic process.

Studies in aquatic ecosystems have shown that the NAO clearly affects lake physics such as water temperature (e.g., George et al. 2000; Gerten and Adrian 2001; Livingstone and Dokulil 2001), lake ice break-up (Livingstone 1999, 2000; Weyhenmeyer et al. 1999), and runoff (Kiely 1999; Hänninen et al. 2000; Bradley and Ormerod 2001). Physical lake conditions can either have a direct impact on water chemistry or they can influence biological processes, which then affect the water chemistry. Numerous studies are available in which NAO effects on freshwater physics and biology have been described (see references in Gerten and Adrian 2002; Straile et al. 2003*b*). In contrast, to date only very few studies have been published in which relationships between the NAO and freshwater chemistry have been established. Published studies (e.g., Monteith et al. 2000; Evans et al. 2001; George 2002) deal mainly with freshwaters in the United Kingdom, where the NAO is known to have a strong influence on meteorological conditions (Davies et al. 1997; Osborn et al. 2000). An exception is the study of Straile et al. (2003*a*); Straile et al. found a relationship between the NAO and physicochemical conditions in Lake Constance in Central Europe. In the United Kingdom, Monteith et al. (2000) observed that nitrate–nitrogen concentrations in March had a strong negative correlation to the North Atlantic Oscillation winter index (NAO_W) in nine lakes and six streams. They explained the negative correlation with increased nitrogen leaching from the catchment after cold winters when the ground starts to thaw. Nutrient leaching processes from the catchment during winter and spring were also named by George (2002) to explain observed relationships between the NAO_W and winter concentrations of dissolved reactive phosphorus in Blelham Tarn, a small, productive lake in the United Kingdom. Apart from Monteith et al. (2000) and George (2002), Evans et al. (2001) found that concentrations of chloride and other marine-derived ions, which have a strong impact on surface-water concen-

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Acknowledgments

This study was partly financed by the European Commission's Environmental and Sustainable Development Program under contracts ENV4-CT97-0453 (REFLECT) and EVK1-CT-2002-00121 (CLIME). I am grateful to everyone at the Department of Environmental Assessment, Swedish University of Agricultural Sciences, who has been involved in sampling and analyzing lake physical, chemical, and biological data. I am also thankful to the Swedish Meteorological and Hydrological Institute, which provided me with ice and meteorological data. Special thanks go to Kevin Bishop, Anders Wilander, Lars Sonesten, Martin Weih, and two reviewers for stimulating comments on the manuscript.

trations of cations with nonmarine sources, followed an approximately decadal cycle at lake sites in North Wales, the Lake District, and Galloway, located at the west coast of the United Kingdom. They suggested that this cycle is in phase with the NAO_W.

Published information about NAO effects on water chemistry is slightly more common for marine studies. Such studies deal with the influence of the NAO on nutrient concentrations, mainly nitrogen. It has been suggested that marine nutrients are affected by changing mixing/upwelling and runoff processes that can be related to the NAO, in particular to the NAO_W (e.g., Lindahl et al. 1998; Hagberg and Tunberg 2000; Williams et al. 2000; Oschlies 2001).

The lack of information about the impact of the NAO on freshwater chemistry might just be a coincidence or it might be that linear relationships between the NAO and freshwater chemistry are restricted to only a few freshwater ecosystems and to certain times of the year. Here I hypothesize that NAO signals on lake water chemistry differ among lakes and lake sites with regard to time and intensity. I suggest that synchrony in the relationships between the NAO and water chemistry is restricted to certain types of variables and to certain times of the year. To test the hypothesis, I carried out linear regressions of the NAO winter index on 13 water chemical variables at 16 sites in Sweden's three largest lakes, Vänern, Vättern, and Mälaren, for each ice-free month from 1981 to 1995.

Study sites and data collection

Lakes Vänern, Vättern, and Mälaren are Sweden's three largest lakes. Water samples have frequently been taken at three stations in Lake Vänern (since 1973), two stations in Lake Vättern (since 1966), and 11 stations in Lake Mälaren (since 1965) (Fig. 1). Sampling has been conducted in the middle of each month during the main growing season from May to October (i.e., ice-out period). In Lake Mälaren, additional water samples have been collected below the ice cover in March. From the national data set of monthly monitoring, data on water temperature and 13 water chemical variables (Table 1) in surface waters (0.5 m) have been used in this study. Only data from 1981 onward have been considered, because all three lakes were subjected to drastic reductions in the loading of phosphorus from the catchment areas in the late 1960s and very early 1970s. It was only at the beginning of the 1980s that phosphorus concentrations in the three lakes stabilized after these reductions (Wilander and Persson 2001). Data after 1995 have also been removed for this study because after 1995, the sampling frequency decreased and different laboratories have been involved in the analyses. The remaining time period of 1981–1995 was regarded to be very suitable for this study, not only because sampling in all three lakes and analyses of all water chemical variables have been carried out by one and the same laboratory, but also because of the completeness of the data. Only very few individual data are missing, and whenever more than one data point was missing for a regression, the regression was not considered (very few cases, indicated in the figures). For more information about the monitoring program in Sweden's largest lakes, see Willén (2001).

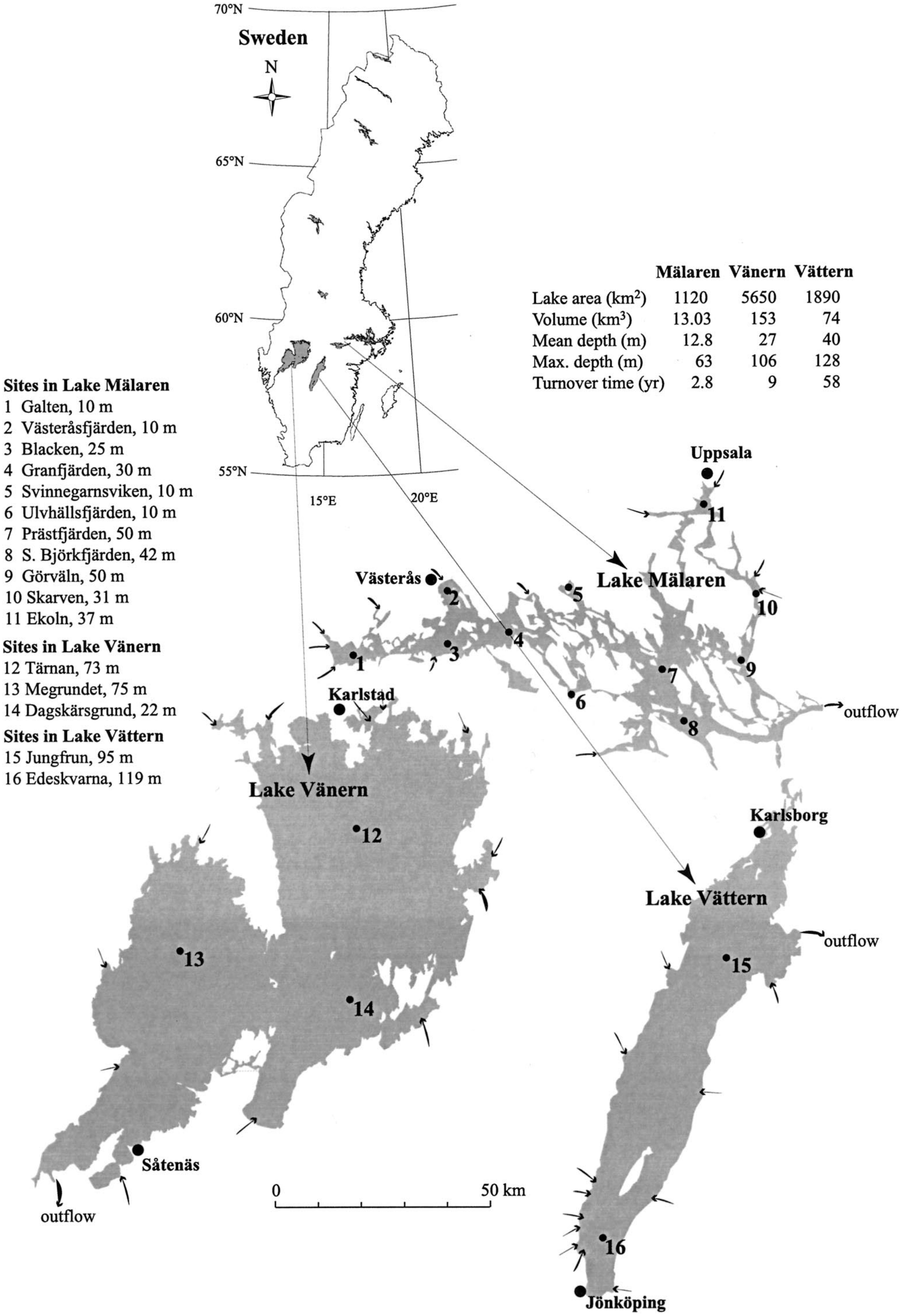
In addition to lake water chemistry data, data on phytoplankton, meteorology, and catchment character were obtained from the Galten basin in Lake Mälaren. The Galten basin was chosen because it is located close to a meteorological station, it is the shallowest of all sites (mean depth: 3.4 m; maximum depth: 19 m), and it has the strongest influence of inflow waters (water turnover time: 0.07 yr). Consequently, it is expected that the response of this basin to changes in meteorological conditions is immediate and predictable.

The Swedish Meteorological and Hydrological Institute provided air temperature data from six meteorological stations close to the lakes Vänern, Vättern, and Mälaren (Fig. 1) for the time period extending from 1981 to 1995. In addition, they sent data on solar irradiation, precipitation, snow depth, and wind velocity measured at the western part of Lake Mälaren at Västerås (Fig. 1), data on the date of ice break-up in the central part of Lake Mälaren, data on the water level of Lake Mälaren, and data on the water discharge of the main inflow waters from the Galten basin (Köpingsån, Hedströmmen, and Arbogaån). The loading of phosphate–phosphorus, nitrate–nitrogen, ammonium–nitrogen, reactive silica, and total phosphorus from Köpingsån, Hedströmmen, and Arbogaån was calculated with data from the national data set of monthly monitoring by multiplying the measured nutrient concentrations in the inflow waters by the water discharge.

Data from the commonly used NAO winter (December through March) index (NAO_W) were taken from the homepage of the National Center for Atmospheric Research (United States; http://www.cgd.ucar.edu/~jhurrell/nao.html). The values of this index differ slightly from those of the well-known winter index of Hurrell (1995) because of continual updates to the data and a change in the base period. The sea-level pressure anomalies at each station were normalized relative to a 120-yr period (1864–1983), while Hurrell (1995) normalized relative to the period extending from 1864 to 1994. Analyses in this study are restricted to the NAO_W. Other NAO indices are available, but the NAO_W is known to usually have the most consistent influence on meteorological conditions, since it accounts for more than 30% of the total variance in the pressure field over the Atlantic (Wallace and Gutzler 1981; Barnston and Livezey 1987). Therefore, most studies, including this study, refer to the NAO_W. The NAO_W is based on data from December through March; thus, winter in this study was defined as the time period extending from December through March.

Methods

The study is based on linear regression analyses. One thousand three hundred twenty-three regressions have been carried out in which the NAO_W was related to monthly data of 13 water chemical variables in surface waters from 16 stations in lakes Vänern, Vättern, and Mälaren from 1981 to 1995. At least 5% of these 1,323 regressions must be regarded as significant ($P < 0.05$) by pure chance for stochastic reasons. Rice (1989) described a sequential Bonferroni correction procedure to control this problem. A



	Mälaren	Vänern	Vättern
Lake area (km^2)	1120	5650	1890
Volume (km^3)	13.03	153	74
Mean depth (m)	12.8	27	40
Max. depth (m)	63	106	128
Turnover time (yr)	2.8	9	58

Sites in Lake Mälaren
1 Galten, 10 m
2 Västeråsfjärden, 10 m
3 Blacken, 25 m
4 Granfjärden, 30 m
5 Svinnegarnsviken, 10 m
6 Ulvhällsfjärden, 10 m
7 Prästfjärden, 50 m
8 S. Björkfjärden, 42 m
9 Görväln, 50 m
10 Skarven, 31 m
11 Ekoln, 37 m

Sites in Lake Vänern
12 Tärnan, 73 m
13 Megrundet, 75 m
14 Dagskärsgrund, 22 m

Sites in Lake Vättern
15 Jungfrun, 95 m
16 Edeskvarna, 119 m

Fig. 1. Sampling sites in the lakes Mälaren, Vänern, and Vättern; locations of main inflow waters and outflow (indicated by arrows); lake morphometric data; and locations of six meteorological stations at the lakes.

consequent Bonferroni correction in this study, however, would decrease the *P* value to 0.00004, which is inappropriate when we take into consideration that only 15 data points (1981–1995) have been included in each regression. It was regarded as more reasonable to adjust the *P* value separately for the number of regressions that have been carried out for each water chemical variable at each lake site (i.e., seven regressions [March, May–October]). Dividing the 0.05 *P* value by seven regressions gives an adjusted *P* value of 0.007. The adjusted *P* value is used as the least significance level. According to this correction procedure, the significance level of 0.01 before correction decreases to 0.001

Table 1. List of lake water variables used in this study and their abbreviations. Given are ranges (10 and 90 percentiles) of monthly data (March, May to October) from surface water (0.5 m) at 16 lake sites in lakes Mälaren, Vänern, and Vättern from 1981 to 1995.

	Secchi depth (m)	Water temperature (°C)	Oxygen (O_2) (mg L^{-1})	pH	Conductivity (mS m^{-1})	Alkalinity (mEq L^{-1})	Ammonium–nitrogen (NH_4) (μg L^{-1})	Nitrate–nitrogen (NO_2) (μg L^{-1})	Total nitrogen (μg L^{-1})	Phosphate–phosphorus (PO_4) (μg L^{-1})	Total phosphorus (μg L^{-1})	Lake water color† ($f_{420/5}$)	Reactive silica (mg L^{-1})	Chlorophyll (mg m^{-3})
Galten	0.6–1.2	0.9–19.3	8.2–11.9	6.9–7.9	8.0–12.0	0.2–0.4	9–87	11–501	621–1,185	5–20	31–67	0.07–0.17	0.2–3.1	3.3–32.9
Västeråsfjärden	0.8–1.3	0.9–19.8	7.9–12.1	7.1–7.9	13.0–15.8	0.4–0.5	17–193	214–796	887–1,654	6–26	35–65	0.06–0.16	0.2–2.6	3.9–32.6
Blacken	0.9–1.9	0.6–18.4	8.1–12.0	7.0–7.7	11.4–14.3	0.3–0.5	8–36	223–622	736–1,188	4–20	24–49	0.06–0.14	0.3–2.4	2.7–16.8
Granfjärden	1.0–1.8	0.9–19.0	7.9–12.4	7.2–7.9	13.1–15.4	0.4–0.5	8–22	169–594	689–1,175	5–22	24–48	0.05–0.11	0.2–2.1	2.2–18.1
Svinnegarnsviken	0.8–1.8	1.1–19.1	8.4–12.8	7.3–8.4	15.2–18.5	0.5–0.7	7–45	42–603	673–1,366	4–22	28–54	0.04–0.10	0.2–1.7	4.0–31.4
Ulvhällsfjärden	1.1–1.7	4.4–19.8	8.0–12.5	7.3–8.1	13.9–16.4	0.4–0.6	10–102	63–540	720–1,197	4–20	29–54	0.05–0.10	0.1–1.8	5.1–25.5
Prästfjärden	1.9–3.8	0.8–18.2	8.5–13.0	7.5–8.1	15.4–18.1	0.6–0.7	5–25	103–399	535–856	3–20	17–43	0.03–0.07	0.1–0.8	1.3–9.5
S. Björkfjärden	2.2–3.9	0.9–19.1	8.6–13.2	7.5–8.4	15.5–18.1	0.6–0.7	4–24	88–322	501–795	2–18	15–33	0.03–0.06	0.1–0.7	1.2–9.0
Görväln	2.0–3.5	1.3–19.0	8.2–13.3	7.7–8.6	19.3–24.7	0.8–1.0	4–29	42–402	515–942	3–20	19–39	0.03–0.06	0.2–1.1	2.4–16.3
Skarven	1.2–2.7	1.2–19.5	7.9–12.0	7.7–8.8	31.4–39.3	1.8–2.1	5–30	223–1,231	912–2,006	5–47	30–73	0.06–0.13	1.5–4.2	1.2–41.4
Ekoln	0.9–2.5	1.3–19.0	7.9–11.6	7.7–8.5	30.6–39.3	2.0–2.2	6–45	711–1,508	1,456–2,370	6–51	31–81	0.08–0.16	1.4–4.3	0.9–23.1
Tärnan	4.1–5.8	3.8–17.5	9.2–12.9	7.2–7.5	9.0–9.7	0.2–0.2	5–20	505–580	774–913	1–3	7–12	0.03–0.05	0.3–0.5	0.9–2.9
Megrundet	4.3–5.5	4.6–17.2	9.3–13.1	7.2–7.5	8.8–9.5	0.2–0.2	5–20	495–582	768–887	1–3	7–12	0.02–0.04	0.2–0.4	1.0–3.0
Dagskärsgrund	3.8–5.2	6.5–18.2	9.4–12.6	7.3–7.5	9.0–10.0	0.2–0.3	4–16	504–597	770–932	1–3	7–12	0.03–0.05	0.2–0.5	1.3–3.1
Jungfrun	9.0–12.4	3.7–16.9	9.4–13.3	7.4–7.8	12.7–13.8	0.5–0.5	4–18	382–512	610–718	1–4	4–9	0.01–0.01	0.2–0.4	0.6–1.4
Edeskvarna	9.0–12.5	3.5–16.2	10.0–13.1	7.5–7.8	12.7–13.7	0.5–0.5	4–18	386–505	634–741	1–3	4–8	0.01–0.01	0.2–0.4	0.5–1.4

* Nitrate–nitrogen includes nitrite–nitrogen, which is less than 5% of the sum of nitrate + nitrite–nitrogen (Wilander pers. comm.).

† Lake color has been measured as light absorption at 420 mm of 0.45 μm filtered water in a 5-cm cuvette.

Table 2. Linear regressions of the North Atlantic Oscillation winter index (NAO_W) on monthly surface water temperatures (March to October) at 16 sites in the lakes Mälaren, Vänern, and Vättern from 1981 to 1995. Given are r^2 values. The P value was corrected for multiple comparisons according to the correction procedure described in the Methods section. ** Indicates $P<0.001$, * $P<0.007$, and — indicates no available data*

Lake site	Mar	Apr	May
Galten	0.46*	—	0.22
Västeråsfjärden	0.46*	—	0.12
Blacken	0.37	—	0.43
Granfjärden	0.45*	—	0.06
Svinnegarnsviken	0.34	—	0.14
Ulvhällsfjärden	—	—	0.32
Prästfjärden	0.24	—	0.36
S. Björkfjärden	0.15	—	0.49*
Görväln	0.18	—	0.37
Skarven	0.44*	—	0.12
Ekoln	0.38	—	0.15
Tärnan	—	—	0.48
Megrundet	—	—	0.50*
Dagskärgrund	—	—	0.31
Jungfrun	—	—	0.63**
Edeskvarna	—	—	0.63**

* No significant relationships ($P>0.007$).

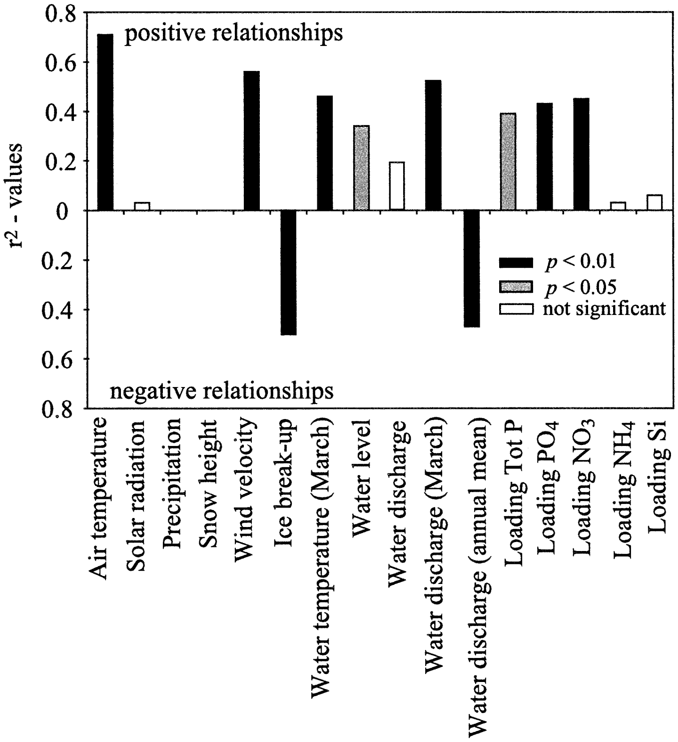


Fig. 2. Linear regressions of the North Atlantic Oscillation winter index (NAO_W) on five meteorological variables measured at Västerås, six lake physical variables of the Galten basin in Lake Mälaren, and five variables that are a measure of the nutrient loading (total phosphorus, phosphate–phosphorus, nitrate–nitrogen, ammonium–nitrogen, and reactive silica) from inflow waters into the Galten basin. If no information is given, variables represent mean winter (December through March) values from 1981 to 1995.

after correction. To address the problem of chance occurrences even further, the focus in this study was on regressions that were significant for the majority of the lake sites at the same time of the year and not on individual significant regressions.

In addition to the above regressions, 854 regressions were conducted to test when and which meteorological and lake physical variables have a significant impact on 13 water chemical variables. Here, the same correction procedure described above was again applied. The correction procedure was also used for relationships between the NAO_W and monthly data of air temperature and surface-water temperature at the 16 lake sites. All statistical tests, including the Jackknife distance method for detecting outliers, were performed in the JMP programme, version 5.0 (SAS Institute, Inc. 2002).

Quite a few data in this study might not be fully independent as they belong to the same water body. This can cause problems, especially in Lake Mälaren, in which case data from 11 sites are considered. However, Lake Mälaren consists of several basins that are hydrologically independent (e.g., water from the western basins, such as Galten, never mixes with water from the northern basins, such as Ekoln or Skarven) (Fig. 1). Consequently, data from the northern basins can be seen as independent of the data from the western basins. Thus, the focus in this study is on regressions that are significant for both the western and the northern basins of Lake Mälaren.

Results

The NAO_W and local meteorological/lake physical conditions — Winter mean air temperatures (December to March) at six meteorological sites close to lakes Mälaren, Vänern, and Vättern (Fig. 1) were all strongly related to NAO_W ($r^2 \geq 0.68$, $P < 0.001$, $n = 15$ for each of the six regressions). The strongest relationships between the NAO_W and air temperatures could be found at Lake Vättern ($r^2 \geq 0.74$, $P < 0.001$, $n = 15$). After winter in April, only air temperatures at Karlstad (Lake Vänern) still showed a relationship to the NAO_W ($r^2 = 0.44$, $P < 0.007$, $n = 15$). No NAO_W effect on air temperature was apparent at the lakes in any of the following months of the year.

In addition, water temperatures in the three lakes were related to the NAO_W. The NAO_W signal on surface-water temperature was observed when the lake sites were more or less ice free (i.e., in March at Mälaren's sites Galten, Västeråsfjärden, Blacken, Granfjärden, Svinnegarnsviken, Skarven, and Ekoln and in May at Mälaren's deep and central sites Prästfjärden, S. Björkfjärden, and Görväln) (Table 2). In the very deep lakes Vänern and Vättern, no measurements of water temperatures were available in March, but water temperatures in May were clearly related to the NAO_W. The strongest relationships between water temperatures and the NAO_W were found in Lake Vättern (Table 2). At this lake, winter air temperatures were also most strongly related to the NAO_W. Differences in the NAO_W signal on May surface-water temperatures among lake sites could well be explained

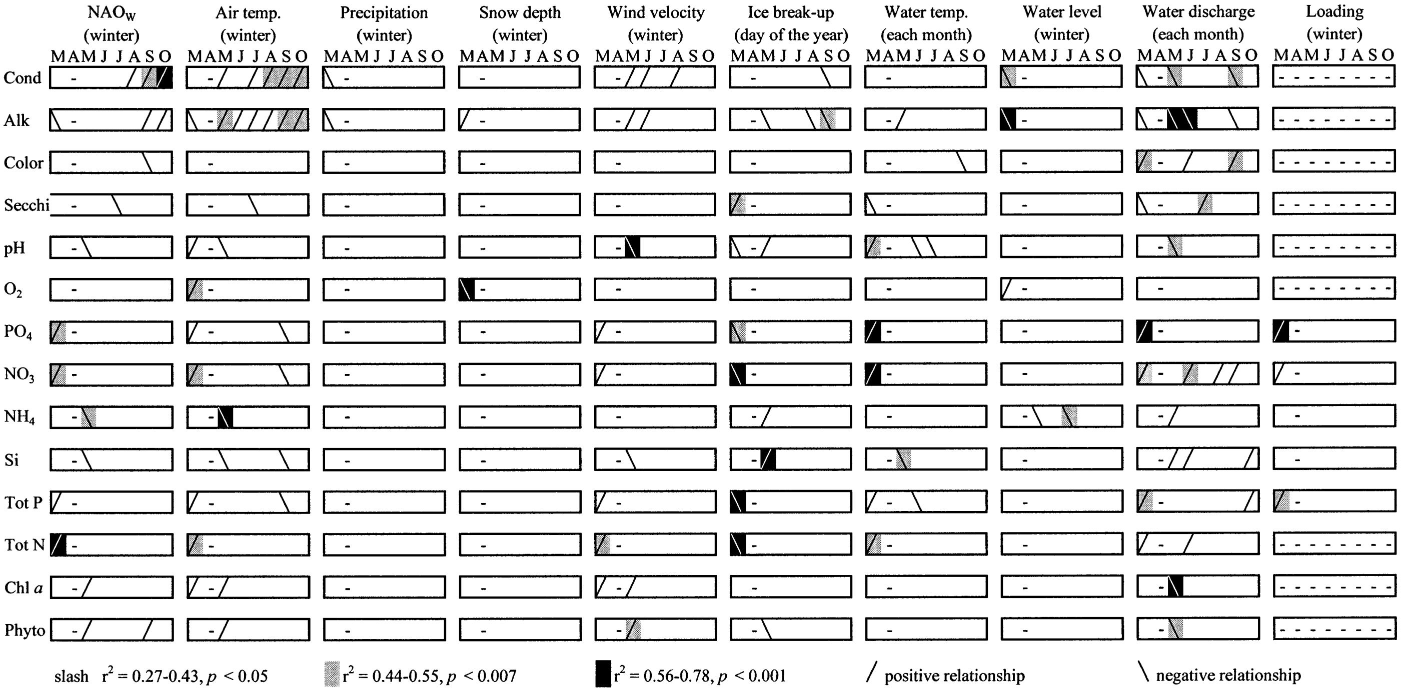


Fig. 3. Linear regressions of the North Atlantic Oscillation winter index (NAO$_W$), four meteorological variables measured at Västerås, and five lake physical variables of the Galten basin in Lake Mälaren on 13 water chemical variables in surface waters of the Galten basin in the period March to October from 1981 to 1995. Except for water temperature and water discharge, all meteorological and lake physical variables are mean winter values. Water temperature and water discharge are taken from the month for which a regression has been carried out. Loading means the winter loading of nutrients from inflow waters into the Galten basin. The loading of total phosphorus was related to total phosphorus in the lake water, the loading of phosphate–phosphorus to phosphate–phosphorus in the lake water, etc. Gray and black boxes indicate that regressions remain significant after a correction of the *P* value (for correction procedure, *see* Methods), empty boxes reflect nonsignificant regressions ($P > 0.05$), and short lines are a symbol for missing data. For abbreviations, *see* Table 1.

by lake morphometry, as the significance in the relationship between the NAO$_W$ and May surface-water temperatures (Table 2) decreased with decreasing water depth at the lake sites (from 10 m at Västeråsfjärden to 119 m at Edeskvarna; $r^2 = 0.62$, $P < 0.001$, $n = 16$ lake sites). Despite the large morphometric differences among the lake sites (Fig. 1), surface-water temperatures in May showed a high coherence among the sites (mean Pearson product-moment correlation coefficient for the 120 pairs of the 16 lake sites: $r = 0.70$). After May, no significant relationship between the NAO$_W$ and surface-water temperatures could be established (*P* values were > 0.007).

Apart from air and water temperatures, lake ice break-up, snow depth, winter wind velocities, and winter water level were related to the NAO$_W$ (Fig. 2). In contrast, winter solar irradiation and winter precipitation at Västerås did not show any relationship to the NAO$_W$, and neither did the water discharge of inflow waters into the Galten basin of Lake Mälaren during winter (Fig. 2). However, the water discharge in March was related to the NAO$_W$. This kind of relationship was positive. whereas the relationship between the NAO$_W$ and the yearly mean water discharge was negative (Fig. 2). A slightly positive trend of the NAO$_W$ during the period extending from 1981 to 1995 goes along with a negative trend of the yearly mean water discharge during that period. De-trending the two time series by a linear function still reveals a relationship between the NAO$_W$ and the yearly mean water discharge ($r^2 = 0.38$, $P < 0.01$, $n = 15$). In contrast, the NAO$_W$ was not related to the amount of yearly precipitation. Of all meteorological and physical lake variables investigated, water discharge showed the most and strongest relationships to water chemistry (Fig. 3). Water discharge strongly affected conductivity, alkalinity, and water color throughout the year as well as nitrate–nitrogen, phosphate–phosphorus, and total phosphorus concentrations in March. After correction of the *P* value, no direct relationships could be established between water discharge and concentrations of reactive silica, ammonium–nitrogen, total nitrogen, and oxygen. Reactive silica and ammonium–nitrogen concentrations in the Galten basin were not even related to loading processes in the catchment (Fig. 3).

Relationships between the NAO$_W$ and water chemistry—Relationships between the NAO$_W$ and individual water chemical variable were numerous (Fig. 4), but at least 165 of the 1,323 regressions were considered significant ($P < 0.05$) only by pure chance for stochastic reasons (*see* Methods). The remaining 69 significant regressions (Fig. 4) were still subjected to chance occurrence, but a few consistent patterns became apparent. The fewest relationships between the NAO$_W$ and water chemistry were found at lake sites in the deep Lake Vättern. In addition, lake sites in the large Lake Vänern showed only a few relationships, whereas most relationships were observed at lake sites in Lake Mälaren.

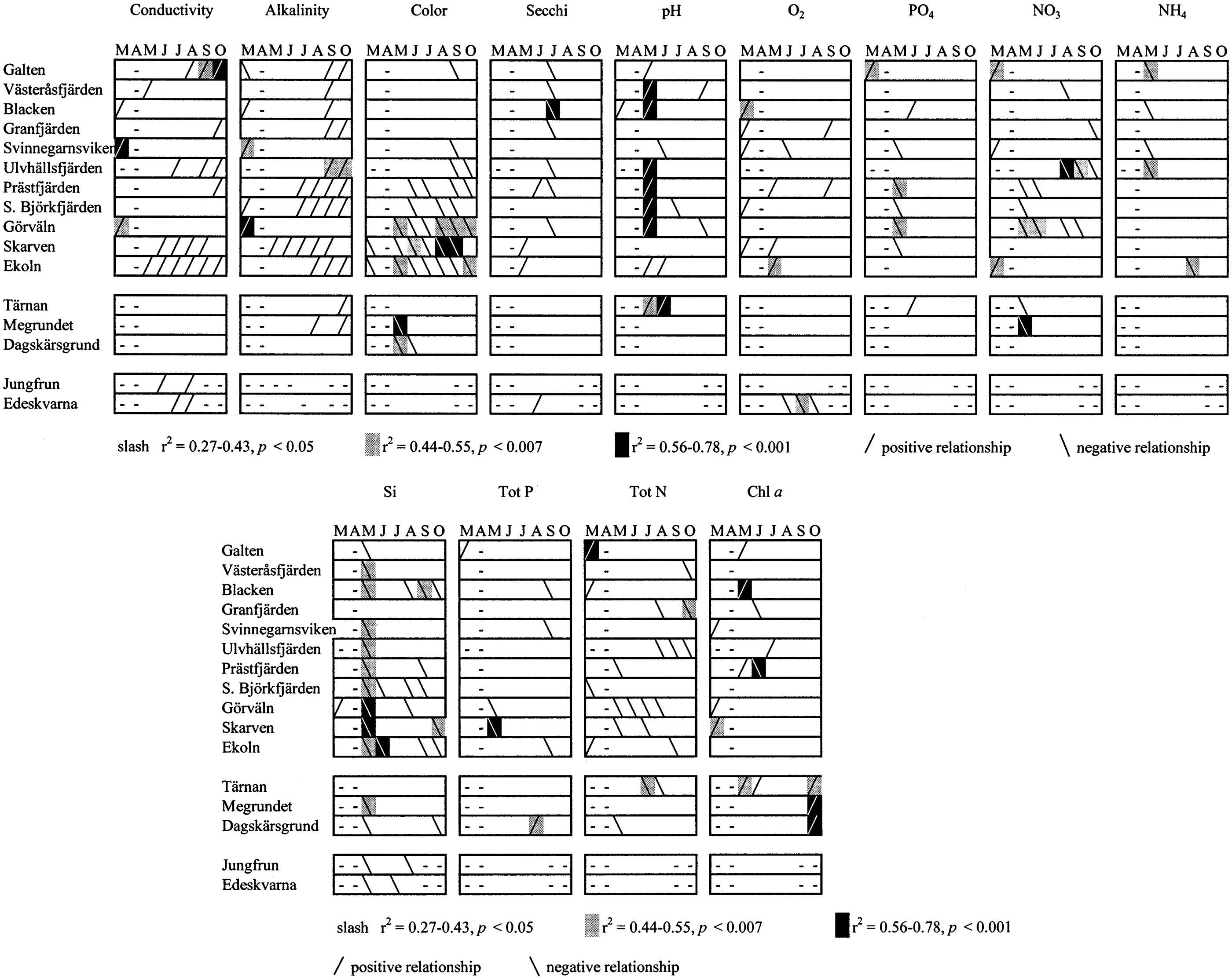


Fig. 4. Linear regressions of the North Atlantic Oscillation winter index (NAO_W) on 13 water chemical variables in surface waters at 16 sites in the lakes Mälaren, Vänern, and Vättern in the period March to October, from 1981 to 1995. Gray and black boxes indicate that regressions remain significant after a correction of the *P* value (for correction procedure, *see* Methods), empty boxes reflect nonsignificant regressions ($P > 0.05$), and short lines are a symbol for missing data. For abbreviations, *see* Table 1.

May was the month in which the NAO_W signal was most apparent. For this month, pH showed the strongest relationship to the NAO_W (r^2 up to 0.78, $P < 0.001$, $n = 15$ at Ulvhällsfjärden in Lake Mälaren). This kind of relationship was found at the majority of the lake sites in Lake Mälaren during May. In May, reactive silica concentrations were also strongly associated with variations in the NAO_W, again at almost all lake sites in Lake Mälaren. The NAO_W signal on reactive silica concentrations in May could even be observed at almost all lake sites in Lake Vänern and Lake Vättern, but only if *P* values before the correction procedure were used. Among all variables tested, reactive silica concentrations and pH showed the strongest association with surface-water temperatures in May. The more a variable was associated with surface-water temperature, the stronger was the NAO_W signal on the variable at the 16 lake sites (Fig. 5). Both pH and reactive silica concentrations in May were not only most strongly related to the surface-water temperature but also to the phytoplankton biomass in May in the Galten basin ($r^2 = 0.71$ respective 0.37, $P < 0.01$, $n = 15$).

Except for pH and reactive silica concentrations, no other water chemical variable showed a dependency on the NAO_W that was consistent for different lake sites. To avoid obtaining good relationships between the NAO_W and pH and reactive silica concentrations only because of similar trends, the series of the NAO_W and pH and reactive silica were detrended by linear function and related to each other. All relationships that were significant before de-rending (corrected *P* value: $P < 0.007$) remained significant after de-trending ($r^2 \geq 0.44$, $P < 0.007$). No outliers that could have caused significant relationships were detected in the time series of reactive silica and pH.

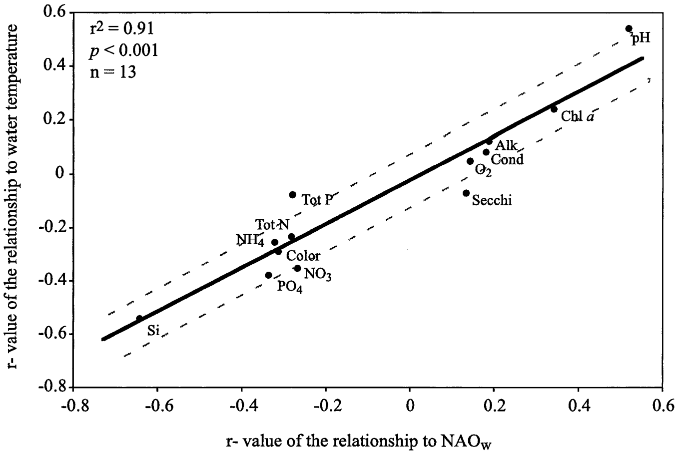


Fig. 5. Relationship between the mean *P* values of the correlation between the North Atlantic Oscillation winter index ($\mathrm{NAO_W}$) and 13 water chemical variables (May values) over the 16 lake sites and the mean *P* values of the correlation between surface-water temperatures and 13 water chemical variables (May values) over the 16 lake sites. The relationship is also valid for each individual lake site ($r^2 = 0.50$–0.94, $P < 0.01$, $n = 13$), except for the lake site Granfjärden. The dashed line represents the 95% confidence interval for the curve fit.

Discussion

The $\mathrm{NAO_W}$ and lake-internal conditions—Water temperature is a typical variable that reflects lake-internal physical conditions. Variations in physical conditions are known to be coherent among lake ecosystems because of their strong association with climate processes (e.g., Kratz et al. 1998; Baines et al. 2000; George et al. 2000). The high coherence of variations in water temperature among lake sites could be confirmed for lake sites in Sweden's largest lakes, Vänern, Vättern, and Mälaren, despite their large morphometric differences (e.g., range of water depths at the lake sites: 10–119 m). Variations in water temperature go along with variations in lake ice break-up. The timing of lake ice break-up is crucial for the development of the spring phytoplankton biomass as a result of drastic changes in the underwater light conditions (Weyhenmeyer et al. 1999; Gerten and Adrian 2000; Straile and Adrian 2000). In the lakes Vänern, Vättern, and Mälaren, a spring (e.g., diatom) phytoplankton peak usually appears around lake ice break-up, when light conditions in the water become nonlimiting and the water sufficiently turbulent. Hence, an earlier ice break-up generally leads to an earlier growth and decline of the spring phytoplankton bloom in these lakes (Weyhenmeyer 2001). In the Galten basin in Lake Mälaren, the phytoplankton spring peak has, for example, shifted from May/June to April/May after warm winters (Weyhenmeyer 2001). The shift in the timing of the phytoplankton spring peak after warm winters could hardly be shown by the present data material, since no consistent pattern in positive relationships between the $\mathrm{NAO_W}$ and chlorophyll *a* concentrations in May could be established. Chlorophyll *a* concentrations, characterized by very large and rapid variations (Kalff 2002), were measured far too rarely (once a month) for shifting peak values to be detected and related to the $\mathrm{NAO_W}$. However, two water chemical variables that are associated with the spring phytoplankton peak could coherently be related to the $\mathrm{NAO_W}$, probably because their variations are not as abrupt as those in chlorophyll *a* concentrations. During a diatom-dominated phytoplankton spring peak, reactive silica is depleted, and its concentration in the water column decreases and remains low for some time (e.g., Eriksson and Forsberg 1992). In addition, the pH increases with increasing phytoplankton biomass, indicated here by a strong positive relationship between the spring phytoplankton biomass and pH in the Galten basin of Lake Mälaren in May. Whenever the phytoplankton spring peak occurs earlier in the year after warm winters with a high $\mathrm{NAO_W}$, the depletion of bioavailable nutrients and the rise of the pH also occurs earlier. Strong positive relationships between the $\mathrm{NAO_W}$ and pH in May and negative relationships between the $\mathrm{NAO_W}$ and reactive silica concentrations in May (Fig. 4) indicate this. The $\mathrm{NAO_W}$ signal on pH and reactive silica concentrations in May was surprisingly coherent among lake sites. Both reactive silica concentrations and pH in May were related to water temperature at the 16 lake sites (Fig. 5). Variables closely related to water temperature seem to follow the pattern of coherence that is known for water temperature. From this study it becomes apparent that a relationship to water temperature (i.e., lake internal conditions) is the prerequisite for temporally coherent $\mathrm{NAO_W}$ signals on lake variables among the 16 lakes sites of Sweden's largest lakes (Fig. 5).

The $\mathrm{NAO_W}$ and processes in the catchment—Processes in the catchment of a lake ecosystem, especially runoff processes, are known to strongly determine lake water chemistry (Wetzel 2001). Conductivity and alkalinity are two examples of variables that are typically associated with runoff processes in the catchment (i.e., they usually decrease with an increasing water discharge [Kalff 2002], as is also seen in the Galten basin) (Fig. 3). In addition, water color is typically associated with runoff processes in the catchment; typically it increases with an increasing water discharge (Kalff 2002; Fig. 3). Since the yearly mean water discharge decreased at the same time when the $\mathrm{NAO_W}$ increased, it appeared that the $\mathrm{NAO_W}$ showed positive relationships to conductivity and alkalinity and negative relationships to water color throughout the year (Fig. 4). These relationships have to be interpreted with care, because the mechanisms behind a relationship between the $\mathrm{NAO_W}$ and the yearly mean water discharge remain unclear with the available data. Since the yearly amount of precipitation was not related to the $\mathrm{NAO_W}$, there might be a possibility that $\mathrm{NAO_W}$-related temperature changes caused changes in the water infiltration rates of the soils and consequently the yearly mean water discharge. In general, water discharge–dependent variables did not show any coherence in the $\mathrm{NAO_W}$ signal on the variable among the 16 lake sites. The lack of coherence is probably a result of differences in the catchment characteristics and arrival time of river water at the lake site. The latter becomes especially obvious when comparing $\mathrm{NAO_W}$ signals on water chemical processes in Lake Mälaren with those in Lake Vättern. In Lake Mälaren, relationships between the $\mathrm{NAO_W}$ and water chemistry were most pronounced, whereas they were

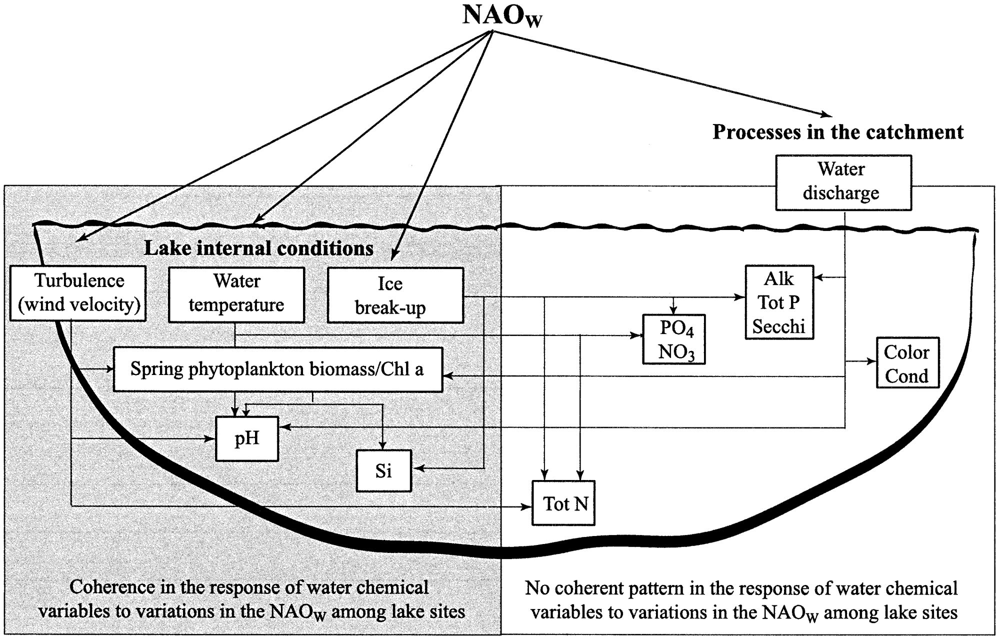


Fig. 6. Mechanism for how synchrony in relationships between the North Atlantic Oscillation winter index (NAO_W) and water chemical variables among Sweden's largest lakes is achieved. Each arrow indicates a significant relationship found in the Galten basin of Lake Mälaren (*see* Fig. 3). Coherence in the response of a water chemical variable to variations in the NAO_W among the 16 lake sites of lakes Mälaren, Vänern, and Vättern has only been observed for variables directly related to water temperature (*see* also Fig. 5).

least pronounced in Lake Vättern (Fig. 4), despite the fact that at the latter, the NAO_W had the strongest impact on local meteorological/lake physical conditions (Table 2). Lake Vättern has an extremely long water turnover time of 58 yr. Thus, in this lake, a distinctive time lag between changes in the climate and changes in the water chemistry related to catchment processes is expected. In contrast, the relatively shallow Lake Mälaren, and especially the Galten basin in Lake Mälaren (water turnover time 0.07 yr), reacted quickly and in a predictable way to changes in meteorology, as reflected by numerous relationships between the NAO_W and water chemistry (Fig. 4).

In addition, nutrient concentrations in lakes can be affected by runoff processes and consequently by the NAO_W, as observed in the Galten basin of Lake Mälaren (Fig. 3). Winter (March) nutrient concentrations, such as total phosphorus, phosphate–phosphorus, total nitrogen, and nitrate–nitrogen, increased in the Galten basin when winters became warmer. During warmer winters, the nutrient loading from inflow waters to the lake is expected to occur earlier in the year as a result of an earlier thawing of the soils and the snowpack in the catchment. This idea is supported by the observed positive relationships between the nutrient loading from inflow waters and nutrient concentrations in the lake water during warm winters with a high NAO_W (Fig. 3). Also, Groffman et al. (2001) observed increased nitrate–nitrogen concentrations during warm winters with only mild freezing. Working with soils in a northern hardwood forest, they explained the nitrate–nitrogen increase in the soils by physical disruption. Physical disruption was likely to increase fine root mortality, reduce plant nitrogen uptake, and reduce competition for inorganic nitrogen, allowing soil nitrate–nitrogen levels to increase. These increased nitrate–nitrogen levels might then be released from the soils and be transported to the lakes.

The results for the Galten basin in Lake Mälaren seem to contradict the results of Monteith et al. (2000), who found that high nitrate–nitrogen concentrations during March were associated with cold winters (i.e., years with a low NAO_W). The reason for the apparent contradiction might be that March values in the Galten basin represent a different time of the year than those in the lakes and streams in the United Kingdom. During cold winters, March values in the Galten basin represent a time of the year when soils and waters are still frozen. These freezing conditions make the nitrogen loading to the Galten basin negligible. In contrast, March values in the lakes and streams in the United Kingdom during cold winters represent the time of the year when nitrogen leaching reaches its maximum. This maximum is reached later in the year in Sweden, as indicated by negative relationships between the NAO_W and nitrate–nitrogen concentrations in May (Fig. 4). These negative relationships and the results of Monteith et al. (2000) coincide with the results of Mitchell et al. (1996), who reported that high nitrate concentrations and high drainage water losses from forested watersheds in the Northeast United States followed an anomalous cold period.

Most of the water chemical variables showed a dependency on both lake-internal conditions (i.e., on lake ice break-up, water temperature, and/or wind velocity) and processes in the catchment (i.e., on water discharge) (Fig. 6). The association of these variables with the NAO_W is complex and not easily predictable. Easier to predict seems to be the NAO_W effect on water temperature–dependent variables such as reactive silica and pH in May, as shown in this study. Water temperature–dependent variables were synchronously related to the NAO_W among the 16 lake sites, despite the fact that the sites strongly differed in morphometry (range of lake area: 61–3,582 km^2; range of mean water depth: 3.4–39.8 m), hydrology (range of theoretical water turnover time: 0.07–58 yr), and trophic status (oligotrophic to hypertrophic). To detect this kind of synchrony helps to determine climate-induced water chemical changes and to distinguish them from water chemical changes that occur locally because of changes in the catchment area. Since this study includes a wide variety of lake sites, it is likely that the results (i.e., changes in the seasonal cycle of silica as a response to changes in the NAO) can be applied to many other lakes. This theory needs to be tested. In addition, future studies should focus more on water discharge–dependent variables that did not show temporally coherent relationships to the NAO_W. Here the time lag between runoff generation and the arrival of river water at the lake sites has to be considered.

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Received: 2 June 2003
Accepted: 19 February 2004
Amended: 1 March 2004