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Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes

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Abstract

Based on a unique dataset of more than 50 000 observations of ice phenology from 1213 lakes and 236 rivers in 12 different countries, we show that interannual variations in the timing of ice-on and ice-off on lakes and rivers are not equally pronounced over the entire Northern Hemisphere, but increase strongly towards geographical regions that experience only short periods during which the air temperature falls below 0 °C. We explain our observations by interannual fluctuation patterns of air temperature and suggest that lake and river ecosystems in such geographical regions are particularly vulnerable to global warming, as high interannual variability is known to have important ramifications for ecosystem structure and functioning. We estimate that the standard deviation of the duration of ice cover, viewed as a measure of interannual variability, exceeds 25 days for lakes and rivers located on 7% of the land area of the Northern Hemisphere. Such high variability might be an early warning signal for a critical transition from strictly dimictic, ice-covered systems to monomictic, open-water systems. Using the Global Lake and Wetland Database, we suggest that 3.7% of the world's lakes larger than 0.1 km^2 are at high risk of becoming open-water systems in the near future, which will have immediate consequences for global biogeochemical cycles.

Keywords: aquatic ecosystems, climate change, lake and river ice, Northern Hemisphere, variability

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Introduction

The behaviour of lakes and rivers, and in particular the behaviour of their biogeochemical processes and food–web interactions, is strongly seasonally dependent (Sommer *et al*., 1986; Stottlemyer & Toczydlowski, 1999). Recent observations indicate that the seasons are shifting in time in response to climate change (Thomson, 2009). Of particular importance for high-latitude and high-altitude lake and river ecosystems is the timing and duration of the ice season. Ice phenology is driven to a large extent by variations in air temperature (Williams, 1971; Vavrus *et al*., 1994; Livingstone, 1997). Several studies have demonstrated the importance of ice phenology for freshwater ecosystems (Adrian *et al*., 1999; Weyhenmeyer *et al*., 1999; Gerten & Adrian, 2000). Freshwater lake and river ecosystems are not distributed evenly across the globe. Most lakes and rivers are located in the Northern Hemisphere in regions in which air temperatures fall below 0 °C in winter (Downing *et al*., 2006), resulting in frequent ice cover. Changes in ice phenology will affect ecosystem services such as the production of food and drinking water, nutrient cycling, climate control, and the provision of recreational opportunities (Schröter *et al*., 2005). Since ice phenology is one of the very few freshwater variables that are directly driven by climate and that are globally available, the timing of ice-on and ice-off can serve as good indicators of the impacts of climate change on freshwater ecosystems on local, regional and supra-regional scales (Magnuson *et al*., 2004; Adrian *et al*., 2009). We therefore chose ice phenology to assess climate change impacts on freshwater ecosystems in the Northern Hemisphere. More specifically, we investigated geographical differences in the response of ice-cover dynamics to temperature changes and modelled them using a simple approach with minimal data requirements.

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Materials and methods

We used a global dataset of the timing of ice-on and ice-off on a total of 1449 water bodies – 1213 lakes and 236 rivers – distributed over 12 countries in the Northern Hemisphere. When both the timing of ice-on and the timing of ice-off were available, the duration of ice cover was determined as the difference of the two observations. The lengths of the time-series of available observations varied from 1 to 315 years. For each of the 1449 water bodies, we determined long-term mean values in the timing of ice-on and ice-off and the duration of ice cover. We then grouped the water bodies according to their long-term mean values. To achieve comparable numbers of data points within each group, the groups at each of the two extremes included values that were smaller and larger, respectively, resulting in a total of 11 groups for ice-on, nine for ice-off and 18 for ice duration. For 148 water bodies, complete 30-year time-series were available for the period 1961–1990. These 148 water bodies, of which four were rivers and 144 were lakes, were located in Canada, the United States, Sweden, Finland and Russia. The ice data were taken from the Global Lake and River Ice Phenology Database maintained by the North Temperate Lakes Long Term Ecological Research program. In addition to the ice data, we used $0.5^\circ \times 0.5^\circ$ gridded mean (1961–1990 and 1991–2000) annual mean air temperature data from the Northern Hemisphere (T_m) and mean (1961–1990 and 1991–2000) monthly minimum air temperatures (Climate Research Unit high resolution climate data, version 2.1), available at http://www.ipcc-data.org/. For each grid cell, we determined the mean annual air temperature amplitude (T_a) by subtracting the mean annual minimum temperature (T_min), determined from the monthly minimum temperatures, from T_m. Each water body was then assigned the values of T_m and T_a of the nearest grid cell. Five water bodies appear as outliers: the four rivers and Lake Baikal (marked in Fig. 1a). Since the ice phenology of rivers and large lakes is a result of complex water circulation processes (Magnuson *et al*., 2000), we excluded the four rivers and Lake Baikal from our modelling approach where we estimated the timing of ice-on ($t_\text{ice-on}$) and ice-off ($t_\text{ice-off}$) and the duration of ice cover (D_ice) for 143 lakes with complete time series during 1961–1990 (black squares in Fig. 1a). The estimates were initially based on a simple function developed for Swedish lakes where air temperatures and solar radiation covary well (Weyhenmeyer *et al*., 2004a)

$$t_\text{ice-on} = -\frac{365.25}{2\pi}\arccos\left(\frac{T_\mathrm{m}}{T_\mathrm{a}}\right) + 55, \qquad (1)$$

$$t_\text{ice-off} = -\frac{365.25}{2\pi}\arccos\left(\frac{T_\mathrm{m}}{T_\mathrm{a}}\right) + 55, \qquad (2)$$

$$D_\mathrm{ice} = \frac{365.25}{\pi}\arccos\left(\frac{T_\mathrm{m}}{T_\mathrm{a}}\right), \qquad (3)$$

where $t_\text{ice-on}$ and $t_\text{ice-off}$ are the timing of ice-on and ice-off in days of the year, D_ice the duration of ice cover in days, T_m the annual mean air temperature in °C, and T_a the annual air temperature amplitude in °C. The constant 365.25 is the length of a year in days, and the constant 55 is a phase offset in days. The arc cosine form of the model is a result of the approximately sinusoidal variation of air temperature during the course of a year, and the arc cosine function describes the period during which the sinusoidal fit to the air temperature lies below 0 °C. The arc cosine model is valid only when daily mean air temperatures lie below 0 °C for a substantial period of time in winter (Livingstone & Adrian, 2009). Where this is not the case, the arc cosine model needs to be supplemented by a probabilistic component that accounts for the occurrence of air temperatures <0 °C even when the sinusoidal fit to the air temperature never goes below 0 °C (Livingstone & Adrian, 2009). We did not include the probabilistic component here since it has a significant effect only when the period during which the air temperature is <0 °C is shorter than $\sim$55 days or longer than $\sim$310 days, conditions that were not encountered when we tested the validity of the arc cosine model on 30-year mean values of 143 lakes that had complete time series during 1961–1990. We did not try to model river ice phenology, as we had only four rivers available with complete 30-year time series.

In addition to the modelling of long-term mean values, we further analysed interannual fluctuations in the timing of ice-on and ice-off, as many processes in freshwater ecosystems are strongly affected by interannual variability in ice phenology (Weyhenmeyer, 2009a). For these analyses, we considered all available ice data, both from lakes and rivers. It is important to note that although the calendar dates of ice-on and ice-off on rivers deviate from those of ice-on and ice-off on lakes, their interannual variability patterns are comparable. When examining interannual variability, we therefore treat lakes and rivers similarly.

All statistical analyses were performed in JMP, version 8 (SAS, 2009).

Results

A simple model for the timing and duration of ice cover in the Northern Hemisphere

Applying the simple arc cosine function of T_m and T_a that was developed for Swedish lakes [Eqns (1)–(3)] to 143 lakes with complete 30-year time series in the Northern Hemisphere, we could explain 28% of the mean ice-on dates, 47% of the mean ice-off dates and 66% of the mean ice duration for the period 1961–1990 ($P < 0.0001$, $n = 143$). Since ice-cover dynamics are strongly dependent on the radiative balance at the lake surface (Leppäranta, 2010), we tried to improve the predictions by including solar radiation, for which we used latitude as a proxy. We considered even altitude, as our gridded T_m and T_a might be too regional to reflect local air temperatures at the lake sites.

We found the residuals of ice-off dates to be strongly related to latitude ($R^2 = 0.47$, $P < 0.0001$, $n = 143$), but this was not the case for the residuals of ice-on dates

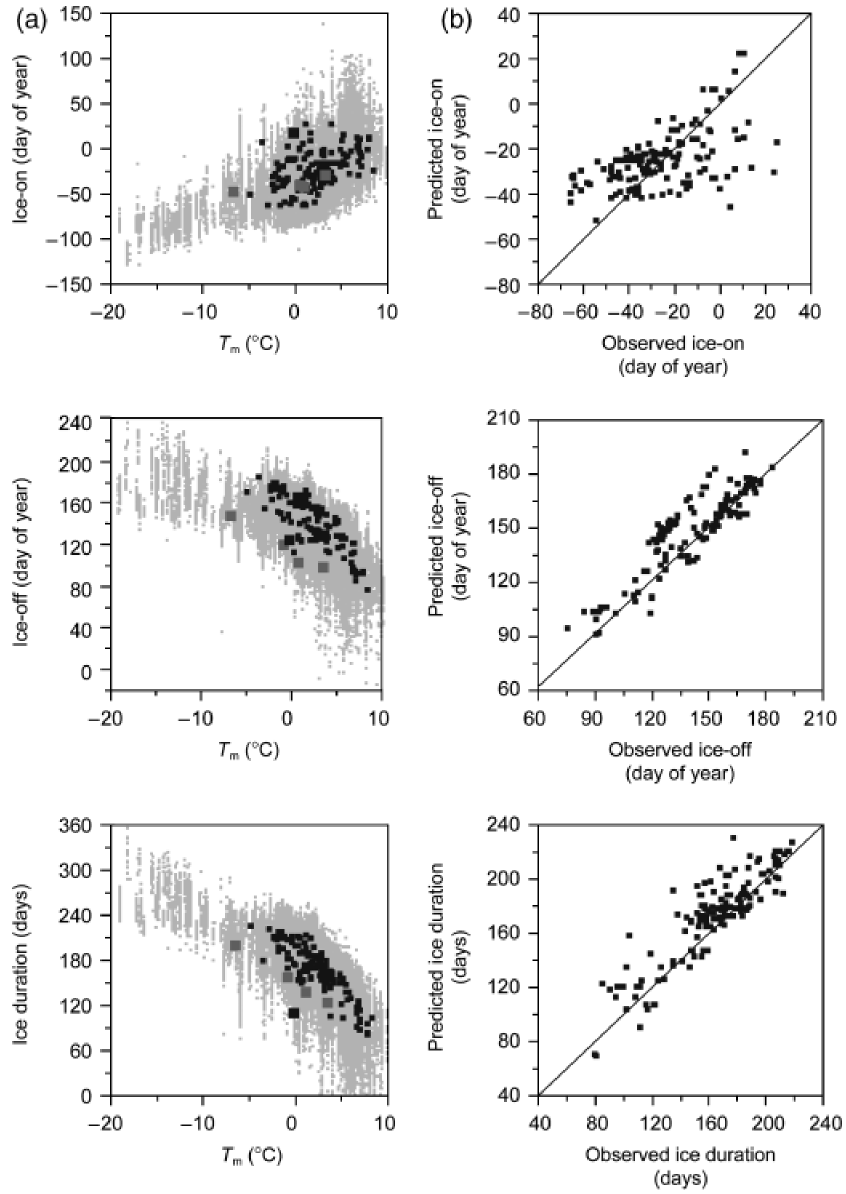

Fig. 1 Observed and predicted timing and duration of ice cover. (a) The observed timing of ice-on and ice-off and the duration of ice cover on 1449 lakes and rivers (small grey squares: all available data; black squares: 30-year mean values for 143 lakes with complete time-series for 1961–1990; large black squares: Lake Baikal; large grey squares: four rivers) as a function of the 1961–1990 mean air temperature (T_m) of the $0.5^\circ \times 0.5^\circ$ grid square in which each lake or river is located. (b) The observed and predicted [see Eqns (4)–(6)] 1961–1990 mean timing and duration of ice cover on the same 143 lakes. The figures include the 1 : 1 line.

($R^2 < 0.01$, $P > 0.05$, $n = 143$). The residuals of ice-on and ice-off dates were only weakly related to altitude ($R^2 = 0.07$, $P < 0.01$, $n = 143$ and $R^2 = 0.04$, $P < 0.05$, $n = 143$, respectively), probably because of the limited range of altitudes represented (50% of the lakes were located below 200 m and only 2.5% above 500 m). Adjusting the Sweden-specific phase offset of the ice-off model to solar radiation by using our observed empirical relationship between the residuals of ice-off and latitude (ϕ) (ice-off residuals $= 2\phi - 100$) we obtained the following equations:

$$t_{\text{ice-on}} = -\frac{365.25}{2\pi}\arccos\left(\frac{T_\text{m}}{T_\text{a}}\right) + 55, \tag{4}$$

$$t_{\text{ice-off}} = \frac{365.25}{2\pi}\arccos\left(\frac{T_\text{m}}{T_\text{a}}\right) + (2\phi - 55), \tag{5}$$

$$D_{\text{ice}} = \frac{365.25}{2\pi}\arccos\left(\frac{T_\text{m}}{T_\text{a}}\right) + (2\phi - 110), \tag{6}$$

where 55, $2\phi-55$, and $2\phi-110$ are phase offsets in days, 2 is a constant in days × °N^{-1}, ϕ is latitude in °N, and 55 and 110 are constants in days. All other parameters are the same as in Eqns (1)–(3). With these simple equations, we achieved cross-validation slopes close to unity and intercepts close to zero, and were able to explain 28% of the variability in mean ice-on dates, 79% of the variability in mean ice-off dates and 81% of the variability in mean ice cover duration for 143 Northern Hemisphere lakes (1961–1990, $P<0.0001$, Fig. 1b).

Interannual variations in the timing of ice-on and ice-off

Analysing interannual fluctuations in the timing of ice-on and ice-off, we found that the probability density functions (pdfs) of the ice-on and ice-off anomalies changed their shape along with changing ice-on and ice-off dates (Fig. 2a). The broadest pdfs, implying highest interannual variability, were observed for those water bodies with the latest ice-on dates and the earliest ice-off dates. This pattern was the same for lakes and rivers, and no significant difference in the ice-on and ice-off anomalies between lakes and rivers was found (nonparametric Wilcoxon's test: $P>0.05$).

The degree of interannual variability in the date of ice-on varied linearly with the date of ice-on itself (Fig. 2b). The same was true for ice-off dates, up to a mean ice-off date of mid-May (approximately day 130) when the interannual variability in the date of ice-off remained approximately constant at the relatively low value of ± 9 days (Fig. 2b). These water bodies were mainly located north of 61°N (Fig. 2b).

We observed that variations in the duration of ice cover became especially high when $T_m/T_a \geq 0.1$ (Fig. 2c). During 1961–1990, 21% of the land area of the Northern Hemisphere had T_m/T_a values between 0.1 and 0.8. Regions with $T_m/T_a<0.8$ correspond to regions with a mean ice cover duration of more than 75 days according to Eqn (6). In such regions, we expect rivers and shallow lakes to freeze during winter. During 1961–1990, 67% of the land area of the Northern Hemisphere had T_m/T_a values <0.8 (Fig. 3). By the period 1991–2000, for which gridded air temperature data were available, the extent of such land areas had declined to 65%. The decline of 2% could be a result of one exceptional warm year during the 10-year period of 1991–2000 compared with the 30-year period of 1961–1990, but since the kurtosis and the skewness of the distribution of T_m/T_a over the Northern Hemisphere were the same during the two time periods (4.0 and 1.7, respectively), we attributed the decline to a general, significant increase in T_m/T_a over the Northern Hemisphere from 0.63 ± 1.45 during 1961–1990 to 0.69 ± 1.47 during 1991–2000 (nonparametric Wilcoxon's test: $P<0.0001$).

The highest interannual variability of ice-on and ice-off dates with usually more than 25 days was observed in geographical regions south of 61°N with $0.5 \leq T_m/T_a<0.8$. In 1961–1990, these regions accounted for 6% of the land area of the Northern Hemisphere (orange and red colours in Fig. 3). By 1991–2000 this had increased slightly to 7%. Overlaying this with the Global Lakes and Wetlands Database GIS layer (Lehner & Doll, 2004) showed that 3.3% of the world's lakes with a surface area exceeding 0.1 km^2 fell within this region during 1961–1990, and that this had increased to 3.7% by 1991–2000.

Discussion

An arc cosine function to describe ice cover dynamics over the Northern Hemisphere

In this study, we showed that a simple arc cosine function of T_m and T_a was suitable to model ice cover dynamics over the Northern Hemisphere, especially when latitude as a proxy for solar radiation was included into the modelling approach of ice-off dates. Despite the simplicity of our approach, neglecting lake morphometry and a variety of other variables for which measurements were not available throughout much of the Northern Hemisphere, the results achieved were almost as good for the timing of ice-off and ice duration as those achieved by Walsh *et al*. (1998) based on a much more complex numerical model requiring many additional variables (solar radiation, precipitation, longwave radiation, humidity, and wind speed). The estimates of Walsh *et al*. (1998) were substantially better only in the case of ice-on (83% of variability in mean ice-on dates explained), most likely due to their inclusion of lake depth as an explanatory variable. As Leppäranta (2010) pointed out, freezing processes are primarily driven by internal lake properties and processes while thawing processes are primarily dependent on solar radiation. The improvement to our model that resulted by including data on latitude, viewed as a proxy for solar radiation, provides support for this.

The arc cosine function was not only suitable to model long-term average values of ice-on and ice-off dates but also their interannual variability. We suggest that the observed increasing sensitivity of ice phenology to air temperature at latitudes lower than 61°N is primarily a result of the form of the arc cosine function of T_m and T_a [Eqns (4)–(6)]. In regions characterized by values of T_m/T_a close to, but below, 1, not only is the duration of time during which the air temperature is below 0 °C low, but its variability is high (Fig. 4) because of the rapid change in the value of the first derivative of the arc cosine function ($365.25/\pi\sqrt{1-(T_m/T_a)^2}$) that

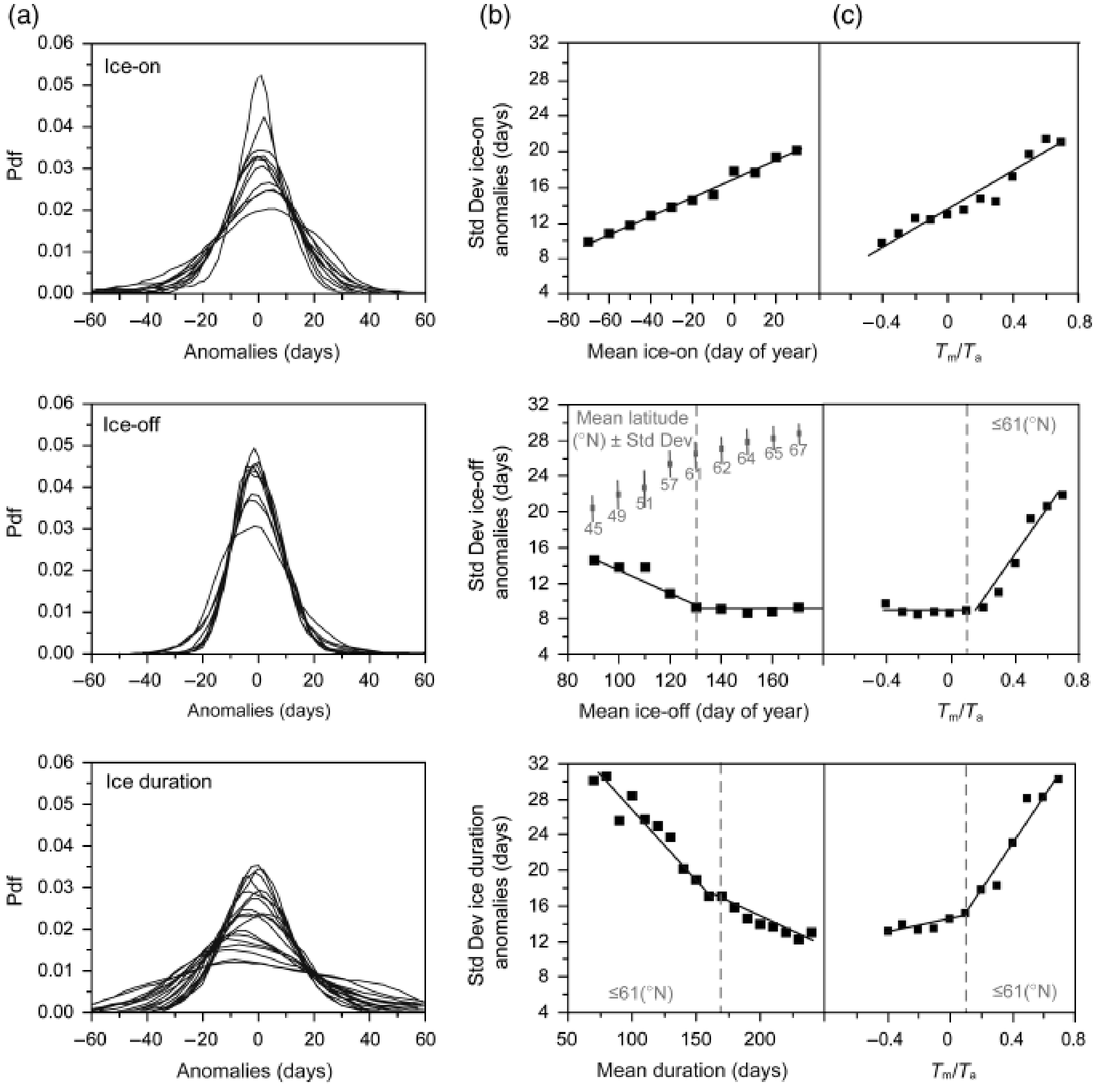

Fig. 2 Differences in the interannual variability of ice-on and ice-off dates and ice cover duration for lakes and rivers in the Northern Hemisphere. (a) The probability density functions (pdfs) of the observed ice-on and ice-off dates and of the duration of ice cover of the 1449 lakes and rivers that were grouped according to their long-term mean values (see Materials and methods). The corresponding standard deviations (Std Dev) are shown in (b) [the lines in (a) correspond to the black squares in (b)]. (c) Changes in the interannual variability of ice phenology as a function of region-specific values of mean annual air temperature (T_m) and the annual air temperature cycle (T_a). We used the latitude 61°N as a breakpoint for linear increases in the interannual variability of the timing of ice-off and the duration of ice cover. All linear relationships at latitudes lower than 61°N were highly significant ($R^2 > 0.93$, $P < 0.001$).

occurs as T_m/T_a approaches unity. This implies that as T_m/T_a approaches unity from below, ice-on and ice-off dates will become increasingly variable and will exhibit an increasingly strong dependence on T_m/T_a (Fig. 2c). At latitudes north of 61°N, we suggest that the strong and predictable seasonal cycle in solar radiation that exists at such high latitudes is the cause of the rather low interannual variability. At latitudes lower than 61°N, the seasonal cycle in solar radiation is weaker, making the timing of ice-off highly sensitive to changes in T_m and T_a (Fig. 2c).

Consequences of increasing interannual variability in the timing of ice-on and ice-off

Our results suggest that a further rise in air temperature as predicted for the Northern Hemisphere (Volodin *et al.*, 2008) will increase the sensitivity of the timing and duration of ice cover on lakes and rivers to air temperature fluctuations in warmer geographical regions below 61°N. As a consequence of this, increases in variability are to be expected not only in the physical processes occurring in lakes and rivers, but also in the

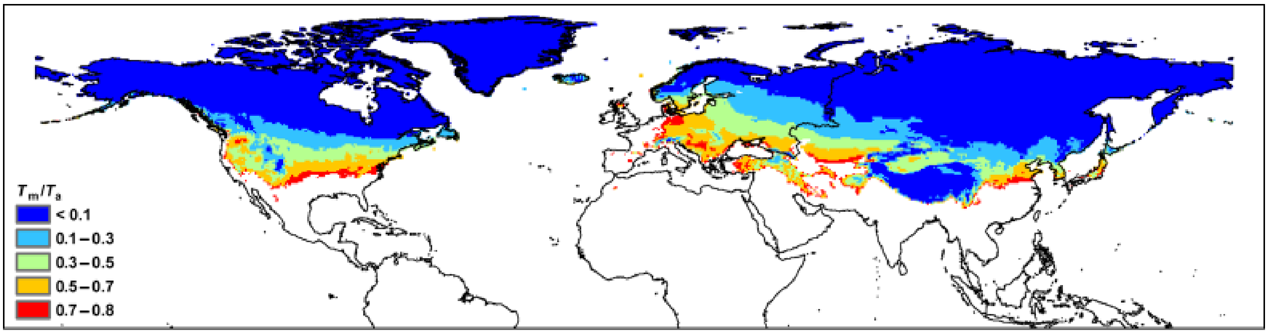

Fig. 3 Map showing the ratio of mean annual air temperature (T_m) to the amplitude of the annual air temperature cycle (T_a) in the Northern Hemisphere for 1961–1990. Gridded (0.5° × 0.5°) air temperature data were used. Based on Fig. 2c, blue corresponds to a predicted interannual standard deviation in ice duration of approximately 15 days, orange to approximately 25 days and red to more than 30 days.

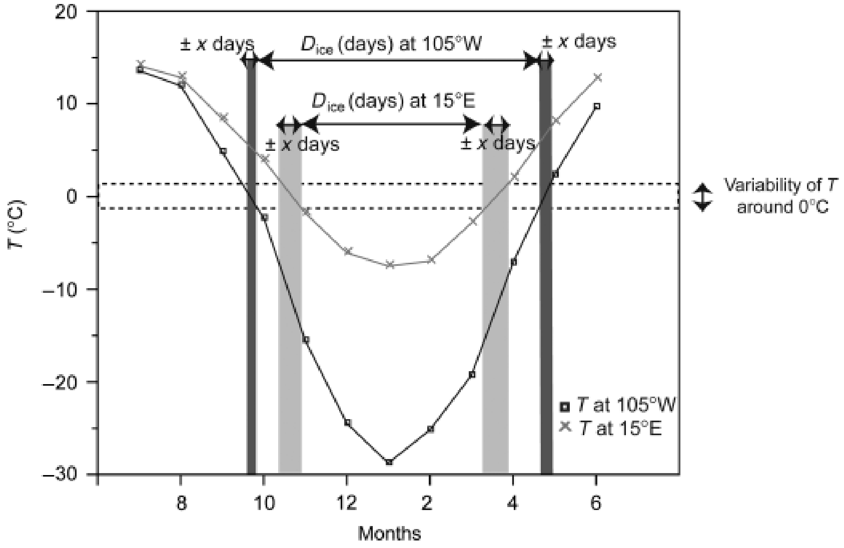

Fig. 4 Mean (1961–1990) annual air temperature cycle at 60°N at two longitudes: 105°W (Canada) and 15°E (Sweden). The data are gridded monthly mean air temperatures. The shape of the annual air temperature cycle determines how long air temperatures vary around 0 °C, which we assume to correspond roughly to the timing of ice-on and ice-off. The shape of the annual air temperature cycle for Sweden yields a short duration of ice cover (D_{ice}) with a high degree of variability in the timing of ice-on and ice-off (light grey areas). In contrast, the shape of the Canadian annual air temperature cycle yields a comparatively long duration of ice cover with a low degree of variability in the timing of ice-on and ice-off (dark grey areas).

chemical and biological processes. For ice-covered lakes in Sweden, for example, it has already been observed that chemical variables that follow the seasonal variations of air temperature undergo a significant increase in variability towards warmer geographical regions and in warmer years (Weyhenmeyer, 2009b). Examples of such variables are nitrate–nitrogen, pH and organic carbon. Increases in variability patterns are increasingly seen as a critical factor driving the structure and function of aquatic ecosystems (Puckridge *et al*., 1998), and they might even foreshadow ecological regime shifts (Carpenter & Brock, 2006; Guttal & Jayaprakash, 2008) with possible catastrophic consequences (Scheffer & Carpenter, 2003). Concerning ice-covered lake ecosystems, one of the most drastic changes that these ecosystems might experience will be a change from strictly dimictic, ice-covered systems to monomictic, open-water systems (Livingstone, 2008). Such changes will have far-reaching implications for life cycles of biota as well as global biogeochemical cycling; for instance, open-water conditions have been identified as particularly critical for photosynthetic production (Melles *et al*., 2007) as well as important regulators of the global carbon cycle (Tranvik *et al*., 2009). A decrease in ice cover duration can also reduce the prevalence of low oxygen conditions that are lethal to many large-bodied temperate fish species (winterkill: Stefan *et al*., 2001). While this may be beneficial to large-bodied fish species, winterkill is critical for the maintenance of unique communities of hypoxia-tolerant but predation-sensitive fish species (Tonn & Magnuson, 1982).

Defining the transition from strictly dimictic, ice-covered systems to monomictic, open-water systems as critical for drastic biogeochemical changes we suggest that geographical regions with $0.5 \leq T_m/T_a < 0.8$, corresponding to a standard deviation in the duration of ice cover of more than 25 days (Fig. 2c), are at risk of transition. In 1961–1990, 6% of the land area of the Northern Hemisphere belonged to this type of area (orange and red colours in Fig. 3), which increased slightly to 7% in 1991–2000. The 3.7% of lakes that fell into these risk areas of transition during 1991–2000 are expected to be subjected to fast biogeochemical changes.

Evaluating temporal changes of 18 different water chemical variables in boreal reference lakes that are located in such risk areas, the fastest changes were observed for water colour, calcium, magnesium, and conductivity (Weyhenmeyer, 2008). The increase in water colour in particular was found to cause changes in phytoplankton composition as well as changes in drinking water quality (Weyhenmeyer *et al*., 2004b).

Based on our results, we suggest that climate adaptation and mitigation measures for lakes should be focused on geographical regions in which $0.5 \leq T_m/T_a < 0.8$, at latitudes ≤ 61°N, where interannual fluctuations in the duration of ice cover usually exceed 25 days (orange and red colours in Fig. 3). Freshwater ecosystems in these risk areas should be carefully monitored, as unexpected changes are likely to occur that might have far-reaching effects on global biogeochemical cycles and temperate freshwater biodiversity.

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