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Atmospheric circulation and its impact on ice phenology in Scandinavia

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Atmospheric circulation is important in affecting surface climate and ecosystems. In this study, we compared the impact of north-atlantic and regional atmospheric circulation, as represented by the North Atlantic Oscillation (NAO) index and a set of regional circulation indices, on ice phenology of 50 Scandinavian lakes. Both ice freeze and ice break-up dates were coherent over the whole region and were significantly correlated with both types of circulation indices. Correlations were especially strong for regional circulation indices. The application of regional indices, here for the first time related with ice data over a large area, allowed the determination of the type (i.e. meridional/zonal wind and cyclonic/anticyclonic conditions) of atmospheric circulation influencing the ice phenology. The results suggest that regional circulation indices are very useful tools, in addition to global circulation, to improve the understanding of the interaction between ecosystem processes and climate.

Introduction

In northern Europe, the duration of the ice covered period and the timing of freeze and break-up greatly affect lake systems (Salonen *et al*. 1984, Weyhenmeyer *et al*. 1999, Järvinen *et al*. 2002). In particular, the timing of ice break-up largely influences the succession events in plankton dynamics (Weyhenmeyer *et al*. 1999, Gerten and Adrian 2000). The timing of the spring phytoplankton bloom for instance depends mainly on the ice break-up date as this physical factor determines light availability and mixing regime, both being of great importance for phytoplankton growth (Reynolds 1989, Huisman *et al*. 1999).

Data on lake freeze and thaw represents one of the longest and widespread limnological data. Changes in these timing events have been used as indicators for regional climate change and its variation (Robertson *et al*. 1992, Assel and Robertson 1995) because ice cover is a significant component of the annual heat budget of most polar and temperate lakes (Likens 2000). The timing of ice freeze and break-up is driven by several meteorological variables, of which air temperature has been shown to be the most important one (Palecki and Barry 1986, Robertson *et al*. 1992, Vavrus *et al*. 1996, Livingstone 1997, Weyhenmeyer *et al*. 2004).

In Europe, late winter and early spring temperatures are mostly influenced by the phases of

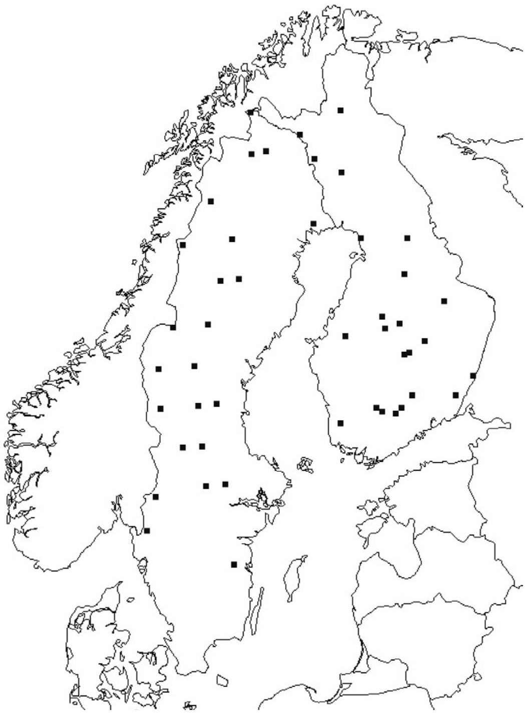

Fig. 1. Map of Fennoscandia showing the geographical position of the 50 lakes used in this study.

the North Atlantic Oscillation (NAO) (Hurrell 1995). The NAO is a measure of the difference in sea-level pressure between the Azores high and the Iceland low (Hurrell 1995). A positive phase of the NAO is associated with an anomalous low pressure in the subartic and high pressure in the subtropics, with stronger westerly winds and enhanced flow of warm and moist air across the North Atlantic and Europe. The NAO has been found to influence local variables such as temperature (Plaut *et al*. 1995, Chen and Hellström 1999), snowfall (Hartley and Keables 1998) and the timing of lake ice break-up (Livingstone 1999, Weyhenmeyer *et al*. 1999, Gerten and Adrian 2000, Yoo and D'Odorico 2002). A dependence on the NAO can be detected even in chemical and biological parameters (e.g. Ottersen *et al*. 2001, Blenckner and Hillebrand 2002, Straile *et al*. 2003).

However, more detailed information on local climate variability can be obtained from circulation indices, which are calculated over a smaller (regional) area (Lamb 1950), such as Scandinavia or the UK. Recently, Chen (2000) established such a set of circulation indices for Scandinavia on a monthly basis, based on a grid-point dataset for the northern hemisphere (Chen 2000). A statistical model of these circulation indices has been found to explain up to 70% of the total variance in January air temperature for Sweden (Chen 2000). The comparison between the NAO and the regional circulation showed that the regional circulation had a higher explanatory skill on ice phenology than the NAO. For example, 73% of the variation in the timing of ice break in Lake Erken (eastern Sweden) could be explained by the circulation indices whereas the NAO only explained 32% of the variation (Blenckner and Chen 2003). The other advantage of the regional circulation, next to its high explanatory skill, is the differentiation between the atmospheric forces (e.g. zonal/meridional wind components and cyclonic/anticyclonic conditions), in order to separate the different forces of the atmospheric circulation components on the target variable.

The aim of this paper is to analyse how the ice freeze and break-up of 50 Finnish and Swedish lakes respond to the NAO and regional circulation over the period 1961 to 2002. Both the spatial pattern and the coherence over the whole region will be tested. We hypothesize that lakes in the south will respond to different atmospheric flows as compared with the lakes in the north, due to differences in the topography.

Material and methods

Ice freeze and ice break-up data were analysed from 50 lakes, which are geographically spread over the whole of Sweden and Finland ranging from 58°N–69°N and 12°E–30°E (Fig. 1). All lake ice data comprised a fairly consistent period from 1961 to 2002 and were obtained from the Swedish Meteorological and Hydrological Institute, the Finnish Environment Institute and the Lammi Biological Station of the University of Helsinki.

The atmospheric circulations for Scandinavia calculated by Chen (2000) were used as a measure for regional-scale circulation. The digital data file can be obtained from the homepage at http://www.gvc.gu.se/ngeo/deliang/deliang.htm. The circulation is represented by zonal (u) and meridional (v) geostrophic wind components and total vorticity (ξ). For each circulation type one index for the whole of Scandinavia is computed based on calculated monthly mean sea level pressure data on a 5° latitude by 10° longitude grid point basis bounded by latitudes 52.5°N–72.5°N and longitudes 5°E–27.5°E (for details *see* Chen 2000).

The winter (December–March) and autumn (September–November) NAO indices were taken from the homepage of the National Centre for Atmospheric Research, U.S. at http://www.cgd.ucar.edu/~jhurrell/nao.pc.html. The index is derived from the principal component time series of the leading empirical-determined orthogonal functions of sea level pressure (for further explanations *see* the homepage above). It provides an optimal representation of the full NAO spatial pattern. In comparison to the regional circulation indices, the NAO comprises more the zonal flow.

Correlation analysis with the Pearson correlation coefficient (r) was employed to establish relationships between any paired variables of interest. Additionally, we applied a normality test (i.e. Shapiro-Wilk's W-test). If the test was significant (i.e. not normally distributed) the data were log transformed. When applying the three regional circulation indices, a stepwise multiple regression method was used. The number of predictors kept in the model was controlled by an F-test, with a significance level for a selected predictor set at 95%. All statistical analyses were performed using Statistica® (StatSoft 1996).

Results

Spatial variation in ice freeze and break-up dates

The freeze and ice break-up dates of the Swedish and Finnish lakes showed an explicit tendency towards latitude (*see* Table 1 and 2). In general, southern lakes froze later (beginning to middle December) and thawed earlier (April to beginning of May) than northern lakes (beginning of November and middle of May to beginning of June). In Sweden, the ice freeze was –2.8 days/degree latitude ($r = -0.50$, $p < 0.05$) and the break-up was 5.4 days/degree latitude ($r = 0.91$, $p < 0.0001$) changing towards the north. In Finland, the ice freeze was –4.5 days/degree latitude ($r = -0.83$, $p < 0.0001$) and the ice break-up was 4.5 days/degree latitude ($r = 0.96$, $p < 0.0001$) changing towards the north. There was a clear trend in the standard deviation of the ice break-up in the Swedish lakes, indicating a higher variation in the ice break-up dates in the south than in the north, with a clear change in the relationship around 62°N (Table 1). This tendency was less pronounced in the ice freeze and totally absent in the ice break-up dates of the Finnish lakes (Table 2). Therefore, we grouped the lakes in three groups for Sweden: south, SS (58–60.9°N), middle, MS (61–64.9°N) and north, NS (> 65°N) and 2 groups for Finland: south, SF (61–64.9°N) and north, NF (> 65°N).

Temporal variations in ice freeze and break-up dates

The long-term series of the grouped data for the ice freeze dates showed no clear trend towards a later freeze date in the recent decade. A linear correlation analysis with time indicated that only 6 lakes froze later in recent years (N. Kornsjön, Västlandasjön, Västervattnan, Simpelejärvi, Oijärvi, Unari), whereas all the groups as defined were not significant. In general, the variability in freeze dates declined towards the north, with a lower variability in Sweden as compared with that in Finland (Table 3).

In the grouped long-term data of ice break-up dates, a significant downward trend with time was obvious in southern lakes in both countries, indicating an earlier ice break-up in recent years (Fig. 2). However, no clear trend was detectable for the other regions. Of individual lakes, only some in SF (Pielavesi, Lappajärvi) and in the north of both countries (Djupträsket, Bouktjaure, Troneträsk, Unari, Ounasjärvi, Mutusjärvi) showed a significant trend, but this could not be seen for any lake in MS. The effects of the extreme warm winters in 1989 and 1990 were only obvious in the ice phenology of the southern lakes (Figs. 2 and 3). However, a strong declining trend in the timing of ice break-up from 1995 onwards was found for all regions.

Coherence

Coherence of the ice freeze presented a clear pattern (Table 4). The SS region was similarly correlated with MS and with SF. Nevertheless, MS was more closely correlated with the north (82%) than with the south (66%). In Finland, the southern region was stronger correlated with SS (62%) and MS (65%) than with NF. The lakes in NS were more closely related to the lakes in the middle region (MS) in the same country than to those of the same latitude in Finland (NF).

The dates of ice break-up are strongly correlated in the following regions (Table 5): south (71%) and north (89%). Again, the correlation between MS and NS is higher than that between the MS and SS, whereas the lakes in northern Finland were stronger related to the lakes in NS than to SF lakes.

North Atlantic Oscillation

The correlation between the NAO in autumn (NAO_{SON}) and the ice freeze dates for the regions was significant (Table 6) with the exception of NF. The winter NAO (NAO_{DJFM}) was strongly correlated with the ice break-up in all regions, ranging from 55% (SS) to 19% (NF). In Sweden, the relationship between the NAO and the timing of ice break-up decreased with increasing latitude, indicating that the lakes in SS were more influenced by the NAO as compared with those in the other regions (Fig. 4). This gradient was totally absent in the Finnish data (Fig. 4).

Regional circulation

As compared with the NAO_{SON} index, the

Table 1. Basic description of the ice onset and ice break-up of the Swedish lakes with the number of samples (*n*), the average (mean), the minima (min), the maximum (max) and the standard deviation (SD). Ice onset on 31 December = 0. Ice break-up = days from 1 January.

Lake			Ice freeze				Ice break-up			
	Latitude (°)	*n*	mean	min	max	SD	mean	min	max	SD
Önn	58.17	41	–18	–43	31	15	99	35	126	18
Fåfallasjön	58.18	41	–19	–52	73	19	98	32	122	18
N. Kornsjön	58.88	41	–25	–50	62	18	103	29	130	22
Västlandasjön	59.53	41	–37	–59	–6	13	105	54	126	15
Stora Flat	59.62	41	–37	–62	30	17	114	57	133	14
Dammsjön	59.73	41	–32	–56	–4	12	118	81	135	11
Björken	60.23	41	–38	–57	–6	12	118	80	136	11
Bysjön	60.25	41	–36	–56	–6	11	118	83	135	10
Öjen	60.78	41	–41	–66	–12	12	129	110	169	10
Orsasjön	61.00	41	–20	–47	14	12	125	90	139	9
Orsjön	61.53	41	–35	–56	–10	9	127	106	144	8
Västervattnan	62.33	41	–64	–81	–42	9	145	129	156	7
Rätan	62.48	41	–50	–65	–32	7	136	118	151	7
Storsjön	62.78	41	–47	–69	–2	10	144	125	157	7
Näckten	62.90	41	–24	–53	0	11	136	117	151	7
Tåsjön	64.15	41	–33	–53	–4	10	140	121	178	8
Murusjön	64.45	41	–30	–51	–10	10	138	119	153	7
Bäsksjön	64.72	41	–67	–86	–33	11	142	123	156	7
Jåkarn	64.90	41	–68	–84	–31	10	138	124	149	6
Västansjön	65.73	41	–53	–71	–29	9	153	135	165	6
Skärfajaure	66.43	41	–52	–69	–32	8	153	138	164	6
Djupträsket	66.32	41	–56	–76	–31	10	138	122	153	6
Bouktjaure	66.75	41	–65	–82	–46	8	141	125	151	6
Jukkasjärvi	67.78	41	–62	–82	–38	10	151	123	164	8
Torneträsk	67.78	41	–10	–42	22	12	163	137	181	9

explained variability of the ice freeze dates was generally higher in regional circulation indices, ranging from 25% to 45% (Table 7). The dates of ice freeze were influenced by the combination of the meridional and zonal wind component in November in both southern regions. In middle Sweden, the *v* component in October and November was of relevance. In the northern region, different variables were important. In NS, the *v* component in September and October together with the vorticity in October were of importance. In NF, the vorticity in September in combination with the *u* wind in October were of relevance.

Table 2. Basic description of the ice onset and ice break-up of the Finnish lakes with the number of samples (*n*), the average (mean), the minima (min), the maximum (max) and the standard deviation (SD). Ice onset on 31 December = 0. Ice break-up = days from 1 January.

Lake			Ice freeze				Ice break-up			
	Latitude (°)	*n*	mean	min	max	SD	mean	min	max	SD
Pääjärvi	61.03	37	–19	–46	20	15	121	103	136	8
Saimaa	61.04	38	–29	–51	0	13	120	94	131	7
Pyhäjärvi	61.06	34	–28	–59	20	15	120	91	134	10
Vesijärvi	61.10	25	–31	–48	–11	11	126	108	138	6
Päijänne	61.10	27	–22	–41	15	14	125	103	138	7
Iso-Roinevesi	61.12	35	–27	–52	–1	12	123	101	137	7
Längelmävesi	61.25	38	–32	–61	12	15	121	110	129	6
Jääsjärvi	61.33	26	–44	–72	–6	15	124	105	135	7
Simpelejärvi	61.36	41	–38	–69	–6	14	122	98	138	8
Konnevesi	62.36	33	–34	–61	–4	14	127	111	149	7
Hankavesi	62.37	28	–38	–61	–3	15	123	104	136	6
Kallavesi	62.53	41	–31	–58	–3	11	116	91	131	9
Kolimajärvi	63.10	31	–45	–73	–6	15	128	111	149	7
Pielavesi	63.11	32	–43	–71	–10	13	131	119	142	6
Lappajärvi	63.15	36	–40	–68	–6	13	129	116	139	6
Nurmesjärvi	63.32	33	–43	–77	–9	13	131	118	145	6
Pyhäjärvi	63.40	40	–49	–84	–13	16	131	120	142	6
Oulujärvi	64.23	32	–48	–72	–26	12	132	119	141	6
Naamankajärvi	65.05	34	–58	–78	–37	11	130	115	149	7
Oijärvi	65.37	41	–66	–85	–40	11	132	118	148	7
Unari	67.08	40	–65	–85	–40	10	134	120	150	7
Jerisjärvi	67.56	41	–72	–85	–48	8	138	124	152	6
Ounasjärvi	68.23	41	–66	–81	–42	9	139	126	153	7
Mutusjärvi	68.56	41	–54	–77	–22	10	136	123	151	7
Kilpisjärvi	69.02	42	–55	–109	–35	11	133	120	143	5

Table 3. Regional lake statistics of the ice onset and the ice break-up dates with the number of samples (*n*), the average (mean), the minima (min), the maximum (max) and the standard deviation (SD).

		Ice onset				Ice break-up			
	n	mean	min	max	SD	mean	min	max	SD
SS	42	–31.8	–50.2	–5.5	10.7	111.7	64.3	130.7	13.5
MS	41	–44.0	–61.5	–24.1	7.2	137.5	118.6	150.0	6.4
NS	41	–49.9	–65.0	–31.2	7.4	150.2	133.3	160.0	6.1
SF	42	–36.0	–58.3	–7.2	11.7	127.2	110.9	137.6	5.7
NF	42	–63.1	–78.5	–40.4	8.5	149.8	136.7	162.0	6.5

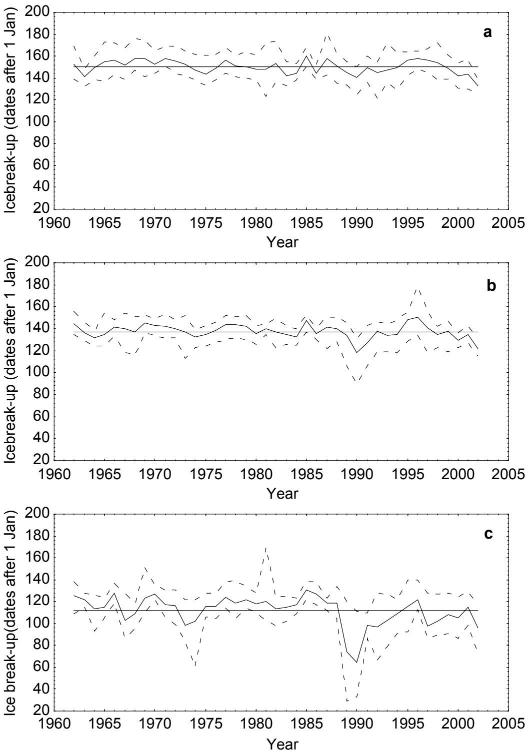

Fig. 2. Ice break-up dates from (**a**) northern, (**b**) middle and (**c**) southern Sweden showing the mean (the middle line), the minimum (the lower line) and the maximum (upper line) values. The long-term average is also given (the straight line).

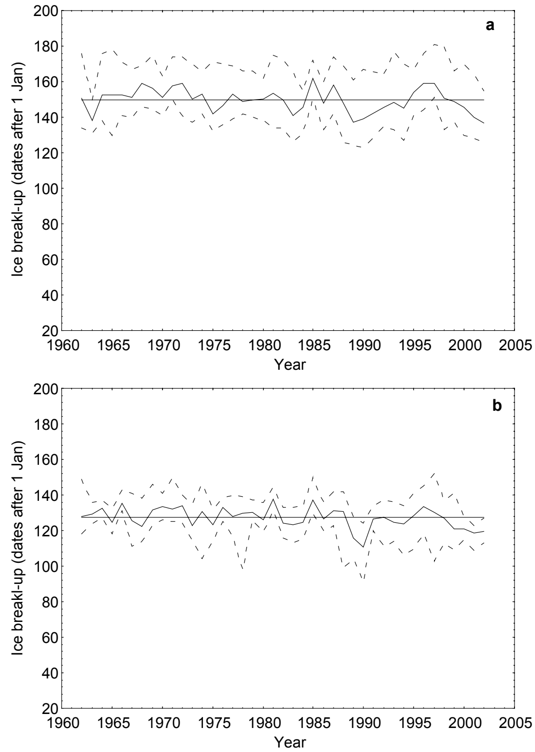

Fig. 3. Ice break-up dates from (**a**) northern and (**b**) southern Finland showing the mean (the middle line), the minimum (the lower line) and the maximum (upper line) values. The long-term average is also given (the straight line).

Table 4. Coherence (a mean Pearson product moment correlation coefficient, *r*) of ice onset. All correlations significant at least at < 0.05.

	SS	MS	NS	SS
MS	0.66			
NS	0.46	0.82		
SF	0.62	0.65	0.47	
NF	0.34	0.71	0.68	0.47

Table 5. Coherence (a mean Pearson product moment correlation coefficient, *r*) of the timing of ice break-up, All correlations significant at least at < 0.01.

	SS	MS	NS	SF
MS	0.66			
NS	0.42	0.78		
SF	0.71	0.70	0.57	
NF	0.44	0.68	0.89	0.68

The explained variance in ice break-up dates was high, ranging from 43% to 76%. The southern region was mostly determined by the zonal wind in January, February and March as well as by the meridional wind in May. In middle Sweden, the ice break-up depended on the zonal wind in January and May. The northern region depends on the zonal wind in January and May

Table 6. Correlation coefficients between ice onset/break-up and the NAO_{SON} and NAO_{DJFM}. Significance levels are $p < 0.01$ (**) and $p < 0.0001$ (***); n.s. non-significant.

	Ice onset NAO_{SON}	Ice break-up NAO_{DJFM}
SS	0.40*	–0.74***
MS	0.53**	–0.52***
NS	0.41**	–0.49**
SF	0.46**	–0.53***
NF	n.s.	–0.44**

together with the vorticity in January (NF) and February (NS) (*see* also Table 3).

Discussion

The focus of our study was to use for the first time in a geographically broad comparison (ranging from 58°N–69°N and 12°E–30°E) atmospheric circulation indices (NAO and the regional circulation) as atmospheric indicators of lakes in Sweden and Finland. A similar kind of approach has earlier been carried out for hydrological characteristics of Finnish and Russian lakes and their response to atmospheric indices (Gronskaya *et al*. 2002).

A general description of the ice phenology data was necessary in order to analyse the spatial

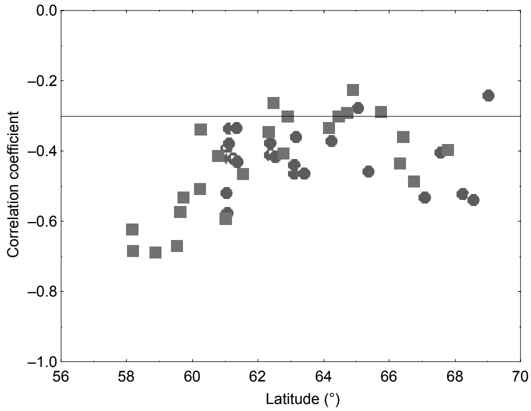

Fig. 4. Correlation coefficient of the NAO_{DJFM} and the ice break-up dates over the whole latitudinal gradient for Sweden (■) and Finland (●). The line represents the 0.05 significance level.

Table 7. Multi regression on the dependent variables ice onset and ice break-up by applying the regional indices. Listed are the explained variance (r^2), the *F* ratio, and the significance levels (*$p < 0.05$, **$p < 0.01$, ***$p < 0.0001$) for the complete regression model. Furthermore, estimates of the regression coefficient (*B*) are given for the intercept and each independent variable included in the model.

Dependent variable	Region	r^2	*F*	*P*	Intercept	Variable included	*B*
Ice freeze							
	SS	0.38	5.05	< 0.01	–39.83	v_{Nov}	0.51**
						u_{Nov}	0.35**
	SF	0.45	7.11	< 0.01	–47.33	v_{Nov}	0.53**
						u_{Nov}	0.35*
	MS	0.40	5.73	< 0.01	–52.61	v_{Nov}	0.48*´
						v_{Oct}	0.37*
	NS	0.25	2.88	< 0.05	–54.99	v_{Nov}	0.38*
						v_{Sep}	0.35*
						ξ_{Oct}	–0.34*
	NF	0.32	5.54	< 0.01	–69.95	ξ_{Sep}	–0.42**
						u_{Oct}	0.42**
Ice break-up							
	SS	0.76	26.45	< 0.0001	125.00	u_{Mar}	–0.42***
						u_{Jan}	–0.36**
						v_{May}	0.33**
	SF	0.59	12.33	< 0.0001	130.86	u_{Mar}	–0.40**
						u_{Feb}	0.32**
						v_{May}	0.31**
	MS	0.43	6.49	< 0.01	139.66	u_{Jan}	–0.34*
						u_{May}	–0.31*
	NS	0.46	7.42	< 0.0001	154.04	u_{Jan}	–0.42**
						u_{May}	–0.29*
						ξ_{Feb}	0.28*
	NF	0.55	7.77	< 0.0001	154.60	u_{May}	–0.42**
						u_{Jan}	0.38**
						ξ_{Jan}	–0.34*

differences among the lakes. An expected trend towards latitude was detectable, which has also been found in other studies for Finnish (Palecki and Barry 1986) and for Swedish lakes (Eklund 1999) as well as in North American lakes (Assel and Herche 2000). Laaksonen (1976) found a decrease of the annual temperature of 0.49 °C per degree latitude, indicating that the temperature effect is strong in the latitudinal gradient.

More surprising was the fact that strong change of the variability appears below 62°N. Related to that, it was previously noted by Ångström (1974) and Hellström *et al*. (2001) that temperature and precipitation variability in Sweden as well as ice break-up dates (Weyhenmeyer *et al*. 2004) completely change around the same latitude. The reason for this drastic change can be assumed to be the Scandes (the mountain range between Norway and Sweden), which drastically affect the zonal circulation. This geographical pattern might also explain why no single lake in middle Sweden, at least from our lake list, showed any trend in the freeze and break-up dates over time. It should be kept in mind that the indices are calculated for the sea level. Therefore, they have different impact on mountain and plain areas. For example, the mountain range would slow down the westerly atmospheric flow, as the lakes are situated at the lee side of the mountain chain. In the north (as compared with the middle region), more lakes show a trend towards an earlier ice break-up, which is an indication for a warming trend in the northern latitude. Extreme warm winters, like those in 1989 and 1990, are obvious in the southern ice data, whereas their impact was totally absent in the north. This can be explained by the much lower average winter temperature in the north. This means that an equivalent change in, for example, break-up dates in the southern and northern regions would indicate a larger magnitude shift of temperature in the northern region, as also shown by Palecki and Barry (1986).

The coherence between the regions was significant. This was expected as the variation of physical variables (e.g. ice phenology) is more coherent between the lakes than variations in chemical or biological variables (Magnuson *et al*. 1990, George *et al*. 2000). However, the lakes in MS are more related to those in the north. It may also explain the strong and significant relationship between the correlation coefficient of the NAO with the ice break-up dates and the latitude in Sweden (*see* Fig. 4). The effects of the NAO have been found to be most pronounced in winter (Hurrell 1995). This is the reason why the NAO_{SON} explains the ice freeze variability to less extent (28%) than the winter NAO does for the ice break-up (up to 55%). Generally, it appears as if the influence of the NAO on local climate is less pronounced north of 65°N. In fact, Chen and Hellström (1999) found also a much stronger correlation between the NAO and the monthly air temperature in winter in SS as compared with that in NS. In the same study, they found that the persistency of monthly air temperature is different between these two regions, indicating that the two subregions are affected by different circulation regimes.

Conclusively, there might be a different circulation which dominates the northern region as indicated by Busuioc *et al*. (2001) and D. Chen (unpubl. data).

When testing the impact of circulations on a smaller scale, we found that the general explanatory skill of regional circulation indices was much higher, ranging from 25% to 45% for the ice freeze and from 43% to 76% for the ice break-up data. In terms of the ice freeze, the combination of meridional and zonal wind in November was important, one reason why the relationship between the NAO_{SON} and the ice freeze dates was significant. In middle and northern Sweden, the conditions in October play an important role. This can explain why the coherence of middle with northern Sweden is higher than with the south. Northern Finland is influenced by the vorticity in September and the zonal wind in October.

The ice break-up in southern Finland and Sweden was mostly influenced by the zonal wind in March, as westerly (easterly) wind brings warm (cold) and moisty (dry) air from the Atlantic (Siberia) and so leads to an earlier (later) ice break-up. In the both regions, the meridional wind in May appears to be important, as in some extreme years the ice break-up occurred in May, where probably northern wind transported cold air into the region. Middle Sweden differed in the response to the atmospheric circulation and the strength of the relationship as this was low in middle Sweden ($p < 0.01$, $F = 6.49$). The timing of ice break-up in this area is probably more determined by the very local climate because of the topography, the lee side of the Scandes during westerly atmospheric flow, which was also shown by Uvo (2003). By moving to the north, the zonal component of January becomes important for both regions, whereby NF is more influenced by the zonal wind in May than Sweden. In this region, the timing of ice break-up is more influenced by the weather conditions in May as the mean date of ice break-up is later compared to NS, which is also reflected in the lower correlation coefficient with the winter NAO.

This encompassing analysis clearly displayed the strong impact of the regional circulation and demonstrated to what extent atmospheric circulation influences the heat budget of lakes. Generally, the timing of ice break-up is more strongly related to atmospheric processes than ice-on as it is predominantly steered by temperature and wind, while the ice freeze is also fairly dependent on lake morphometry (Palecki and Barry 1986, Eklund 1999).

Our results clearly indicate the influence of the large-scale (NAO) and regional scale circulation on local lake ice phenology. This has strong implications on abiotic and biotic lake processes (Weyhenmeyer *et al*. 1999, Gerten and Adrian 2000). Moreover, this type of analysis is, to our best knowledge, the first study showing the strong and varying influence of regional atmospheric flows on Scandinavian lake ice cover. From these results, it can be concluded that atmospheric circulation is a key actor in determining the winter climate and hence the ice conditions in Scandinavian lakes (over a wide geographical area) and probably also elsewhere. With the regional circulation indices the impact of climate can be studied in a more process-oriented way to assess which circulation pattern influences the system. This approach has the advantage over that of the NAO index of describing in principle only the zonal flow. Furthermore, it has been shown that the impact of the NAO on ice phenology is not stationary over time (Livingstone 1999, Omstedt and Chen 2001), whereas the application of regional circulation indices has already been found to have a stable impact over time (Omstedt and Chen 2001). Therefore, regional circulation indices are a useful tool for climate impact assessment studies for physical variables such as lake ice, but also for chemical and biological processes (Blenckner and Chen 2003) in lakes and ecosystems in general.

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