Long-term characteristics of ice phenology in Karelian lakes

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Received 7 December 2011, accepted 16 January 2013

Abstract. The statistical relationships between lake ice phenology (freeze and break-up dates, ice duration), air temperature and North Atlantic Oscillation (NAO) index are analysed for eight lakes in Karelia from 1950 to 2009. Linear trends over this time period are estimated. It is shown that in the last 20 years trends in the timing of ice phenomena are more evident than in the entire 60-year period. The statistical relationship between lake ice phenology and variability of regional air temperature is used in the empirical model to assess ice-related events on previously unstudied lakes in NW Russia.

Key words: long-term data, lakes, ice phenology, climate change.

INTRODUCTION

The formation and melting of ice are important seasonal processes in the temperate zone. The timing of initial ice cover freezing and final thawing and the duration of the ice-covered period are referred to as ice phenology. Ice phenology is sensitive to synoptic conditions and climatic variability (Palecki & Barry 1986; Magnuson et al. 2000; Adrian et al. 2009; Livingstone et al. 2009) and individual characteristics of lakes (Stewart & Haugen 1990; Williams et al. 2004). In the Northern Hemisphere (North America, Northern and Central Europe), air temperature has increased in recent decades, especially in winter and spring. This has resulted in trends of later freezing, earlier break-up and shorter ice cover duration (e.g., Assel & Robertson 1995; Livingstone 2000; Magnuson et al. 2000; Futter 2003; Weyhenmeyer et al. 2004, 2011; Duguay et al. 2006; Korhonen 2006; Jensen et al. 2007; Bernhardt et al. 2012). For Russia, this information is available only for the largest lakes: Baikal, Ladoga and Taimyr (Gronskaya & Lemeshko 2004; Karetnikov & Naumenko 2008; Shimaraev 2008). The resulting trends give evidence of later freezing and earlier break-up, and thus a reduction of ice cover length due to increasing air temperatures.

An extensive amount of long-term observational data on ice events published for the lakes of Northwest Russia for the period 1881–1953 (Piotrovich 1958) and summarized in the hydrological yearbooks (1936–1989) was used to develop a stochastic model (Efremova & Palshin 2011). The present study aims to evaluate the linear trends of ice events for a 60-year period (1950–2009) in eight lakes of Karelia and define their relationship with the global parameter variability of the North Atlantic Oscillation (NAO) index and the regional characteristics of the air temperature, as well as to improve a previously developed empirical model for assessment of ice events due to climatic effects.

MATERIALS

A detailed analysis of long-term data of ice events for 72 lakes in Northwest Russia (Fig. 1), including 7 lakes located on the territory of Belarus and Estonia, was performed to determine which geographical factors are most important in predicting the date of freeze and break-up (Efremova & Palshin 2011). For 55 lakes we gathered annual data from hydrological yearbooks for the period from 1936 to 1989. For 35 lakes we used previously averaged published data (Piotrovich 1958) from 1881 to 1953. The time series of measured ice parameters differ among the lakes and also have different duration, from 11 to 72 years. About 45% of lakes in question have been monitored for over 40 years and 23% during less than 20 years. The lakes are situated between 55° and 67°N and 28° and 37°E (Fig. 1). Their morphometric features vary in a wide range. Some characteristics of the lakes are shown in Table 1.

Ice phenology data (dates of freeze, break-up and number of ice cover days) of eight lakes in the Republic of Karelia (1950–2009) are used to detect the response of different types of lakes to changes in regional climate. Lakes Topozero, Segozero, Rugozero, Vigozero, Syamozero, Vodlozero, Tulmozero and Onego are located in the northern, central and southern parts of Karelia and have

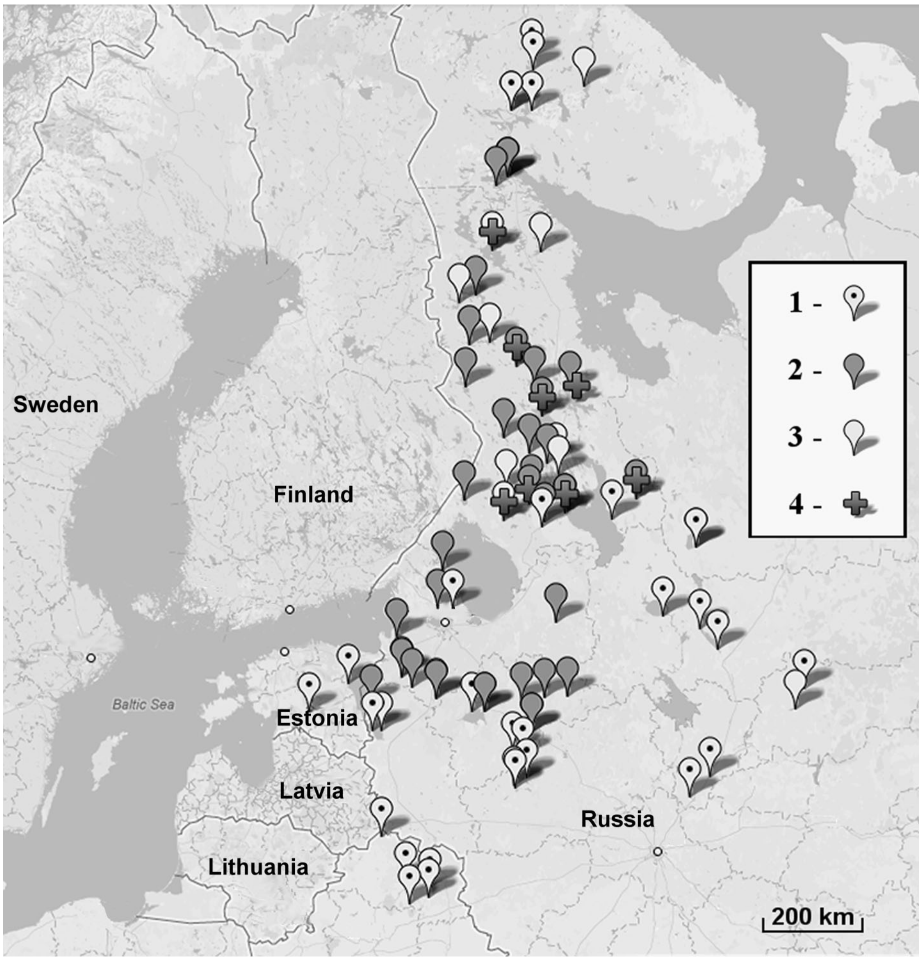

Fig. 1. Map of the study area and investigated lakes with the following observation periods: 1, 1881–1953 (Piotrovich 1958); 2, 1936–1989 (hydrological yearbooks); 3, closed bays; 4, data for the Republic of Karelia with the observation period up to 2009.

Table 1. Characteristics of the lakes

Parameter	Range
Latitude, deg., from–to	54°42′–68°21′N
Longitude, deg., from–to	25°37′–42°41′E
Elevation above sea level, m	8.6–204.8
Area, km^2	0.36–2670
Mean depth, m	1.1–29
Max depth, m	4.3–103
Volume, km^3	0.002–23.4
Residence time, year	0.06–76.8

significantly different morphometric characteristics (Fig. 1, Table 1). Observational data have been gathered by the Republic of Karelia Center for Hydrometeorology and Environmental Monitoring. The closest representative weather station was chosen for each lake. For comparability all data on air temperature, NAO indices and ice phenology are considered for the same period 1950–2009.

RESULTS AND DISCUSSION

Year-to-year changes in the weather have a profound effect on the seasonal dynamics of lakes. One of the most important factors influencing the winter weather in northern Europe is the atmospheric feature known as the NAO (Hurrell 1995, 1996). In Karelia the NAO index (NAOI) accounts for 36–40% of the variation in air temperature during winter months (December–March) ($r > 0.6$, $p < 0.001$).

Analysis of observational data from eight weather stations associated with the lakes presented in Table 2 showed that the increase in the mean annual air temperature during the study period was 0.2–0.3 °C/decade ($p < 0.01$). Changes in the average monthly air temperature are not uniform. The most significant warming occurred in spring (March–April). The average increase in the air temperature in March was 0.5–0.6 °C/decade and in April 0.3–0.5 °C/decade ($p < 0.05$) at all the weather

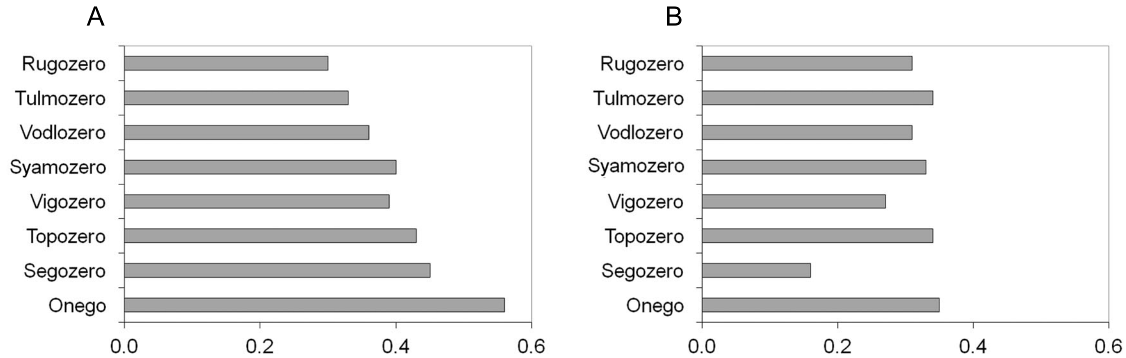

Fig. 2. Correlation coefficients (absolute values) between NAOI (January–February) and the break-up dates (**A**); between NAOI (October, November) and freezing dates (**B**) in 1950–2009. Lakes are listed from top to bottom according to increasing water volume.

Table 2. Limnological features of the Karelian lakes

Lake	Location	Altitude, m	Area, km^2	Mean depth, m	Max depth, m	Volume, km^3
Onego	61°48′N, 34°26′E	33.3	9777.4	26.8	119	262
Rugozero	64°04′N, 32°45′E	129.1	10.7	2.5	8	0.026
Segozero	63°19′N, 33°26′E	113.6	815	29	103	23.4
Syamozero	61°55′N, 33°17′E	106.5	266	6.7	24.5	1.79
Topozero	65°46′N, 31°48′E	109.5	986	16	56	15.6
Tulmozero	61°39′N, 32°15′E	75.7	14.5	5	24	0.073
Vigozero	63°27′N, 35°20′E	89.3	1140	6.2	25	6.46
Vodlozero	62°20′N, 36°53′E	138.3	322	2.8	16.3	0.906

stations. Consequently, there is a clear warming trend of air temperature in the spring months. The break-up dates are best correlated with the seasonal NAOI values from January–February. This relationship is best seen for the large deep lakes: Onego ($r = -0.57$), Segozero ($r = -0.46$) and Topozero ($r = -0.43$) (Fig. 2). The freeze dates are related to the NAOI in October and November, but the correlation coefficients are significantly less ($r \approx 0.30$), except for Lake Segozero. A significant correlation between the seasonal NAO winter index and the duration of ice cover was observed only for two large and deep lakes (Onego and Segozero). The regression explained 12% of the variance ($p < 0.01$).

Similar values of correlation coefficients of the NAOI with the dates of ice events and duration of ice cover were obtained for the Finnish Lake Pääjärvi (George et al. 2004). A reflection of the NAO signal has been detected in the ice phenology of lakes in Estonia, Finland, Sweden and UK (George et al. 2004; George 2007; Livingstone et al. 2009). In Russia the evidence of the NAO signal has been detected in the ice phenology for large lakes such as Ladoga (Karetnikov & Naumenko 2008) and Baikal (Shimaraev 2008).

Temporal trends for ice freeze and ice break-up dates were calculated using least-squares linear regression. Linear trends of parameters of ice phenology for eight lakes in Karelia from 1950 to 2009 showed a later freezing and earlier break-up, but statistically significant trends ($p < 0.05$) were not found (Figs 3, 4). Lake Segozero is an exception: it freezes in December, nearly a month later than other lakes. A linear trend for the freeze data in Segozero (3.7 days/decade) is significant ($p < 0.001$). A time shift of ice formation over the 60-year period by 2–12 days has been observed in other lakes, but the trends are not statistically significant. The break-up dates of over 60 years have shifted to earlier time by 2–8 days. The linear trends for the freezing date during the last 20 years are more pronounced than similar trends for the entire 60-year period. In the past ten years the duration of ice cover on lakes has decreased, on average, by 11–16 days, and for Onego and Segozero by more than 20 days.

The dates of ice events in lakes of different types can be expressed in terms of the relevant mean (climatological) values and deviations from them:

$$D_{i,j} = \overline{D_{i,j}} + \Delta D_{i,j} + D'_{i,j}, \quad (1)$$

where $\overline{D_{i,j}}$ are the (climatological) average values of ice events, $\Delta D_{i,j}$ are their deviations from the inter-annual variability (climatic component) and $D'_{i,j}$ characterize short-period variability (synoptic and diurnal). The indices i and j denote the lake and the date of the formation of ice or final thawing.

A regression model to evaluate $\overline{D_{i,j}}$ was developed from observational data for 72 lakes in NW Russia (Table 1, Fig. 1). The equations take into account the lake dimensions and zonal factors (Efremova & Palshin 2011):

$$\overline{D_{i,f}} = 450 + 28.6 \lg \overline{H} - 2.27\varphi - 0.091Z, \quad (\pm 3.7;\ R = 0.95), \quad (2)$$

$$\overline{D_{i,b}} = -90.9 + 3.42\varphi + 0.048Z + 2.09 \lg S + 0.26\overline{H}, \quad (\pm 2.4;\ R = 0.98), \quad (3)$$

where $\overline{D_{i,f}}$ and $\overline{D_{i,b}}$ are the average dates of freeze and break-up of ice (in days starting from 1 January); $\overline{H}$ is the average depth of the lake (m); S is the area of the lake (km^2); φ is the geographic latitude (deg) and Z is the elevation above sea level (m).

The sequence of predictors in the equations is in the order of decrease in their weight. Root-mean-square deviations and multiple correlation coefficients (R) of the observed and predicted dates are given in brackets.

Thus, the dates of lakes freeze-up are most influenced by mean depth, geographic latitude and elevation above sea level. No correlation was found between freeze-up dates and the fetch or the lake area.

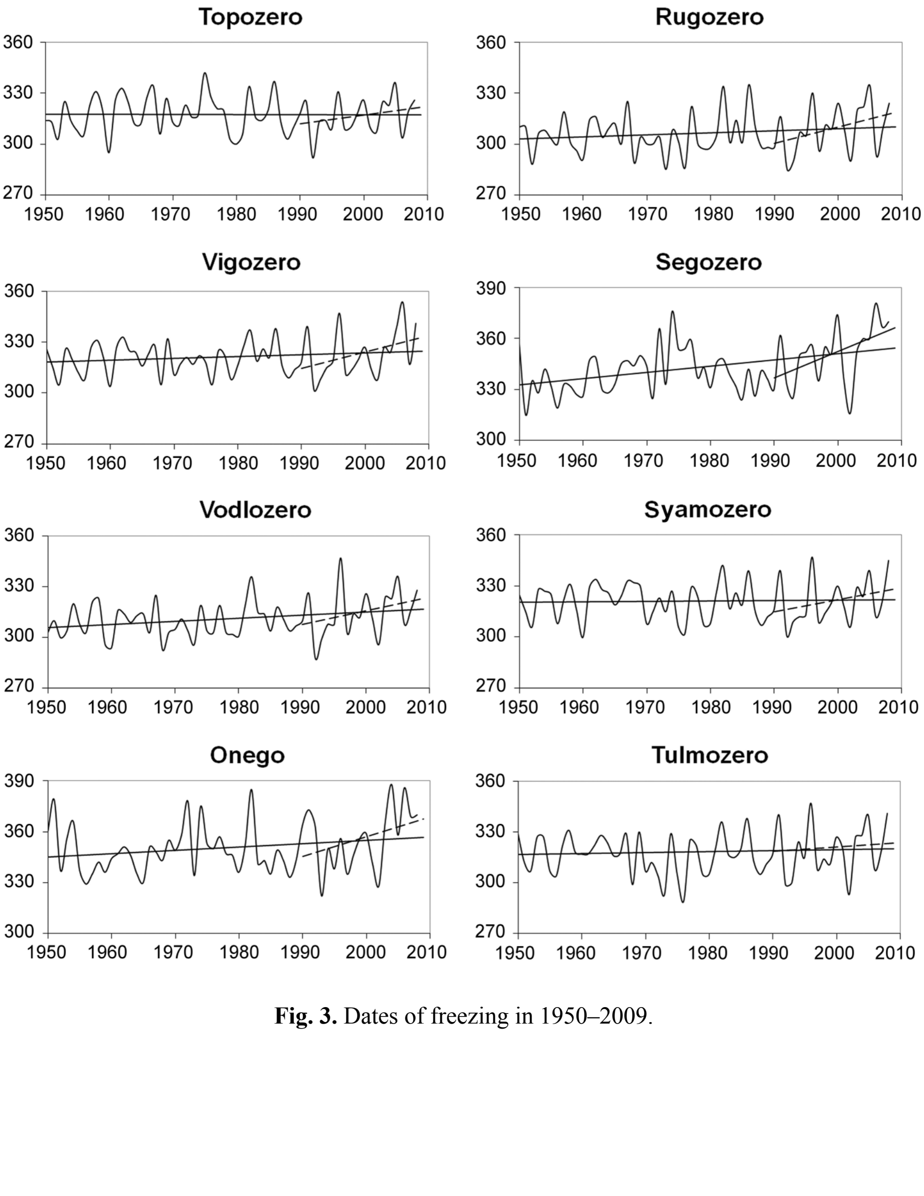

Fig. 3. Dates of freezing in 1950–2009.

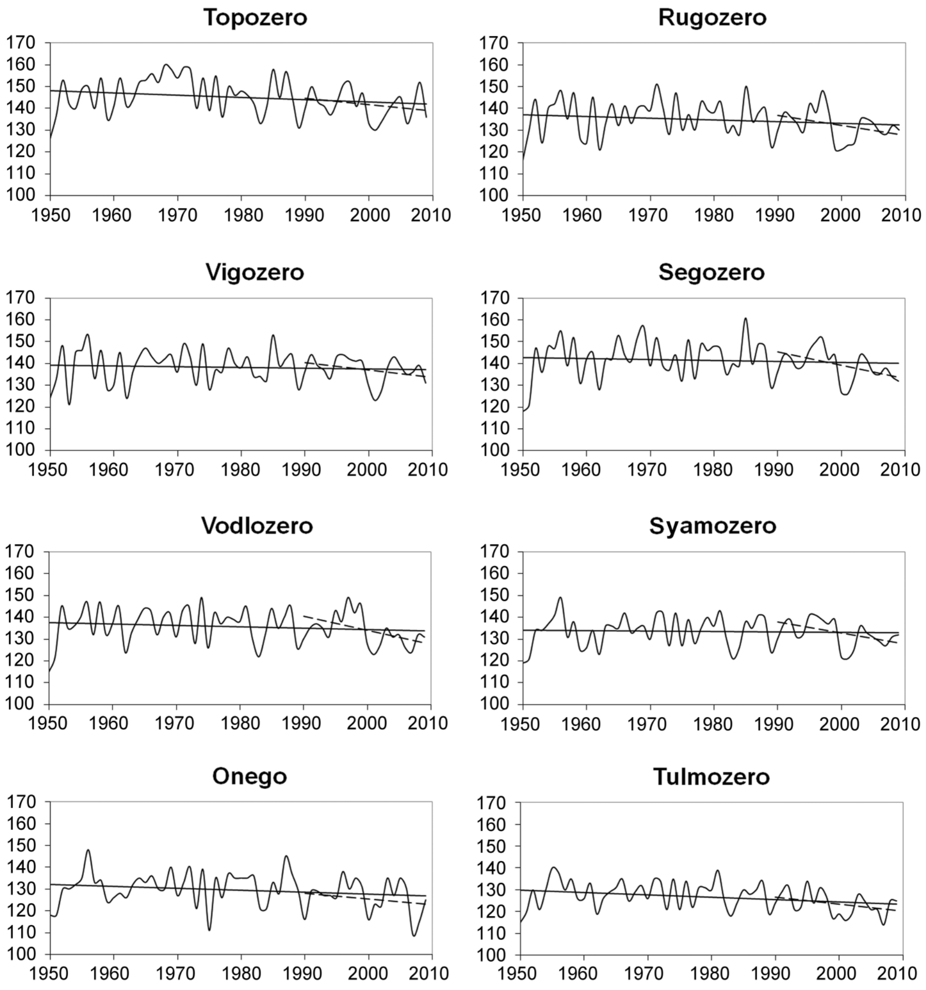

Fig. 4. Dates of ice break-up in 1950–2009.

According to Eq. (1), lakes freeze up 2.27 days earlier with every degree of geographic latitude (~111 km). For frozen lakes in North America (Williams et al. 2004) with the range of latitude (40 N–82.5 N) this value was found to be 2.31 days/deg N. The relationship between the freeze dates and mean depth is nonlinear because the sample set includes both shallow (mean depth <3 m) and deep (mean depth >15 m) lakes. In shallow lakes ($1 \le \overline{H} \le 5$ m) freezing occurs later (by about 5 days/m) when the average depth increases. A later beginning of the ice cover by 1.5–2 days/m is observed in lakes with an average depth of 5–10 m and by 0.5–0.8 days/m in deep lakes ($\overline{H} > 10$ m).

Break-up dates (Eq. (3)) correlate primarily with zonal factors. The variance explained through pairwise correlation alone is more than 0.9, and the standard error is about 3.5 days. At the geographic latitude 15° higher lakes become free of ice 50 days later (3.33 days/deg N), which corresponds closely to the resulting regression coefficient 3.54 days/deg N for lakes of North America (Williams et al. 2004). At 100 m higher elevations a.s.l. ice break-up lags behind by about 5 days. The regression analysis has shown that the depth (that is the most important parameter in freeze-up) has hardly any effect on break-up.

Mean air temperatures over fixed calendar periods are often used to find the relationship between air temperature and lake freeze and break-up dates (Palecki & Barry 1986; Williams et al. 2004). Our analysis indicates that the weather conditions over two months from October to November best reflect the freeze dates, and those over April and May – the break-up dates. Only for lakes Segozero and Onego it is better to use average values of air temperature from November to December in the regression analysis for the date of their freezing. All observed freeze-up and break-up dates in the lakes of Karelia fall into this period.

Deviation of ±1 °C air temperature from the averages for the two months preceding the ice events shifts the date of ice freezing ±3.9–5.6 days, and the date of break-up ±2.9–4.4 days for the eight lakes in Karelia. As shown for lakes in Finland (Palecki & Barry 1986), scatter of regression coefficients depends on the duration of the observation period on lakes. For 35 lakes in Karelia, under the air temperature increase by ±1 °C, the freezing occurs on average 2.9 days later, and the break-up 2.5 days earlier (Williams et al. 2004; Efremova & Palshin 2011).

To clarify the integral values of the coefficients for the model (1), we used the unique 60-year observation period for lakes in consideration (Fig. 5). Deeper lakes are known to freeze-up at lower air temperatures than shallow lakes (Efremova & Palshin 2011). On the northern lakes ice cover is formed earlier and the ice melts later than on the southern lakes. Therefore, instead of absolute values we employed annual deviations of ice phenomena timing and air temperature from multiyear averages:

$$\Delta D_{i,f} = 4.5\Delta T_1, \quad (\pm 7.8; \quad r = 0.77), \qquad (4)$$

$$\Delta D_{i,b} = -3.9\Delta T_2, \quad (\pm 5.0; \quad r = 0.74), \qquad (5)$$

where $D_{i,f}$, $D_{i,b}$ are the deviations in annual freeze and break-up dates and ΔT_1, ΔT_2 are the deviations of mean air temperature in October–November and April–May from multiyear averages.

The dates of freezing (Fig. 6) and break-up (Fig. 7) were calculated by Eqs (1)–(5). Lakes Onego and Topozero were not taken into consideration, since observations reflect the situation in a semi-enclosed bay rather than the open part of the lake. The resulting estimates reflect well the interannual variability of the freezing and break-up of lakes. Lakes with an average depth of 5–6 m usually froze at a temperature in the bulk of the water column of about 1 °C and the formation of the surface layer of cooler water. As a result of daily and synoptic variability ($D'_{i,j}$), which is not included in the model, the lake freeze-up date may vary. Ice cover on lakes can be formed at a temperature of about 2 °C by rapid cooling when there is no wind, but at a temperature of about 0 °C in strong winds for a long period (Petrov et al. 2006). This effect is more evident in large deep lakes, such as Lake Segozero (Fig. 6). In addition to temperature, the time of break-up is greatly influenced also by cloudiness, wind, thickness and texture of snow and ice cover (Kirillin et al. 2012).

The dispersion, mean and extreme values of the observed and modelled dates of freezing and break-up of lakes are shown in Fig. 8. The average observed freezing date of Lake Topozero has shifted to an earlier date, as the monitoring stations on these lakes are in the bays. The differences between the observed and calculated timing of ice events are greatest for the large and deep Lake Segozero. Dispersion and extreme values estimated for all lakes were slightly less than the measured values. This is because the calculations do not take into account synoptic and daily variability. An assessment of the ice events with all components of heat flux on the surface of the lake and the redistribution of heat in the water column is usually done using numerical models, but this requires daily meteorological data, which are often not available (Bernhardt et al. 2012; Kirillin et al. 2012).

CONCLUSION

Time series analysis for eight lakes of Karelia showed that in the period 1950–2009 the freezing of all lakes was shiffed to a later date, while ice melting was shiffed to the earlier date compared to the long-term average.

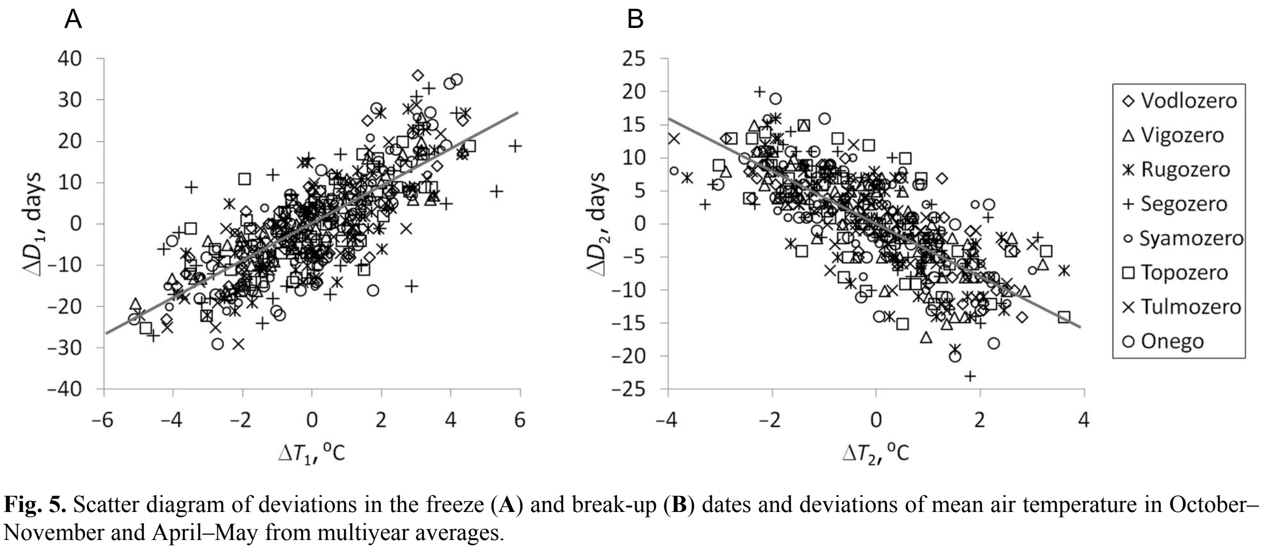

Fig. 5. Scatter diagram of deviations in the freeze (**A**) and break-up (**B**) dates and deviations of mean air temperature in October–November and April–May from multiyear averages.

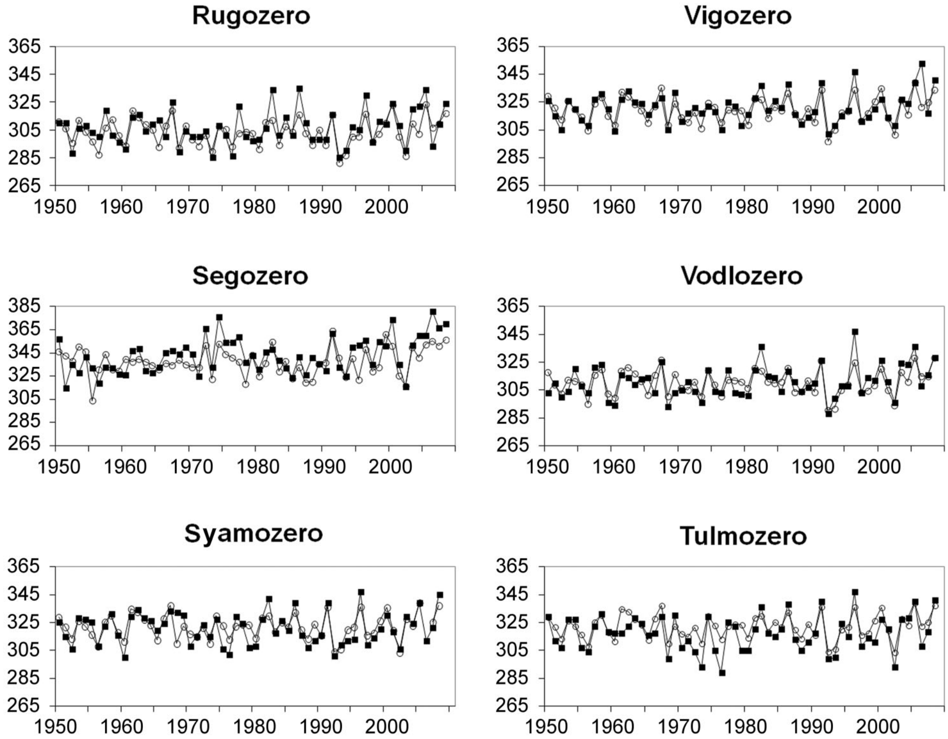

Fig. 6. Observed (line with black squares) and modelled (line with white circles) dates of freeze-up of the studied lakes in Karelia.

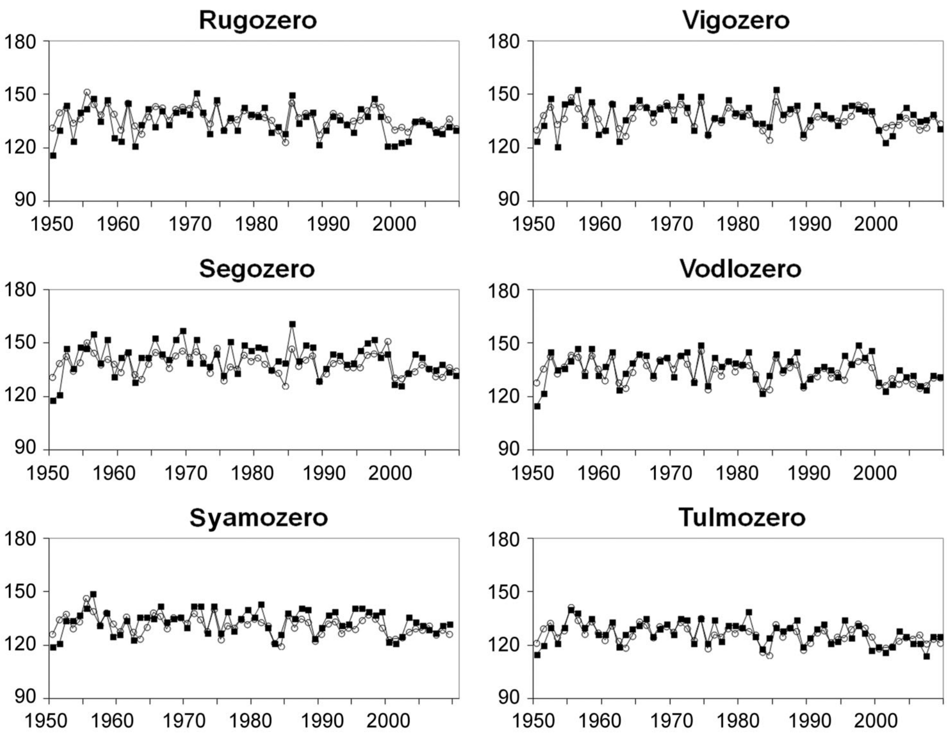

Fig. 7. Observed (line with black squares) and modelled (line with white circles) dates of ice break-up of the studied lakes in Karelia.

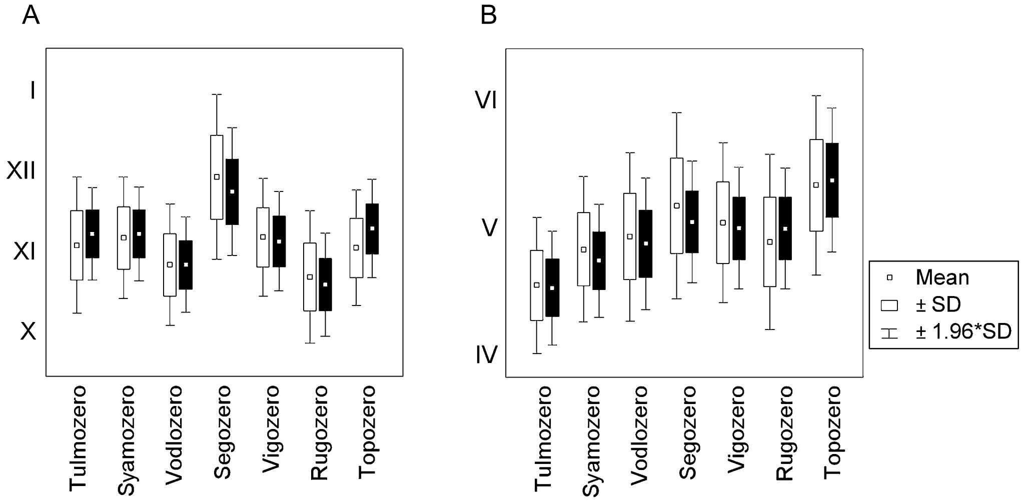

Fig. 8. Average, earliest and latest observed (light) and model (black) freeze dates (**A**) and the break-up dates (**B**) of lakes in Karelia. The lakes are ordered along the horizontal axis according to their location from south to north.

However, a significant linear trend ($p < 0.05$) was obtained only for the formation of ice in deep Lake Segozero that freezes 30–40 later than the other lakes.

Over the past 10 years, the duration of ice cover decreased by 11–16 days, for lakes Onego and Segozero by more than 20 days compared to the average for the entire 60-year period.

The NAO indices influence the variability of weather conditions in Karelia, accounting for 30–40% of the variation in air temperature in winter and 10–12% of the variance ($p < 0.01$) in the timing of ice phenology of lakes. The NAO signal is most pronounced (18–32% of the variance) on the date of break-up of large deep lakes.

It was found that the average air temperature for two months from October to November and April to May best reflect the date of freezing and break-up of lakes, accounting for 55–60% of the variance. A deviation of ±1 °C from the long-term average in mean air temperature over the two months preceding the development of ice phenomena shifts the freeze-up date by ±4.5 days. A deviation of ±1 °C from the long-term value of mean air temperature in April–May causes a ±3.9 day change in the ice break-up date.

An empirical model was developed for the different types of lakes in Northwest Russia. This model can be used to estimate ice events for previously unexplored lakes and forecast changes of ice phenomena under the potential climate change conditions.

Acknowledgements. The present study was supported by the Russian Academy of Science and the Russian Fund of Basic Research (projects 10-05-00963 and 10-05-91331-DFG).

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Jääkatte fenoloogia pikaajalised karakteristikud Karjala järvedel

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On analüüsitud statistilisi seoseid jääkatte fenoloogia (jää tekkimise ja lagunemise kuupäevad, jääkatte kestus), õhutemperatuuri ning Põhja-Atlandi ostsillatsiooni (NAO) indeksi vahel kaheksa Karjala järve kohta ajavahemikul 1950–2009 ja leitud alaperioodide lineaarsed trendid. On näidatud, et viimase 20 aasta trendid on silmanähtavalt selgemad kui kogu 60 aasta omad. Leitud statistiliselt olulisi seoseid on rakendatud empiirilises mudelis, hindamaks jääkatte karakteristikuid seni uurimata Loode-Venemaa järvedel.