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The impact of the North Atlantic Oscillation on the development of ice on Lake Windermere

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Abstract Windermere, the largest lake in England, seldom freezes over but the sheltered bays are usually covered with ice for several days every year. Here I analyse the meteorological factors influencing the development of ice on the lake between 1933 and 2000 and relate these to the regional and global changes in the weather. The results demonstrate that the methods used to describe the development of ice at high latitudes can also be used to predict the formation of ice on this temperate lake. The best indicator of change was the number of ice-days recorded every winter. Regression analyses based on a Poisson model showed that there were significant negative correlations between the number of ice-days and the local air temperature, the Central England Temperature and the North Atlantic Oscillation Index (NAOI). The relationship with the NAOI was particularly pronounced and explained 50% of the observed inter-annual variations. A hindcasting model based on the NAOI correctly predicted the most severe winters reported in the area between 1864 and 1910. The observed and predicted numbers of ice-days were also correlated with an index of sea ice in the Baltic. The results demonstrate that the number of ice-days reported on Windermere can be used as a proxy indicator of climate change and show that the NAO has had a major effect on the development of ice on this lake for at least a hundred and thirty years.

1 Introduction

Historical records of lake ice phenology are now widely used as indicators of climate change (Tramoni et al. 1985; Palecki and Barry 1986; Assel and Robinson 1995; Magnuson et al. 2000). In lakes that are covered with ice for several weeks in the year, the best indicator of climate change is the date at which the ice starts to break in the spring. A general trend towards earlier break-up has recently been reported from lakes in northern Europe (Kuusisto 1987), central Europe (Livingstone 1997) and continental America (Anderson et al. 1996). In milder climates, a more effective measure of change is the number of days of partial or complete ice cover. Records of ice cover in lakes exposed to a mild climate are rare, but

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analyses have been published for Loch Leven in Scotland (IFE 1996) and the Müggelsee in Germany (Adrian and Hintze 2000).

In this paper, I summarise the results of a sixty-seven-year study of ice phenology on Windermere, the largest lake in the English Lake District. This lake seldom freezes over, but the more sheltered bays are usually covered with ice for several days in the year. The paper includes an analysis of the climatic factors influencing both the duration of ice cover and the date of first freezing. One of the most important factors influencing the severity of winters in northern and western Europe is the atmospheric feature known as the North Atlantic Oscillation (NAO). The North Atlantic Oscillation Index (NAOI) is a measure of the large-scale meridional fluctuations in air pressure which develop over the North Atlantic. When the NAOI is high (positive), there is a strong westerly flow of air over the Atlantic and winters over most of Europe are relatively mild. When the NAOI is low (negative), the reverse conditions apply and winters in Europe are colder and dryer. Livingstone (2000) has shown that the position of the NAO has a significant effect on the break-up dates of ice in Finland, Switzerland and Russia but no ice records have hitherto been analysed from the UK. Here, I examine the influence of the NAO on the development of ice on Windermere and relate these variations to the phenological changes reported elsewhere in Europe.

2 Methods

2.1 The ice records

Long-term records of lake-ice are very rare in the UK but daily observations have been conducted on Windermere (Cumbria) since the early 1930's. Windermere is the largest lake in the English Lake District and is divided into two basins by a large island and a region of shallows. The ice records are based on observations in a bay near Wray Castle (54° 23.7′N; 2° 57.7′W) between 1933 and 1955 and a bay near Ferry House (54° 21.1′N; 2° 56.3′W) between 1955 and 2000. The two bays are situated in sheltered locations on the western side of the lake and follow the same basic freeze-thaw cycle. The development of ice in these bays was recorded every day between 1933 and 1989 but weekend observations were discontinued in 1990. The only reliable statistics that can be extracted from these records are:

1. The number of days when the bay was partially or completely covered with ice.
2. The first date on which ice was reported in the bay for three successive days.

On most occasions, the development of ice in the bays was both rapid and progressive. Typically, a thin sheet of ice appeared in the shallow littoral and then extended into the open water. The lake usually starts to freeze in January but some ice is occasionally recorded in December. Here, I have used the number of ice-days recorded between the beginning of December and the end of March as the most reliable measure of winter conditions. The date of first freezing is more difficult to define since the first covering of ice often melts within a few hours. A more detailed analysis of these freeze-thaw sequences showed that the most reliable indicator was the date on which ice was recorded on the lake for three consecutive days. Since no ice was ever recorded in November, the date of first-freezing was counted from the first day of December.

2.2 The meteorological records

In this paper, the development of ice on Windermere is related to the year-to-year variations in the local weather, a regional climate index and the position of the NAO. Daily records of air temperature, wind speed, rainfall and the number of hours of bright sunshine were obtained from a meteorological station situated at the northern end of the lake. The regional index used is the 'Central England Temperature' (CET) series, originally developed by Gordon Manley and now updated by the UK Meteorological Office (Manley 1974; Parker et al. 1992). The CET is the most widely reported temperature indicator in the UK and has recently been used to interpret long-term changes in the break-up dates of lakes by Livingstone (1997). The NAO index used here is the normalised winter average suggested by Hurrell (1995). This is based on the difference in atmospheric pressure recorded between Stykkisholmur in Iceland and Lisbon in Portugal. This version of the index provides the best measure of winter conditions in western Europe (Jones et al. 2003) and is readily available from a web site maintained by the U.S. National Centre for Atmospheric Research (http:/www.cgd.ncar.edu/cas/climind/nao_winter.html).

2.3 The statistical analyses

Time-series analyses were performed on the ice records for the periods before and after the historical maximum and showed that there were no significant autocorrelations in the collated records. The residuals in the regressions were also checked for autocorrelation and only one significant value ($p < 0.05$) detected in the time-series analysed. All the analyses relating the change in ice phenology to the climatic drivers were performed using Poisson regressions. Standard regression procedures assume a normal distribution for the errors associated with the predicted mean and the same variance for all observations. Counts with a high proportion of zero values, such as those analysed here, violate these assumptions but their frequency can be represented by a Poisson distribution. Poisson regressions are usually based on a logarithmic transformation but tests with the ice data showed that a square transformation produced better predictions. The fitted curves are thus quadratics, where the dependent variable is a square function of a basic linear equation. The proportion of the variance explained by the regressions was calculated by correlating the observations with the predictions and using the square of these r values as coefficients of determination.

3 Results

3.1 The long-term ice record for Windermere

Figure 1A shows the year-to-year variation in the number of ice-days recorded on Windermere between 1933 and 2000. The average number of ice-days recorded was 7.8 and the calculated coefficient of variation was 130%. The most extreme event in the time-series was the sixty two days of ice recorded in 1963. The winter of 1963 was one of the coldest on record and was the result of an unusual atmospheric 'blocking' event centred over Iceland (Davies et al. 1997). Such rare reversals of the normal pressure distribution result in a meridional rather than a zonal pattern of circulation and a mass movement of polar air over much of Europe. If this single extreme event is excluded from the analysis, the Windermere measurements can empirically be divided into three contrasting periods:

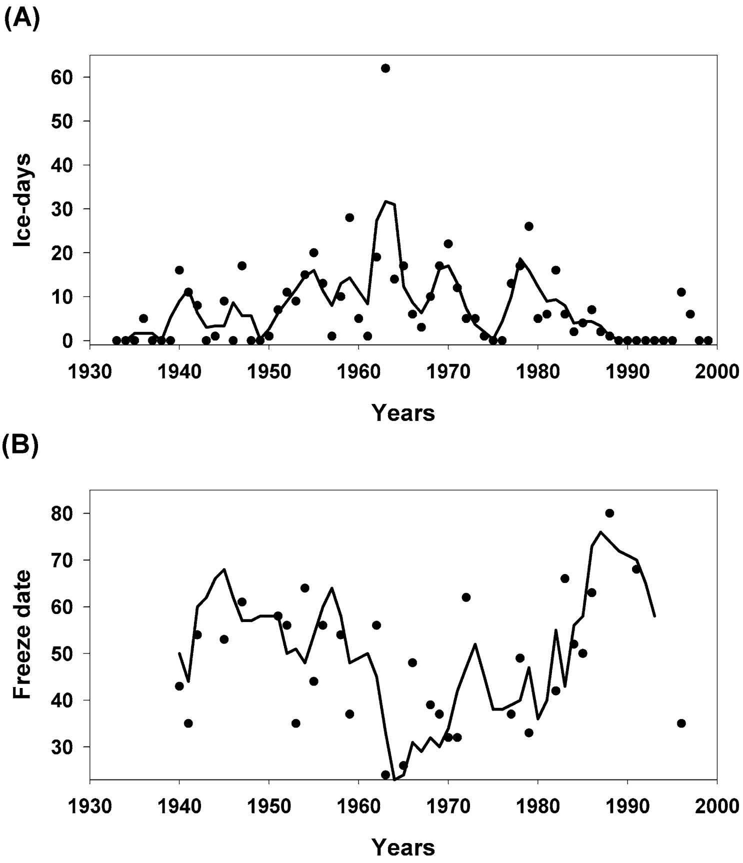

Fig. 1 The year-to-year variations in (A) The number of ice-days recorded on Windermere between 1933 and 2000. (B) The freeze dates recorded on Windermere between 1933 and 2000. The points are the observations and the lines are three-point running averages

1. A period of increasing ice cover that extends from 1933 to 1962.
2. A period of diminishing ice cover that extends from 1964 to about 1990.
3. The recent period when very little ice was reported on the lake.

The parameters in Table 1A quantify these trends as a series of regression coefficients. A linear regression that related the number of ice-days to the year of observation during the period of increasing ice cover explained 23% of the variation and was significant at the 1% ($p < 0.01$) level. The decline in ice cover was less systematic and a linear regression fitted to this portion of the record explained 16% of the variation and was significant at the 5% ($p < 0.05$) level. The average rate of increase in the number of ice-days recorded between 1933 and 1962 was 0.42 days per year whilst the rate of decrease recorded between 1964 and 1990 was 0.37 days per year.

Figure 1B shows the year-to-year variations in the freeze dates recorded between 1933 and 2000. The average freeze date for the 67 year period was day 49 (18 January) and the calculated coefficient of variation was 28%. In recent decades, these variations mirror those recorded for the number of ice-days with the date of first freezing being delayed by up to 40

Table 1 The calculated trends in (A) the number of ice-days and (B) the date of first freezing in Windermere in two contrasting periods (1933–1962 and 1964–1990)

	Estimate	Standard error	*T* statistic	*P* value
(A) Trend in 'ice-days' recorded during the period of increasing ice cover (1933–1962)				
Intercept	−811	283	−2.86	0.008
Slope	0.42	0.14	2.89	0.007
Trend in 'ice-days' recorded during the period of decreasing ice cover (1964–1990)				
Intercept	753	335	2.24	0.034
Slope	−0.38	0.17	−2.22	0.035
(B) Trend in date of first freezing during the period of increasing ice cover (1933–1962)				
Intercept	1.58	802	0.002	0.998
Slope	0.03	0.41	0.064	0.949
Trend in date of first freezing during the period of decreasing ice cover (1964–1990)				
Intercept	−2083	839	−2.48	0.024
Slope	1.08	0.42	2.53	0.022

days. The regression parameters in Table 1B show the results of relating these freeze dates to the year of observation. No significant trend ($p < 0.05$) was recorded during the period of increasing ice cover but a linear regression fitted to the period of decreasing ice cover explained 28% of the variation and was significant at the 5% ($p < 0.05$) level. The average delay in the freeze date recorded between 1964 and 1990 was 1.1 days per year with a 95% confidence interval of ± 0.85 days.

3.2 Factors influencing the appearance of ice on Windermere

A number of meteorological factors can influence the development of ice on lakes but the most important is the local air temperature. Table 2 shows the results of an analysis where the number of ice-days recorded in each year was related to the air temperature, rainfall and wind speed experienced during the first ten weeks of that year. This period provides the best measure for the limnological winter since the average water temperature is then very close to 4°C. The results confirm that the development of ice on these sheltered bays was largely controlled by the variations in the air temperature. The fitted multiple regression explained 46% of the variation and the most significant driving variable was the local air temperature ($p < 0.001$).

Historically, a variety of techniques have been used to determine the relationship between ice cover and the air temperature. The most widely used techniques are the fixed period regression method (Rannie 1983) and the moving average method described by McFadden (1965). In the fixed period method, the date of first freezing is related to the air temperature

Table 2 The influence of antecedent weather conditions on the number of ice-days recorded on Windermere. The dependent variable is ice-days and the meteorological averages have been calculated for the first ten weeks of each year

Parameter	Estimate	Standard error	T statistic	*P*-value
Constant	18.80	4.41	4.26	0.0002
Air temperature	−4.54	1.04	−4.34	0.0001
Rainfall	0.58	0.62	0.94	0.353
Wind speed	−0.03	1.11	−0.02	0.938

recorded during a predetermined interval of time. In the moving average method, the date of first freezing is estimated by noting the point at which a smoothed time-series of measurements fall below a pre-determined threshold. Figure 2A shows the result of correlating the date of first freezing with the average air temperature recorded every week from the beginning of December to the end of March. The results show that the highest correlations were recorded with measurements taken in the last two weeks of the year i.e. weeks 3 and 4. The best predictor of freeze-up was the temperature recorded in week 3, the penultimate week of the year. The linear regression in Fig. 2B shows the extent to which the date of first-freezing can be predicted from the average air temperature measured in week 3. The fitted regression only explained 21% of the measured variation but was still significant at the 1% ($p < 0.01$) level. Figure 3A shows the result of using a moving average to predict the onset of freezing. The example selected covers the period between 1 October 1940 and 31 March 1941. Preliminary analyses using a variety of smoothing 'windows' demonstrated that freezing occurred very close to the date when the 7-day running mean of the mean daily air temperature passed through 0°C. Ragotzkie (1978) found that the point of interception of a 3-day running mean provided the best predictor of freeze-up for shallow lakes up to 3 m deep. The average depth of the South Basin of Windermere is 40 m but the bays used for these measurements had an average depth of *ca.* 6 m. Figure 3B shows the extent to which this moving average method can be used to predict the freeze date on Windermere. There is a much stronger correlation ($r = 0.71$, $p < 0.001$) between the freeze dates predicted by the 7-day running mean and the actual freeze dates recorded between 1933 and 1999. The most pronounced difference between the predicted and the observed dates was that recorded during the winter of 1969 when the air temperature fell from +6 to –2°C in only 4 days. Once the lake has become isothermal, further reductions in the air temperature have a pronounced effect on the amount of heat lost from the surface. If there is very little wind, the cooling effect is confined to a thin surface layer which can then freeze in just a few hours.

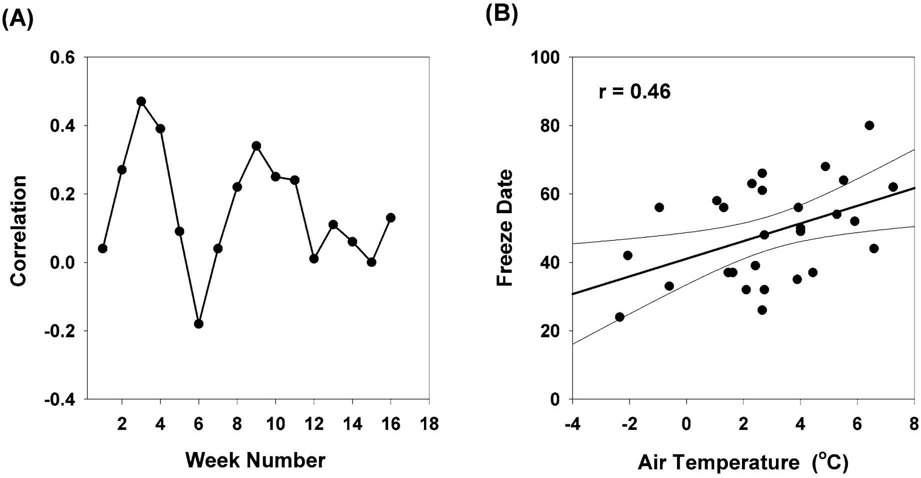

Fig. 2 (A) The correlation between the date of first freezing and the average weekly air temperatures measured each week from 1 December to 31 March. (B) The relationship between the date of first freezing and the average air temperatures measured in week 3

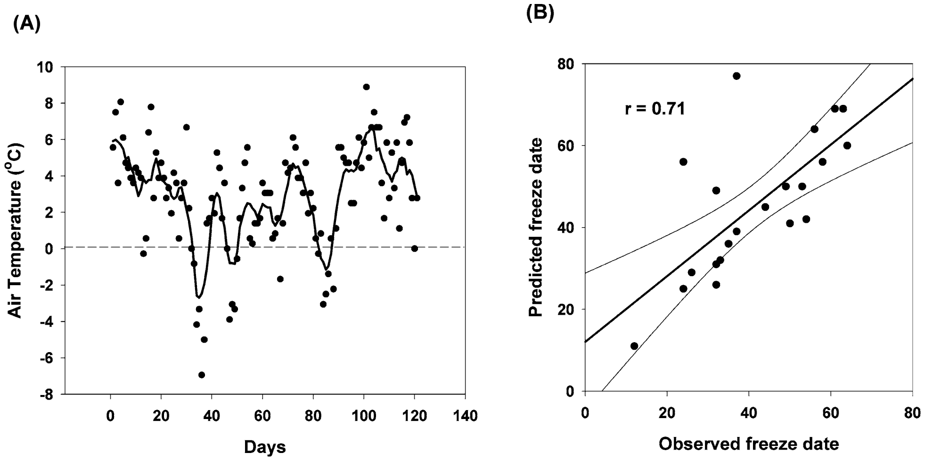

Fig. 3 (A) The result of using a seven-day moving average of the local air temperature to predict the date of first freezing. The example given is for the winter of 1940–1941. (B) The relationship between the date of first freezing predicted by the seven day moving average and the observed date of first freezing

3.3 The influence of the 'local' and 'regional' air temperature on the duration of ice cover and the date of first freezing

Figure 4A shows the relationship between the number of days when ice was recorded on Windermere and the average winter air temperature. The average winter air temperature is that calculated for the first ten weeks of each year i.e. the period used in the multiple regression analysis in Table 1. There was a strong negative correlation between the two variables ($r = -0.59$) and the fitted regression was significant at the 0.1% ($p < 0.001$) level. Figure 4B shows the relationship between the date of first freezing and the average winter air temperature. There was a positive correlation between the two variables ($r = 0.46$) and the fitted regression was significant at the at the 1% ($p < 0.01$) level. Figure 5A shows the relationship between the number of days when ice was recorded on Windermere and the average winter air temperature recorded in the 'Central England' series. There was a strong negative correlation ($r = -0.63$) between the two variables and the fitted regression was significant at the 0.1% ($p < 0.001$) level. The linear regression in Fig. 5B shows the relationship between the date of first freezing and the CET. There was a positive correlation between the two variables ($r = 0.39$) and the fitted regression was significant at the 0.1% ($p < 0.001$) level.

3.4 The influence of the North Atlantic Oscillation on the duration of ice cover and the date of first-freezing

Figure 6A shows the relationship between the number of days when ice was recorded on Windermere and the NAOI. There was a particularly strong negative correlation between the two variables ($r = -0.70$) and the fitted Poisson regression was statistically significant at the 0.1% ($p < 0.001$) level. Figure 6B shows the relationship between the date of first freezing and the NAOI. The correlation between the freeze date and the NAOI was somewhat weaker ($r = -0.59$) but the fitted Poisson regression was still statistically significant at the 0.1% ($p < 0.001$) level. An important point to note is the strength of these 'global-scale' correlations when compared with the 'local' and 'regional' correlations noted above. The best single

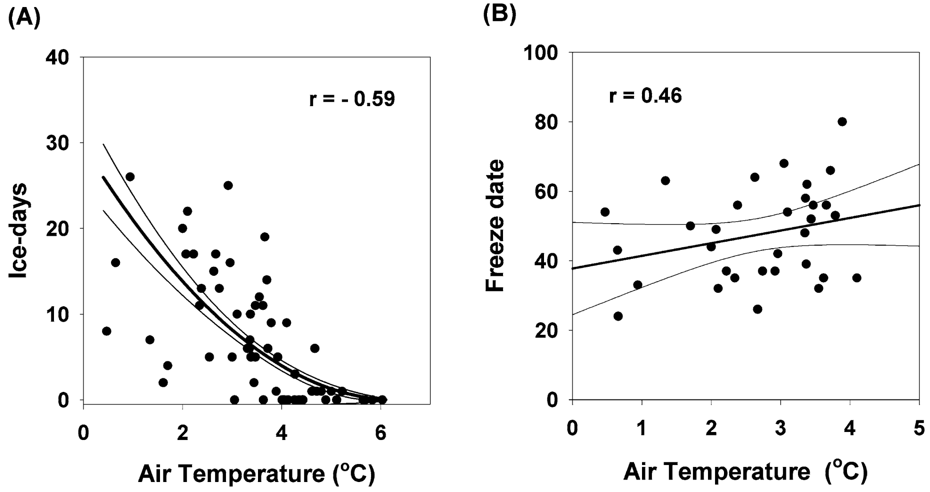

Fig. 4 (A) The relationship between the number of ice-days and the average winter air temperature. (B) The relationship between the date of first freezing (counted from 1 December) and the average winter air temperature

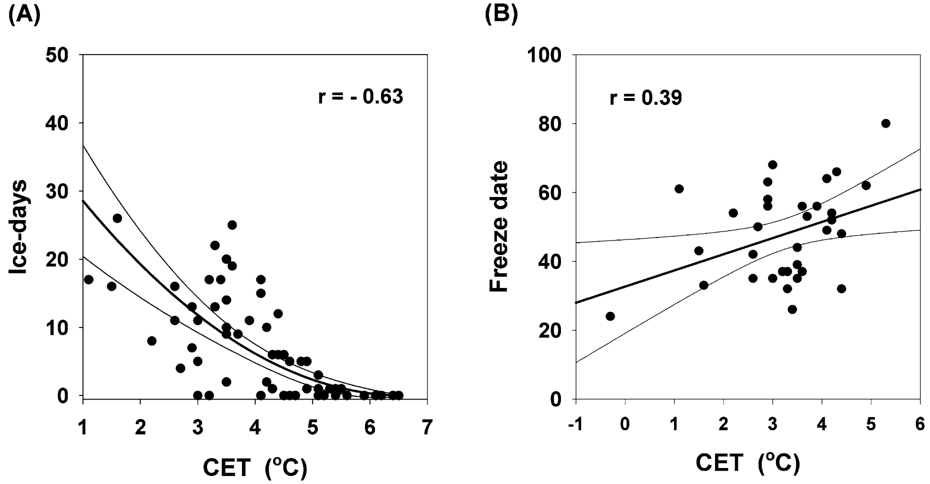

Fig. 5 (A) The relationship between the number of ice-days and the average winter air temperature in the 'Central England' series. (B) The relationship between the date of first freezing and the average winter air temperatures temperature in the 'Central England' series

predictor of the duration of ice cover on Windermere was the NAOI. The regression relating the number of ice-days to the NAOI explained 49% of the recorded variance in contrast to the 40% explained by the CET and the 35% explained by the local air temperature.

3.5 Using the NAOI to extend the historical record

The first scientific observation of ice on Windermere is that reported here for 1933. Annual estimates of the NAOI are, however, available for a much longer period and can be used to

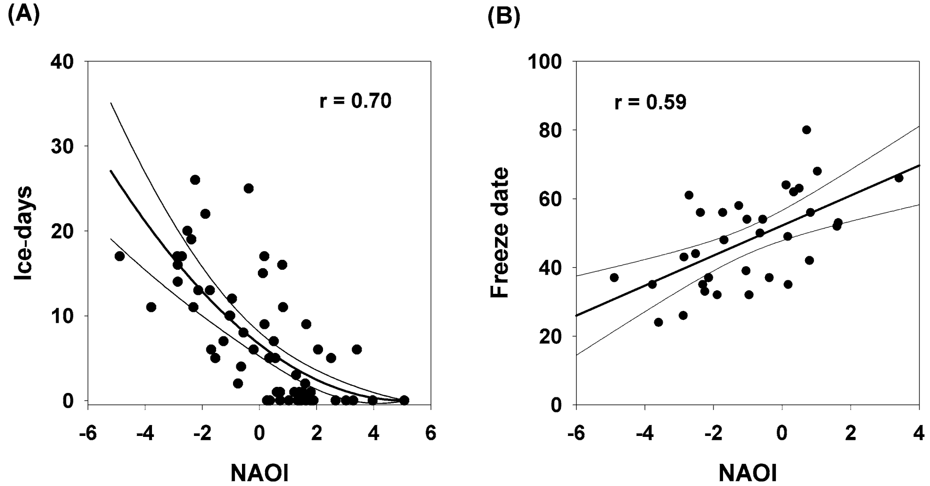

Fig. 6 (A) The relationship between the number of ice-days and the North Atlantic Oscillation Index. (B) The relationship between the date of first freezing and the North Atlantic Oscillation Index

'hindcast' the presence of ice on Windermere at the turn of the century. The time-series in Fig. 7 shows the number of ice-days predicted for the period between 1864 and 1910 and is based on the Poisson regression:

$$\text{Ice} = \text{days}^{0.5} = 7.66 + -2.49\text{NAOI}$$

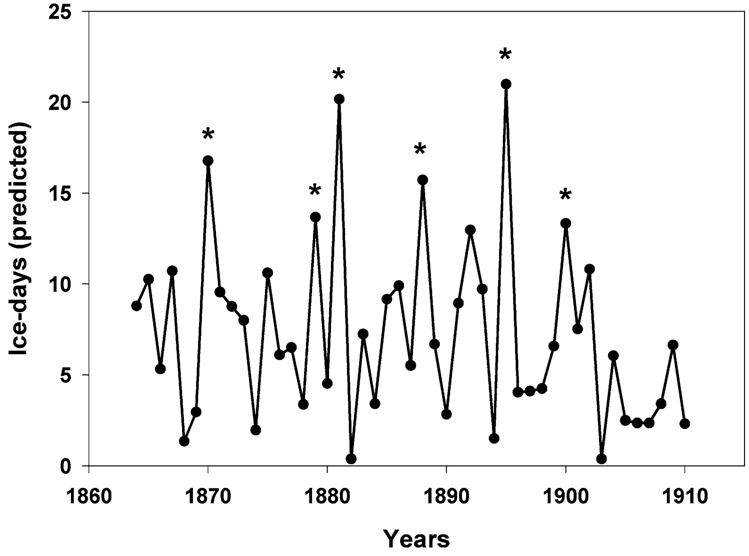

Fig. 7 'Hind-casting' the number of ice-days on Windermere using historical records of the NAOI (1864–1910). The asterisks mark the years when severe weather conditions were recorded in a local Almanack

This period is of considerable historical interest since the model predictions can then be compared with local records of exceptionally cold winters. The first railway connection to Windermere was established in 1847 and resulted in a rapid increase in the number of tourists visiting the area during the winter to skate on the lakes. The most reliable accounts of these activities are those given in the annual Almanacks produced by Titus Wilson in Kendal (Wilson 1864–1929). These Almanacks contain a wealth of information on extreme weather conditions and often refer to events where large numbers of people were skating on the lake. The asterisks in Fig. 7 identify all the severe winters reported in these publications between 1864 and 1910. The three ‘coldest’ winters predicted from the NAOI were the winters of 1871, 1881 and 1895. In the first cold winter (1871), there is no reference to skating on Windermere but the Almanack reports that an ice-boat was working on a local canal. In the second cold winter (1881) Windermere was reported to be frozen over by 9 January and there were several accounts of skating on Bowness Bay. In the third cold winter (1895), the ice-boat was again reported to be working on the canal and there were further reports of skating on the lake. It is worth noting that several exceptionally mild winters were also recorded during this early period. No ice was recorded in 1880 (one year after the second ‘big freeze’) or in 1894 (one year before the third severe winter). The only year where skating was reported on Windermere when the NAOI was not strongly negative was 1902. The NAOI for that year was –1.41 and the lake was reported as being ‘sufficiently frozen to allow skating’ by 12 February.

3.6 The association between the Windermere records and ice observations in other areas

The only data that can be directly compared with the Windermere records are the ice records from Loch Leven in southern Scotland and the Müggelsee in northern Germany. The climate in these areas is relatively mild and these lakes are also located at low altitude. A daily record of ice cover on Loch Leven was kept by staff from the Nature Conservancy between 1968 and 1995 and analysed by Alexander Lyle from the Institute of Freshwater Ecology (IFE 1996). There, the most reliable indicator of change was the number of days in each year when the loch was completely frozen. The loch is exposed to very strong winds so areas of partial ice cover can form and disperse in a few hours. Comparisons with Windermere nevertheless showed that there was a highly significant correlation between the two ice measurements ($r = 0.66, p < 0.001$). The only other western European lake with long-term ice records is the Müggelsee near Berlin (Adrian and Hintze 2000). In the Müggelsee, the statistic used was the number of days when $>80\%$ of the lake was covered with ice. Although, the period of observation was relatively short (1977–1998) there was still a significant positive correlation between this statistic and the number of ice-days reported on Windermere ($r = 0.52$, $p < 0.05$).

Year-to-year variations in the maximum extent of ice on the Baltic Sea provide one of the best indicators of severe weather in northern Europe. In mild winters, the ice is restricted to the Bay of Bothnia but in cold winters the whole of the Baltic is frozen. The most commonly used measure of Baltic ice is the maximum ice extent (MIE) as recorded in late February or early March. Systematic records of the MIE were started in the eighteenth century and have been analysed by Koslowski and Loewe (1994) and Koslowski and Glaser (1998). These analyses demonstrate that the development of ice is strongly influenced by the NAO and that severe winters are associated with synoptic situations with a weak westerly air-flow. The solid line in Fig. 8 shows the long-term changes in the MIE between 1864 and 1992. The MIE index was provided by Matti Leppäranta from the University of Helsinki and has been

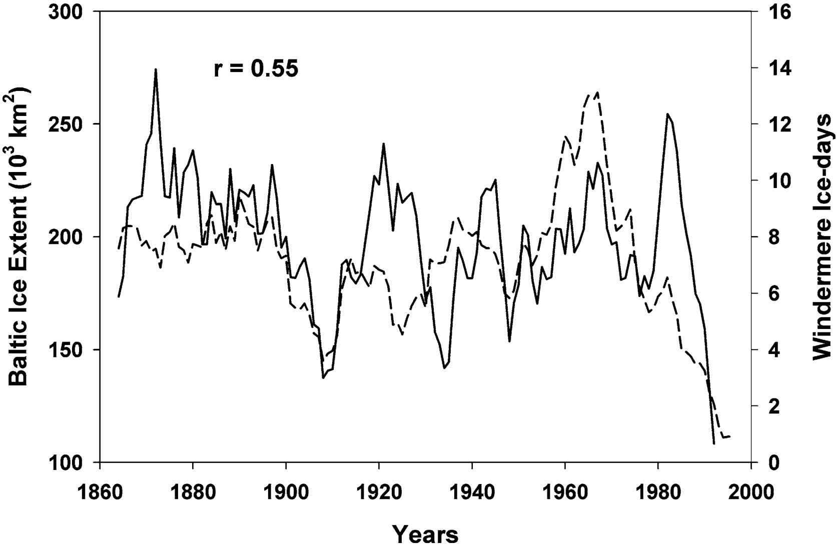

Fig. 8 The long-term variations in the predicted number of ice-days on Windermere (–) and the maximum annual extent of ice in the Baltic Sea (- - -). Both time-series have been smoothed using a 10-point moving average

smoothed using a 10-year moving average. The main features of interest are the unusually cold winters recorded in the 1870's and the 1920's and, to a lesser extent, in the 1940's and 1980's. In recent years, there has been a marked decrease in the area covered by ice but periods of reduced ice cover were also reported in the early 1900's. The broken line in Fig. 8 shows the predicted variation in the number of ice-days recorded on Windermere over the same period. This time-series has been generated using the NAOI as the driving variable and smoothed using the same 10-year moving average. The results demonstrate that the long-term changes projected for Windermere are very similar to those observed in the Baltic. The calculated correlation between the ice-days predicted for Windermere and the MIE was 0.55 ($p < 0.001$) but the two records diverged in the 1870's and 1920's as well as the 1980's. Chen and Li (2004) have shown that the correlations between the MIE and the atmospheric circulation are very time-dependent. They report that the strongest correlations appear at the longer time-scales (>64) years and the weakest at a time-scale of 32 years.

4 Discussion

Historical records of lake ice cover are becoming increasingly important as 'proxy' indicators of climate change. The most important records are those collated for lakes at high latitudes where the effects of global warming are most pronounced. Records of ice conditions in lakes located at lower latitudes are relatively rare but this study demonstrates that they can also be used as indicators of climatic change. The study also shows that the methods used to analyse the development of ice at high latitudes can also be applied to lakes at low latitudes. The best predictor of freezing on Windermere was the moving average method described by McFadden (1965). In the sheltered bays, the date of first freezing was very close to the date when a 7-day running mean of the daily air temperature passed through the 0°C threshold. Ragotzkie (1978) found that the point of interception of a 3-day running mean provided the best predictor of freeze-up for shallow lakes. The average depth of Windermere is 20 m but the bays used for the ice measurements had an average depth of around 6 m.

From a climate change point of view, the most significant feature of the Windermere time-series was the progressive reduction in the number of ice-days since the early 1960's. During this period, the number of ice-days fell by 0.39 days per year while the average winter air temperature increased by 0.05 °C per year. The only European ice records that can be directly compared with the Windermere observations are those for Loch Leven in Scotland and the Müggelsee in Germany. These records are very much shorter but the same reduction in ice cover has also been observed in the 1980's and 1990's. In the 21 years between 1977 and 1998 the number of ice-days reported on the Müggelsee fell by 2.6 days per year while the comparable reduction for Windermere was 1.0 days per year. No freeze dates are available for Loch Leven, but the recent records from Windermere and the Muggelsee follow the same general pattern. In Windermere, the average delay in the freeze date between 1977 and 1998 was 3.5 days per°C while the corresponding figure for the Müggelsee was 3.8 per°C. These results are very similar to those reported in northern Finnish lakes (3.3 days) and southern Finnish lakes (5.3 days) by Palecki and Barry (1986) and in a number of Canadian lakes (4.3 days) by Tramoni et al. (1985).

The most striking feature of the Windermere record was the strength of the correlation observed with the NAOI. Between 1933 and 2000, almost fifty percent of the year-to-year variations in the ice-days could be explained by fluctuations in the NAOI. Meteorologists have long been aware that the NAO has a dominating influence on the winter weather experienced at middle and high latitudes (Stephenson et al. 2003). These impacts are particularly strong in northern and western Europe but weaker effects have been detected as far east as Siberia (Livingstone 1999). The most comprehensive accounts of the impact of the NAO on lake ice are those given by Livingstone (1997) and Livingstone (2000). These studies are all based on the break-up dates of ice and demonstrate that an NAO 'signal' can be detected in lakes ranging from San Murezzan in the Swiss Alps to lake Baikal in eastern Siberia. The NAO 'signal' detected in Windermere is, however, much stronger than that detected in most of these lakes. The highest correlation reported by Livingstone (2000) was that between the break-up date of ice on Lake Kallavesi in Finland and the change in the NAO between 1941 and 1990 ($r = -0.65$, $p < 0.001$). The correlation between the number of ice-days reported on Windermere and the NAOI was –0.70 ($p < 0.001$).

The 'hindcasts' reported in this paper further suggest that the NAO has had a significant effect on the development of ice on Windermere for at least a hundred and thirty years. The very cold winters predicted in the 1880's and 1890's could all be substantiated by local records and there were references to mild winters in the intervening years. The predicted pattern of change on Windermere was also very similar to the observed pattern of change in the maximum ice extent in the Baltic. The MIE is one of the best indicators of change in the region and has recently been correlated with atmospheric circulation variations over a range of time-scales (Chen and Li 2004).

It is not yet clear what significance can be attached to the unprecedented number of ice-free winters reported in the 1990's. Much of this variation can be related to the ameliorating effects of the NAO but the index itself may be influenced by anthropogenic factors. Most climatologists agree that atmospheric processes are the primary drivers of the NAO but there is some evidence that the decadal-scale variations are driven by physical changes in the deep-ocean (Latif and Barnett 1995; Latif et al. 1996). Coupled ocean-atmosphere models are currently being developed to quantify the impact of regional air-sea interactions on the dynamics of the NAO. Until the impact of these feedback mechanisms are fully understood, we cannot be sure if the changes recorded in recent years are the direct result of global warming or part of a natural cycle. If the trends established in the 1990's continue, there will be no Windermere ice-records to analyse in the present century. The results presented here should, however, encourage others to collect ice cover records from lakes in western Europe, particularly those exposed to a more 'continental' climate.

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References

Adrian R, Hintze T (2000) Effects of winter air temperature on the ice phenology of the Müggelsee (Berlin, Germany). Verh Internat Verein Limnol 27:2808–2811

Anderson WL, Robertson DM, Magnuson JJ (1996) Evidence of recent warming and El-Nňio-related variations in ice breakup of Wisconsin Lakes. Limnol Oceanogr 41:815–821

Chen D, Li X (2004) Scale-dependent relationship between maximum ice extent in the Baltic Sea and atmospheric circulation. Glob and Planet Change 41:275–283

Assel RA, Robertson DM (1995) Changes in winter temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. Limnol Oceanogr 40:165–176

Davies TD, Viner D, Jones PD (1997) Changes in atmospheric circulation and climate over the North Atlantic and Europe. In: George DG, Jones JG, Puncochar P, Reynolds CS, Sutcliffe DW (eds) Management of Lakes and Reservoirs during Global Climate Change. NATO ASI Series, Kluwer, Dordrecht, pp 1–13

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: Regional temperature and precipitation. Science 269:676–679

IFE (1997). The Loch Leven ice record. Annual Report of the Institute of Freshwater Ecology (1995–1996). Institute of Freshwater Ecology, Windermere, p. 31

Jones PD, Osborn TJ, Briffa KR (2003) Pressure-based measures of the North Atlantic Oscillation (NAO): a comparison and an assessment of changes in the strength of the NAO and its influence on surface climate parameters. In: Hurrell JW, Kushnir I, Ottersen G, Visbeck I (eds) The North Atlantic Oscillation: Climatic Significance and Environmental Impact. Geophysical Monograph, 134, American Geophysical Union, Washington, pp 51–62

Koslowski G, Loewe P (1994) The western Baltic sea ice season in terms of a mass-related severity index: 1879–1992. Part 1. Temporal variability associated with the North Atlantic Oscillation. Tellus 46A:66–74

Koslowski G, Glaser R (1998) Variations in reconstructed ice winter severity in the Western Baltic from 1501 to 1995, and their implications for the North Atlantic Oscillation. Clim Change 41:175–191

Kuusisto E (1987) An analysis of the longest ice observation series made on Finnish lakes. Aqua Fennica 17:123–132

Latif M, Barnett TP (1995) Interactions of the tropical oceans. J Clim 8:952–964

Latif M, Kleeman R, Eckert C (1997) Greenhouse warming, decadal variability, or El Nino? an attempt to understand the anomalous 1990's. J Clim 10:2221–2239

Livingstone DM (1997) Break-up dates of alpine lakes as proxy data for local and regional mean surface air temperatures. Clim Change 37:407–439

Livingstone DM (1999) Ice break-up on southern Lake Baikal and its relationship to local and regional air temperatures in Siberia and to the North Atlantic Oscillation. Limnol and Oceanogr 44:1486–1497

Livingstone DM (2000) Large-scale climatic forcing detected in historical observations of lake ice break-up. Verh Internat Verein Limnol *Verh* 27:2775–2783

Magnuson JJ, Robertson DM, Benson BJ, Wynne RH, Livingstone DM, Arai T, Assel RA, Barry RG, Card V, Kuusisto E, Granin NG, Prowse TD, Stewart KM, Vuglisksi VS (2000) Historical trends in lake and river ice cover in the northern hemisphere. Science 289:1743–1746

Manley G (1974) Central England Temperature: monthly means 1659–1973. Quart J Roy Met Soc 100:389–405

McFadden JD (1965) The interrelationship of lake ice and climate in central Canada. Technological Report No. 20, Department of Meteorology, University of Wisconsin-Madison, Wisconsin

Palecki MA, Barry RG (1986) Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: a case study for Finland. J Clim Appl Met 25:893–902

Parker DE, Legg TP, Folland CK (1992) A new daily Central England temperature series. J Climatol 12:317–342

Ragotzkie RA (1978) Heat Budgets of Lakes. In: Lehrman A (ed) Lakes: Chemistry, Biology and Physics. Springer-Verlag, New York, pp 1–18

Rannie WF (1983) Break up and freeze up of the Red River at Winnipeg, Manitoba, Canada in the 19th century and some climatic implications. Clim Change 5:283–296

Stephenson DB, Wanner H, Bronnimann S, Luterbacher J (2003) The history of Scientific Research on the North Atlantic Oscillation. In: Hurrell JW, Kushnir I, Ottersen G, Visbeck I (eds) The North Atlantic Oscillation: Climatic significance and environmental impact. Geophysical Monograph, 134, American Geophysical Union, Washington, pp 37–50

Tramoni F, Barry RG, Key J (1985) Lake ice cover as a temperature index for monitoring climate perturbations. Zeit Gletsch Glaz 21:43–49

Wilson T (1864–1929) Wilson's Household Almanack. Titus Wilson, Kendal