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The influence of the North Atlantic Oscillation on the winter characteristics of Windermere (UK) and Pääjärvi (Finland)

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The atmospheric pressure gradient known as the North Atlantic Oscillation (NAO) has been shown to influence the dynamics of lakes in a number of European regions. Here, we compare the impact of the NAO on the winter dynamics of Windermere, a lake located in the north-west of England, and Pääjärvi, a lake situated in southern Finland. At both sites, the variations in the NAO index had a significant effect on the winter weather and the physical and chemical characteristics of the lakes. At Windermere, the strongest correlations were those noted for the air temperature, precipitation, the number of days when ice was recorded on the lake and the de-trended concentration of nitrate. At Pääjärvi the strongest correlations were with the air temperature and the de-trended concentrations of nitrate. One striking difference between the sites was the sign of the correlations noted between the NAO index and the de-trended nitrate. At Windermere, this correlation was negative and appeared to be driven by the enhanced terrestrial uptake of nitrate in mild winters. At Pääjärvi, the correlation was positive and was associated with the earlier 'flush' of melt water from the catchment. The results are discussed in relation to the regional effects of climate change and the sensitivity of boreal lakes to subtle changes in the 'centre of action' of the NAO.

Introduction

Year-to-year changes in the weather have a profound effect on the seasonal dynamics of lakes. These effects vary from region to region but are frequently driven by the same global-scale variations in the atmospheric circulation. In Europe, the dominant component of this atmospheric variability is the feature known as the North Atlantic Oscillation (NAO). The NAO is a measure of the large-scale meridional fluctuations in air pressure that develop over the North Atlantic. When the NAO index (NAOI) is high (positive) there is a strong westerly flow of air over the Atlantic and winters in Europe are relatively mild. When the NAO index is low (negative) the reverse conditions apply and winters in Europe are colder and drier. The influence of the NAO is particularly strong in winter but almost a third of the inter-annual variation in the northern hemisphere air temperature is also associated with the NAO (Hurrell 1996). The influence of the NAO on the climate of Greenland was first described in 1745 (Saabye 1942) but the early Norse settlers were also aware of these quasi-cyclical variations (Anonymous 1917). One of the first scientific accounts of the NAO was that produced by Walker in 1924 who related these variations to other large-scale processes in the Pacific as well as the Atlantic.

Over the years, a number of investigators published papers on the meteorological and oceanographic effects of the NAO (Rossby *et al*. 1939, Lorenz 1951, Ratcliffe and Murray 1970). Recently, more attention has been paid to the environmental effects of the NAO with the number of ecological papers published increasing by an order of magnitude between 1996 and 2001 (Stephenson *et al*. 2003). Research on the influence of the NAO on aquatic systems is still in its infancy but a number of multidisciplinary studies have recently appeared. These include studies on the thermal characteristics of lakes (Livingstone 2000), their chemical responses (George 2000a) and the impact of the NAO on several species of freshwater plankton (Weyhenmeyer *et al*. 1999, Straile 2000, George 2000b). In this paper, we compare the impact of the NAO on the physical and chemical characteristics of Windermere, the largest lake in England, and Pääjärvi, a large lake in southern Finland. These lakes have been sampled using standard methods for several decades and the time-series analysed here (1964–2000) includes years when the NAO index was in its strong negative as well as its strong positive phase.

Description of sites

The lakes of the English Lake District have been studied scientifically for more than sixty years (Macan 1970). The most intensively studied lakes are those located in the Windermere catchment (54°18´N, 2°54´W) which contains six lakes and seven distinct basins. The data analysed here was acquired from the North Basin of Windermere between January 1964 and December 2000. The North Basin is separated from the South Basin by a large island and has a mean depth of 25 m and a maximum depth of 64 m. In physical terms, the basin is stably stratified from the beginning of June to early October but is usually only partially covered with ice for a few days every year. In recent years, both Windermere basins have been enriched by treated sewage effluent but the North Basin is still relatively unproductive with an average chlorophyll concentration of ca. 5.5 μg l^{-1}. The catchment of the lake is dominated by improved pasture and mixed forest with some areas of moorland rising to more than 700 m.

Pääjärvi is a lake situated in the southern boreal zone of Finland (61°04´N, 25°08´E) and has been studied systematically since the mid 1960s. The surface area of the lake is 13.4 km^2 and it has a mean depth of 14.1 m and a maximum depth of 85 m. In physical terms, it is a dimictic brown water lake with steep thermal stratification in summer and inverse stratification in winter. The ice cover period typically lasts from the beginning of December until early May. In chemical terms, the lake is still classified as oligo-mesotrophic but it does contain very high concentration of nitrate-nitrogen (ca. 1000 μg l^{-1}). The average summer concentration of chlorophyll in the lake is 6 μg l^{-1} but the concentration recorded under the ice is typically less than 0.5 μg l^{-1}. The catchment of the lake covers an area of 244 km^2 and is dominated by coniferous forest with smaller areas of agricultural land and peat bogs.

Methods

In this paper, as in previous publications (e.g. George *et al*. 2000), the UK ‘winter’ has been defined as the first ten weeks of each year. This provides a better measure of the winter conditions experienced by a deep lake which retains heat and often supports residual populations of plankton until early November. The same convention has also been applied to the Finnish measurements to facilitate a direct comparison with the data acquired in the UK. Winter conditions in Finland typically extend from November to early April so the seasonal dynamics of these lakes are strongly influenced by the timing of the ‘spring’ thaw.

At Windermere, daily measurements of air temperature, precipitation and snow cover were obtained from a weather station in the village of Ambleside (54°18´N, 2°54´E). The air temperatures were the average of the daily minimum and maximum and the precipitation measured by a rain-gauge located in an open position. Snow depth is not normally measured but a record was kept of the number of days when snow was lying on the ground. At Pääjärvi, the daily measurements of air temperature and precipitation were obtained from a weather station at the Lammi Biological Station. Here, the depth of snow at an open location was recorded daily using a rigid measuring rod. The NAO index used is that suggested by Hurrell (1995) and is based on the atmospheric pressure differences recorded in winter between Lisbon (Portugal) and Stykkisholmur (Iceland). This index has been found to be more strongly related to climatic conditions in Europe than other indices and is readily available from a web site maintained by the U.S. National Centre for Atmospheric Research (http://www.cgd.ucar.edu/~jhurrell/nao.stat.winter.html).

The ice records for Windermere are based on observations in a sheltered bay near Ferry House (54°21.1´N, 2°56.3´W). These observations were made every day until 1989 when weekend observations were discontinued. Two ice statistics have been analysed here: the number of days in each winter when the bay was partially or completely covered with ice and the date on which ice was recorded on the lake for three days in succession. When the lake freezes, the development of ice in this bay is both rapid and progressive. Typically, a thin sheet of ice appeared in the shallow littoral and then extended into the open water. The number of ice-days was that recorded between the beginning of December and the end of March. The ice records for Pääjärvi follow the conventions adopted for monitoring ice on other frozen lakes. They include the number of days when the whole lake was covered by ice, and the day in the year when the lake was first frozen over. The date of ice-on was expressed as days from 1 January and the number of ice-days was the difference between ice-on and ice-off.

Samples of water and plankton were collected from Windermere by lowering a 7-m-long plastic tube into the water column at a representative central site (Lund and Talling 1957). For most of this period, the samples were collected at weekly intervals but fortnightly sampling was introduced during the winter of 1982 and extended to the whole year in 1992. In the laboratory, the water samples were either analysed immediately for nutrients or stored overnight in a cold room at 9 °C. Details of the methods used are given by Mackereth *et al.* (1978). Nitrate-nitrogen was determined using the phenoldisulphonic acid method up to 1972 and then by the cadmium reduction method described by Davison and Woof (1978). Since the first method underestimates the concentration of nitrate-nitrogen, the earliest values were corrected using the relationship given in Sutcliffe *et al.* (1982). At Pääjärvi, water samples were collected by the Finnish Environment Institute and Lammi Biological Station and analysed using the method given in APHA (1998). Since the number of samples collected during the winter was often low, the nitrate-nitrogen concentrations used here were those measured on a single date in March.

Results

The influence of the NAO on the local weather

The average temperatures recorded at Windermere were almost 12 °C higher than those at Pääjärvi but they were both strongly correlated with the NAOI. At Windermere, the fitted regression explained 38% of the recorded variation ($p < 0.001$) (Fig. 1a), at Pääjärvi the proportion accounted for was 37% ($p < 0.001$) (Fig. 1b). At Windermere, most of the precipitation fell as rain and the total often exceeded 8 mm d^{-1}. At Pääjärvi, most of the precipitation fell as snow and the total was often less than 1 mm d^{-1} of water. Despite these differences, the inter-annual variations recorded at the two sites were significantly correlated with the NAOI. At Windermere, the fitted regression explained 40% of the recorded variation ($p < 0.001$) (Fig. 1c), at Pääjärvi this proportion fell to 17% ($p < 0.001$) (Fig. 1d). The snow-cover statistic used at Windermere was the number of days when some snow lay on the ground. The statistic used at Pääjärvi was the average depth of snow recorded in the grounds of the Lammi laboratory. Despite these differences, the strength of the correlations observed with the NAOI at the two sites was similar. At Windermere, the regression fitted to the ‘days of snow’ accounted for 21% of the recorded variation ($p < 0.001$) (Fig. 1e). At Pääjärvi, the regression fitted to the ‘depth of

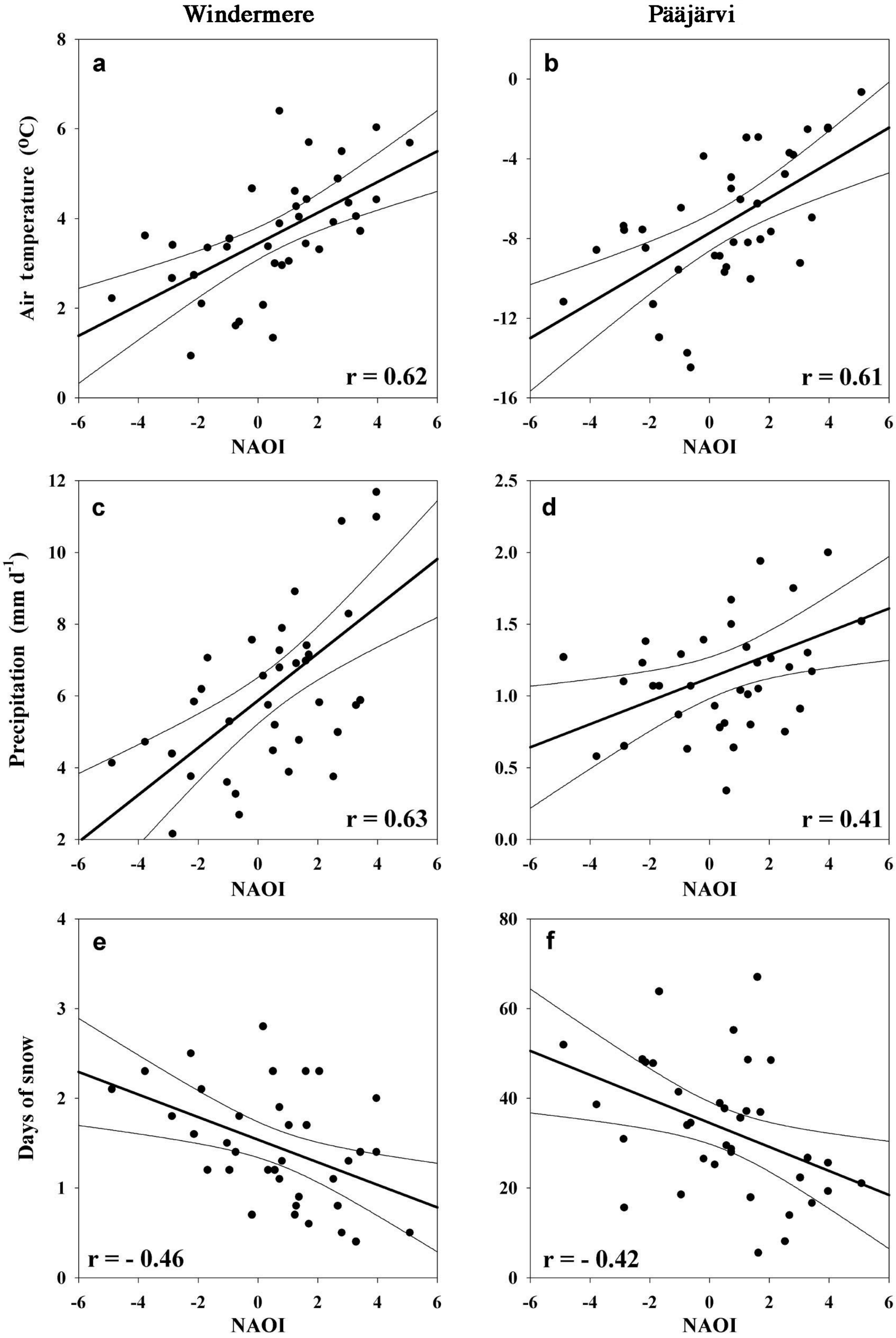

Fig. 1. The influence of the NAO on (**a**) the winter air temperature at Windermere, (**b**) the winter air temperature at Pääjärvi, (**c**) the winter precipitation at Windermere, (**d**) the winter precipitation at Pääjärvi, (**e**) the number of days of snow at Windermere, and (**f**) the average depth of snow (cm) at Pääjärvi.

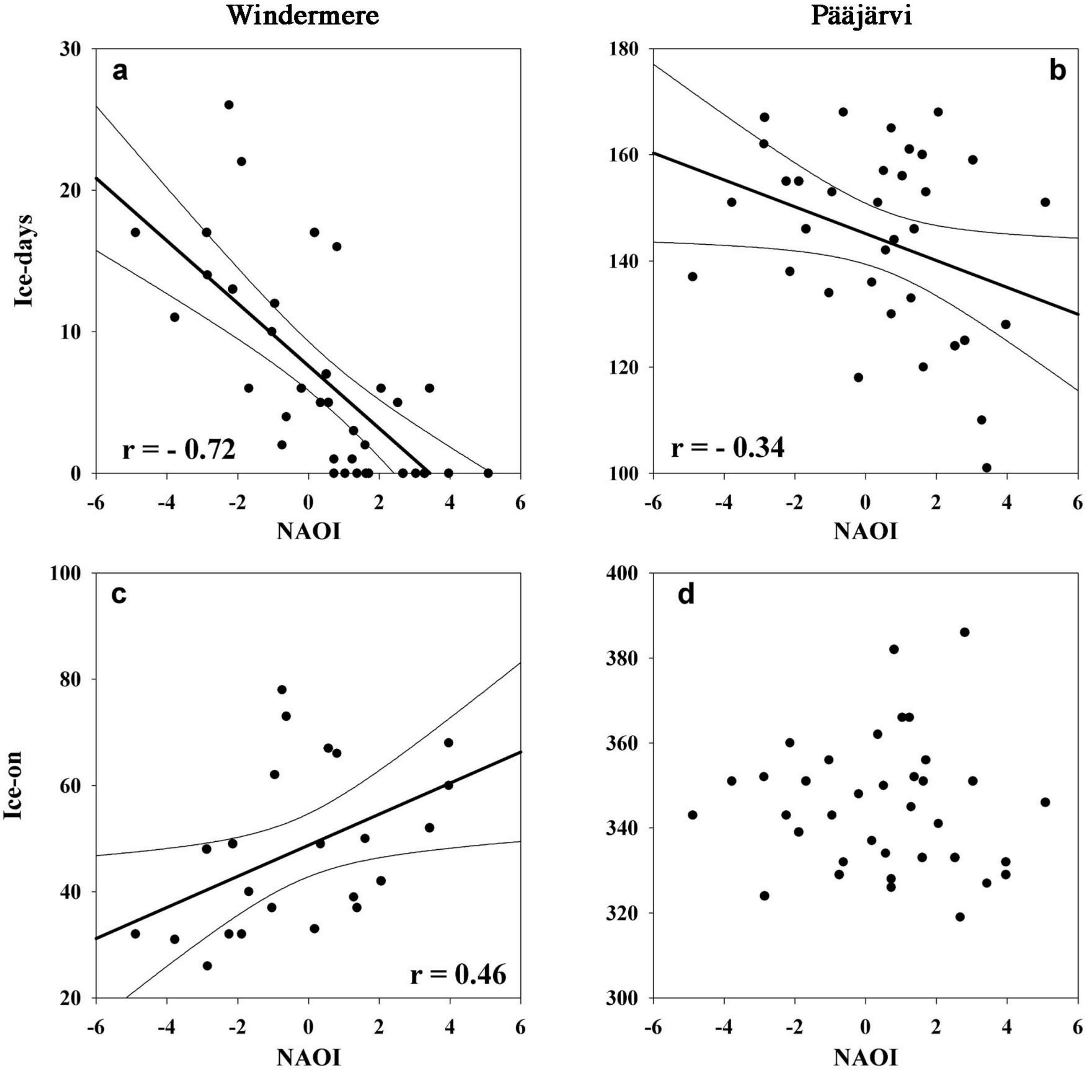

Fig. 2. The influence of the NAO on (**a**) the number of days when some ice was recorded on Windermere, (**b**) the number of days when Pääjärvi was covered with ice, (**c**) the date of first freezing at Windermere, and (**d**) the date of first freezing at Pääjärvi.

snow' accounted for 18% of the recorded variability ($p < 0.01$) (Fig. 1f).

The influence of the NAO on the freezing characteristics of the lakes

Long-term records of lake ice are now widely used as indicators of climate change. At high latitudes and altitudes the most widely used indicators are the date on which the lakes start to freeze and to thaw (Livingstone 2000, Magnuson *et al.* 2000). At more temperate locations, a better measure of change is the number of days in each year when each lake is covered with ice (Adrian and Hintze 2000, George 2000c). Here, we compare the long-term variation in the development of ice on Windermere and Pääjärvi and relate these variations to the NAOI. There was a strong negative relationship between the number of days when some ice was recorded on Windermere and the NAOI and the fitted regression explained 52% of the recorded variation ($p < 0.001$) (Fig. 2a). At Pääjärvi, the relationship between the number of days of complete ice cover and the NAOI was much weaker and the fitted regression only explained 12% of the recorded variation ($p < 0.05$) (Fig. 2b). There is a clear positive relationship between the date on which ice was first recorded at Windermere and the NAOI, and the fitted regression explained 21% of the recorded variation ($p < 0.01$) (Fig. 2c). The relationship between the date on which ice was first recorded at Pääjärvi and the NAOI was not statistically significant but the index was positive in the two years with the latest freeze dates (Fig. 2d).

The influence of the NAO on the concentration of nitrate in the two lakes

In the English Lake District, the concentration of nitrate measured in the lakes during the winter is strongly influenced by year-to-year variations in the weather (George 2000b). The winter concentration of nitrate in these lakes has increased steadily since the early 1950s due to the increased agricultural use of nitrogenous fertilisers. Once this long-term trend is removed by fitting a linear regression to the time-series, the residual variation is negatively correlated with the NAOI (Fig. 3a) and the fitted regression explains 40% of the recorded variation ($p < 0.001$). An analysis of the factors influencing this year-to-year variation suggests that the critical factor was the inter-annual variation in the winter air temperature (Fig. 3c). A likely explanation for this negative response is the effect that mild winters have on the assimilation of nitrate in the surrounding catchment. In Pääjärvi, winter nitrate measurements were only available for six occasions between 1968 and 1976 and seven occasions between 1994 and 2000. These data are, however, sufficient to demonstrate that there is a positive relationship between the detrended concentration of nitrate in Pääjärvi and the NAOI, and the fitted regression explained 34% of the recorded variation ($p < 0.01$) (Fig. 3b). An analysis of the factors influencing this year-to-year variation showed that the critical factor was the depth of snow in the surrounding catchment (Fig. 3d). The most likely explanation for this response is the effect that mild winters have on the transport of nitrate within the Pääjärvi system. Because the soils in the catchment typically remain frozen until April, the main hydrological pathway is the drainage of water from the melting snow. Usually when the daily air temperatures start to increase above 0 °C, the discharge in the inflowing rivers starts to increase, and there can be a simultaneous four to ten-fold increase in the nitrate concentrations. Whether the nitrate comes from the melting snow or from other sources of the catchment is still an open question. Although the snow pack stores most of the atmospheric nitrate deposited on the catchment, the measured concentration in the precipitation (ca. 200 $\mu g\ l^{-1}$) does not explain the increased concentration in the inflowing water.

The influence of the NAO on the temporal coherence of some selected time-series

Lakes located in the same area frequently respond in a similar way to changes in the weather (Kratz *et al.* 1998, George *et al.* 2000, Järvinen *et al.* 2002). Magnuson *et al.* (1990) used the term 'temporal coherence' to describe this spatial synchrony and used Pearson product-moment correlations to quantify the covariance. Lakes located in different geographic regions are likely to be less coherent, but significant correlations can occur if the two regions are influenced by the same atmospheric processes. Here, we explore the extent to which a common response to the NAO can generate significance levels of coherence in two of the time-series collated for Windermere and Pääjärvi.

The results demonstrate that, whilst the absolute temperatures were very different, there was a strong positive correlation ($r = 0.68$, $p < 0.001$) between the average winter air temperatures recorded at Windermere and Pääjärvi (Fig. 4a). The main factor responsible for this synchrony is the difference in the mass transport of air in positive and negative NAO years. When the NAOI is positive, the atmospheric pressure gradient generates a strong westerly flow of air across the Atlantic. This gives rise to milder, wetter conditions over much of Europe and much warmer winters in southern Finland. When the NAOI is negative the direction of the prevailing wind is

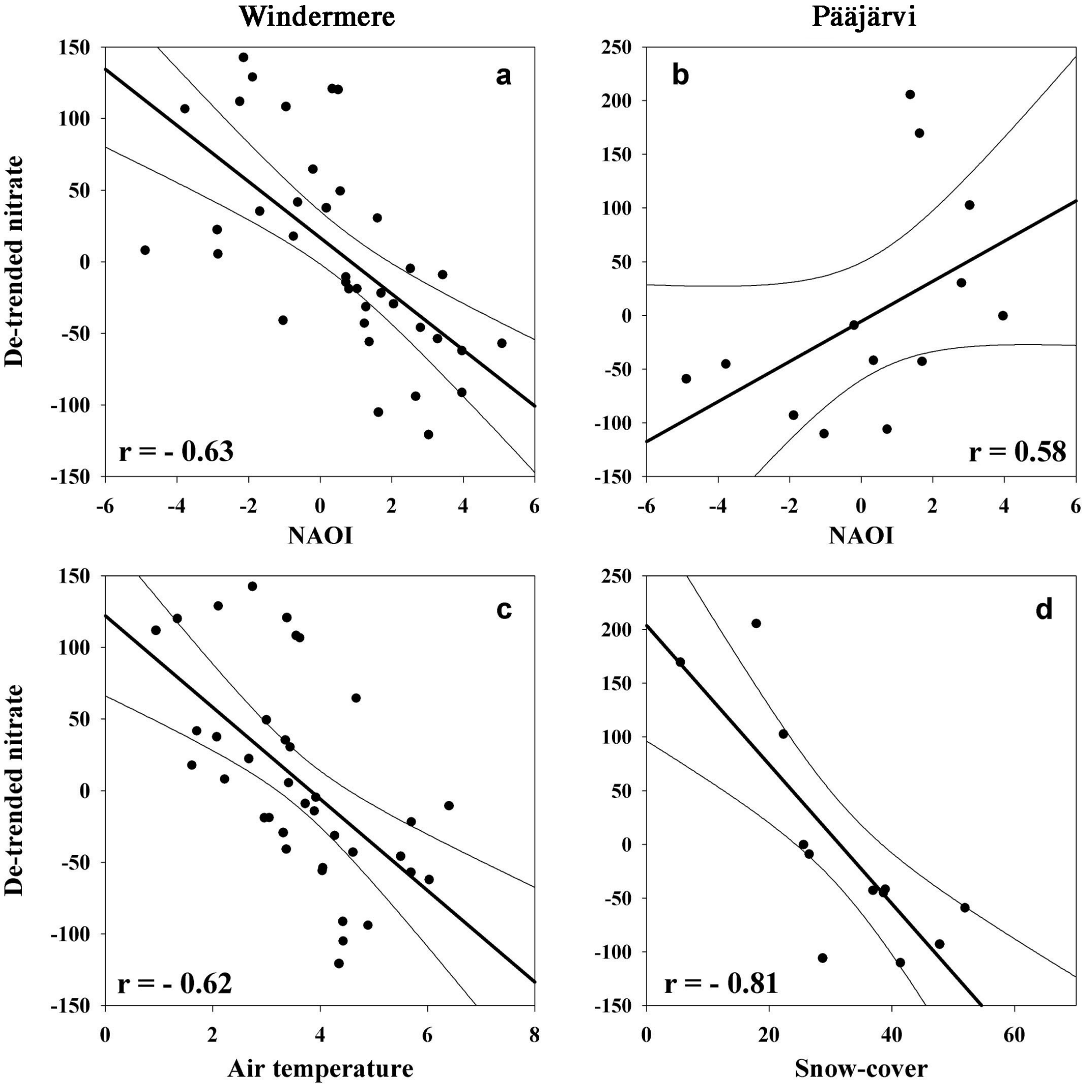

Fig. 3. The influence of the NAO on (**a**) the detrended winter concentrations of nitrate in Windermere, (**b**) the detrended March concentrations of nitrate in Pääjärvi, (**c**) the key factor influencing the nitrate variations at Windermere, and (**d**) the key factor influencing the nitrate variations at Pääjärvi.

reversed and much colder conditions are experienced over most of Europe.

The results show that, whilst there is a large gap in the Finnish record, there is a strong tendency for the ‘high nitrate’ years in the north of England to be associated with ‘low nitrate’ years in southern Finland (Fig. 4b). These estimates are the same as those used in Fig. 3 but the Pääjärvi results have been inverted to simplify the comparison with the Windermere time-series. The calculated correlation between the time-series was –0.57, a value that was still statistically significant at the 95% level. The ultimate driver was again the NAO but the proximate factor was the winter temperature which resulted in an enhanced uptake of nitrate in the Windermere catchment and an increased flow of melt water into Pääjärvi.

Discussion

A significant proportion of the climatic variations recorded in the northern hemisphere can be related to variations in the NAO. The NAOI

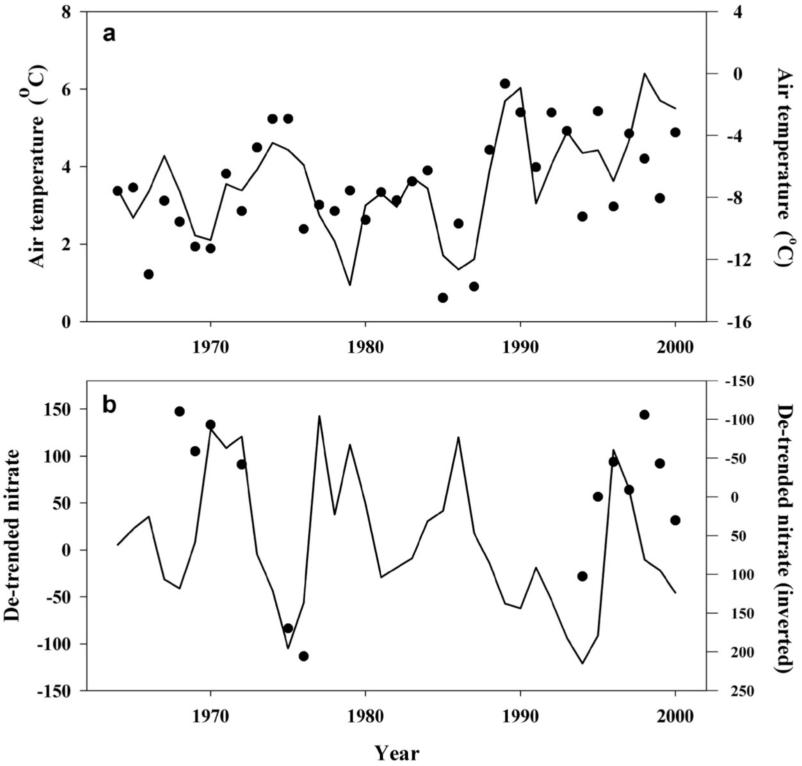

Fig. 4. The temporal coherence between (**a**) the winter air temperatures and (**b**) the residual nitrate concentrations recorded at Windermere and Pääjärvi. The solid lines show the Windermere time-series. The scale for the nitrate time-series at Pääjärvi has been inverted.

is thus frequently used as a proxy measure of change in areas as diverse as the west of Ireland (Jennings *et al.* 2000) and eastern Siberia (Livingstone 1999). In this paper, we have used the NAOI as an appropriate 'frame of reference' to compare the winter dynamics of a pair of lakes situated in two very different geographic regions. Lake Windermere is situated close to the sea in the north of England and experiences mild winters with heavy rain. Pääjärvi is located some distance from the sea in southern Finland and is usually covered with ice for at least 3 months every year. Despite these differences, the inter-annual variations recorded in the two lakes showed a high level of spatial synchrony. Large-scale coherent responses to the NAO have recently been reported from a number of lake districts (George *et al.* 2000, Livingstone and Dokulil 2001) but this is the first European comparison that ranges over ca. 7° of latitude.

The correlations with the winter weather in Windermere and Pääjärvi are similar to those reported elsewhere in Europe. At Windermere, the NAOI accounted for 40% of the variations in the air temperature, 39% of the variation in the precipitation and 21% of the variation in the number of days when snow was lying on the ground. At Pääjärvi, the NAOI accounted for 37% of the variation in air temperature, 17% of the variation in precipitation and 18% of the variation in the depth of snow. The marked reduction in the precipitation effect noted in Pääjärvi can partly be explained by the low rainfall and partly by the more continental location of the site. The 'snow cover' effects noted in Windermere and Pääjärvi are much stronger than expected since very little snow falls in Windermere.

The lake ice correlations reported here are much stronger than anticipated for Windermere and rather weaker than anticipated for Pääjärvi. The trends reported at the two sites were also rather different with a much stronger 'warming' signal being apparent at Windermere. At Windermere, there has been a dramatic reduction in the number of ice-days reported in recent years (George 2000c). In the 1970s, the average number of ice days recorded during the decade was 10.2 but this declined to 1.8 in the 1990s. At Pääjärvi, there has been no systematic change in the duration of ice cover during the same period. Although the ice has melted earlier in the 1990s, this has been compensated by the earlier freezing of the lake in the late autumn and early winter. In southern Finnish lakes, the ice-off is highly correlated with the mean air temperature in April (Palecki and Barry 1986). Accordingly, the timing of ice-off in Pääjärvi correlates with the seasonal NAOI values from February–April ($r = 0.55$, $n = 36$; M. Järvinen unpubl. data), whereas the timing of ice-on is related to the NAO in September–November ($r = 0.36$, $n = 36$; M. Järvinen unpubl. data).

The winter nitrate analyses presented here are rather tentative owing to the large gaps in the Pääjärvi records. The results nevertheless imply that the NAO has a significant effect on the de-trended concentrations reported from both sites with the variations reported in Pääjärvi being the inverse of those reported in Windermere. The negative correlation reported for Windermere is the same as that reported from other lakes in the area (George *et al.* 2000). In all these lakes, the proximate driving variable was the winter air temperature which influenced the rate at which nitrate was assimilated in the surrounding catchments. The uptake of nitrate in soil is usually attributed to two complementary mechanisms: uptake by vascular plants and bacterial de-nitrification. The first mechanism is particularly important in summer but the second mechanism can still consume substantial quantities of nitrate when the soil temperature is very low (Groffman and Hanson 1997). In contrast, the positive correlation reported for Pääjärvi is primarily related to the earlier melting of snow in years when the NAO index is strongly positive. Although approximately 52% of the mean annual nitrate-nitrogen deposition in southern Finland (253 mg NO_3 m^{-2} a^{-1} between 1987 and 1991) falls on frozen ground, the autumnal and winter microbial decomposition processes in soils are thought to be the primary reason for the increased flux of nitrate in positive NAO years (cf. Arvola *et al.* 2002).

The time-series presented here support the conclusions drawn from other geographic studies. Atmospheric events over the Atlantic have recently been shown to influence the dynamics of freshwater ecosystems throughout Europe (Straile *et al.* 2003). The strength of these 'teleconnections' does, however, vary from region to region with the observed correlations with the NAOI becoming weaker in areas exposed to a more continental climate. The strength of the correlations observed between the Windermere time-series can thus be related to the pronounced oceanicity gradient that develops over north-east Europe. Observations on lakes located further to the east (Gronskaya *et al.* 2002) confirm that most Finnish lakes are strongly influenced by their proximity to the Atlantic. North–south movements of the Gulf Stream in the Atlantic are known to influence the dynamics of lakes in Ireland and the UK (George 2002) but no such effects have hitherto been detected in Finland.

In this paper, we have shown that correlations with the NAOI can provide a useful way of quantifying the effects of changes in the weather that operate on a pan-European scale. Such regional analyses are becoming increasingly important as lake managers strive to resolve the practical problems posed by global warming. There is now every indication that the sequence of strong positive NAO years reported in the 1990s is a direct consequence of an increase in the concentration of greenhouse gases. The most convincing evidence is based on the behaviour of the latest range of Global Circulation Models (GCM's) which relate the variations in the NAO to both natural and anthropogenic forcing. The first modelling studies to discuss the influence of greenhouse gas forcing on the NAO appeared almost a decade ago (Graf *et al.* 1995) and concluded that no significant effects could be detected in these simulations. More recently, the circulation changes generated by a number of GCM's have been compared (Gillet *et al.* 2002) and these show that at least some increases in the index can be related to external forcing. The most recent report published by the IPCC (Cubasch *et al.* 2001) adopts a rather cautious approach to these results but all the models suggest an enhancement of the westerly circulation over the Atlantic i.e. the conditions associated with a positive value of the NAO index. Some authors have argued that the change in the NAO is not limited to a simple increase but may also involve a substantial shift in its centre of action (Ullbrich and Christoph 1999). Thus the position of the boundary between the oceanic and the continental climatic regimes could well change and produce a significant shift in the winter dynamics of lakes located near to this critical 'transition' zone.

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