Nonlinear temperature response of lake ice breakup

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[1] A uniquely comprehensive set of four decades of ice breakup data from 196 Swedish lakes covering 13° of latitude (55.7°N to 68.4°N) shows the relationship between the timing of lake ice breakup and air temperature to be an arc cosine function. The nonlinearity inherent in this relationship results in marked differences in the response of the timing of lake ice breakup to changes in air temperature between colder and warmer geographical regions, and between colder and warmer time periods. The spatial and temporal patterns are mutually consistent, suggesting that climate change impacts on the timing of lake ice breakup will vary along a temperature gradient. This has potentially important ramifications for the employment of lake ice phenologies as climate indicators and for the future behavior of lacustrine ecosystems. *INDEX TERMS:* 1630 Global Change: Impact phenomena; 1833 Hydrology: Hydroclimatology; 1845 Hydrology: Limnology; 1863 Hydrology: Snow and ice. **Citation:** Weyhenmeyer, G. A., M. Meili, and D. M. Livingstone (2004), Nonlinear temperature response of lake ice breakup, *Geophys. Res. Lett.*, *31*, L07203, doi:10.1029/2004GL019530.

1. Introduction

[2] The timing of lake ice breakup has been of interest for centuries because of its importance for transportation and fishing [*Adams*, 1981]. It is of critical ecological importance for lakes because the disappearance of the ice cover has a drastic effect on the underwater light climate [*Leppäranta et al.*, 2003], nutrient recycling [*Järvinen et al.*, 2002] and oxygen conditions [*Stewart*, 1976; *Livingstone*, 1993], influencing for instance the production and biodiversity of phytoplankton [*Rodhe*, 1955; *Phillips and Fawley*, 2002; *Weyhenmeyer et al.*, 1999] and the occurrence of winter fishkills [*Greenbank*, 1945; *Barica and Mathias*, 1979]. Air temperature is the key variable determining the timing of ice breakup [*Ruosteenoja*, 1986; *Vavrus et al.*, 1996]. Both long-term trends and short-term variability in air temperature are therefore reflected in the timing of ice breakup [*Palecki and Barry*, 1986; *Robertson et al.*, 1992; *Assel and Robertson*, 1995; *Livingstone*, 1997, 1999; *Magnuson et al.*, 2000; *Sagarin and Micheli*, 2001]. Here we examine regional and temporal differences in the response of lake ice breakup dates to air temperature, based on over 40 yr of data (1961–2002) from 196 lakes in Sweden.

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2. Data and Methods

[3] The 196 Swedish lakes (Figure 1) vary widely in size, from 0.1 to 5,650 km^2. The lakes are situated along a north-south gradient in annual mean surface air temperature ranging from −3°C at about 68°N to 7°C at about 56°N (1961–90). Riverine stations with a characteristic flow velocity of >0.1 m s^{-1} during ice breakup and hydroelectric reservoirs with a regulation amplitude of >3 m were excluded from the lake ice breakup dataset. An overview of the ice data, including methods of observation, has been given by *Eklund* [1999].

[4] In this study we relate both spatial and temporal variations in the timing of lake ice breakup in Sweden to air temperature. The air temperature data utilized in the spatial comparison were atlas reference normals computed from 30 yr of data (1961–90) measured at 510 meteorological stations [*Raab and Vedin*, 1995]. The data for the temporal comparison were obtained from 12 of these stations.

3. Regional Patterns of Lake Ice Breakup

[5] Latitude has been viewed as a simple proxy for air temperature, and linear relationships of lake ice breakup dates to latitude have been reported [*Palecki and Barry*, 1986; *Assel and Herche*, 2000]. However, our data suggest that the latitudinal dependence of the timing of ice breakup might not be simply linear: both the gradient of the curve of ice breakup date versus latitude and the magnitude of the year-to-year variations in ice breakup dates decline at latitudes higher than 62°N (Figure 2). In contrast, lake-to-lake variability in the median date of ice breakup is highest north of 62°N (Figure 2), where isotherms tend to follow longitude rather than latitude [*Raab and Vedin*, 1995]. Because of the influence of the sea and local topography, latitude can be considered a valid proxy for air temperature only on large scales. We therefore carried out a more direct comparison of the ice data with lake-specific mean air temperatures (1961–90 normals [*Raab and Vedin*, 1995]). The data suggest that the timing of lake ice breakup responds in a nonlinear fashion to air temperature (Figure 3a). The response is much stronger in the warmest southern region of Sweden (∼14 d per 1°C), where the duration of ice cover usually varies between 0 and 125 d [*Eklund*, 1999], than in the coldest northern region (∼4 d per 1°C), where it is substantially longer (200–250 d [*Eklund*, 1999]). We explored whether such regional differences in the climatic sensitivity of the timing of ice breakup can be linked to differences in the annual air temperature cycle. To a first approximation the annual cycle can be

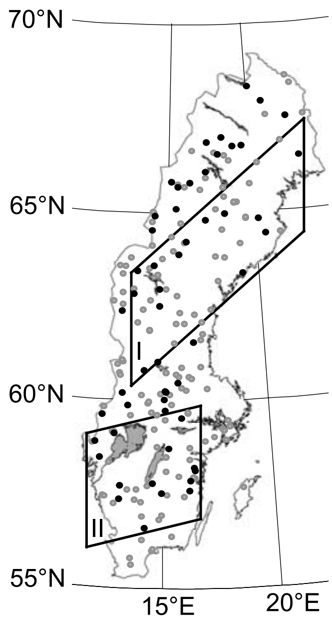

Figure 1. Map of Sweden showing the even geographical distribution of the 196 lakes with available ice data upon which the spatial and temporal comparisons of Figures 2 and 3 were based. The 54 lakes with complete 30-yr time-series (1961–1990) are represented by black dots and the remaining 142 lakes by gray dots. The 14 lakes represented by black dots within each of the geographical regions I and II are those used in the temporal comparison of Figure 3b.

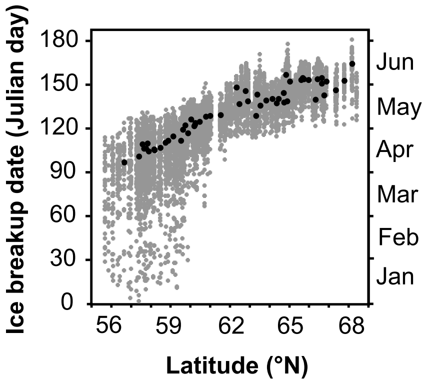

Figure 2. Relationship between the timing of ice breakup in Swedish lakes and latitude. The black symbols represent the median breakup dates during 1961–90 for 54 lakes with complete 30-yr series of ice observations; the gray symbols represent all available breakup dates from 196 lakes during 1961–2002. See Figure 1 for the locations of the lakes.

expressed as a sinusoid, characterized by a site-specific temperature mean (T_m) and amplitude (T_a). The duration of the period with air temperatures below 0°C, $D \approx (1/\pi)$ $\arccos(T_m/T_a)$, responds to changes in T_m approximately linearly if D is between ~3 and ~9 months, but deviates increasingly from linearity as D approaches 0 or 12 months. Employing the above equation for D, the median calendar date of ice breakup (t_B) can be expressed as a nonlinear function of mean air temperature by taking advantage of regional relationships between the means, amplitudes and phase shifts of temperature cycles in air and lake surface water. Based on regional temperature patterns in Sweden [*Raab and Vedin*, 1995], T_a and T_m are related such that T_m/T_a in the above expression for D can be approximated by $2 \cdot T_m/(24°C - T_m)$, thus allowing the slope and curvature of D to be predetermined independently of the ice data. Adding the median deviation of the observed breakup dates (55 d) as a phase parameter reflecting the overall timing of breakup in the region then yields the following equation to predict the median Julian day (t_B, in d) of lake ice breakup in our Swedish lakes based solely on lake-specific annual mean air temperatures:

$$t_B = \left(\frac{365\mathrm{d}}{2\pi}\right)\arccos\left(\frac{2T_m}{24°\mathrm{C} - T_m}\right) + 55\mathrm{d}$$

The timing of breakup of individual lakes is usually related most strongly to air temperatures integrated over periods of 1–3 months previous to the mean date of breakup [e.g., *Palecki and Barry*, 1986; *Robertson et al.*, 1992; *Livingstone*, 1997, 1999]. In our model we used annual

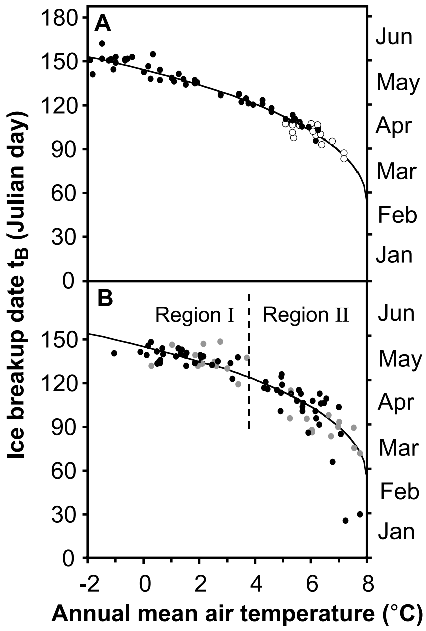

Figure 3. (a) Spatial variation in the relationship between median ice breakup dates during 1961–90 and lake-specific mean air temperatures (1961–90 normals [*Raab and Vedin*, 1995]) for the 54 lakes with complete data series illustrated in Figure 2, and for 16 southern lakes for which at least 28 yr of ice data were available (open symbols; missing data were interpolated from neighboring lakes, which influenced medians by only 0–1 d). The curve illustrated is based on regional patterns in the annual temperature cycle (see text). (b) Temporal variation in the relationship between ice breakup dates (median values for 14 lakes in each of Regions I and II) and annual mean air temperatures (July–June) from 1961 to 1990 (black; all data series complete) and from 1991 to 2002 (gray; a few missing data were interpolated as in Figure 3a). See Figure 1 for the locations of Regions I and II.

mean air temperatures to determine ice breakup dates. Annual means have the advantage of being free of an arbitrary choice of time period, and are therefore particularly useful for studies along a latitudinal gradient with a wide range of breakup dates (in Sweden, these extend from January to June). In addition, annual means are rarely limited by data availability (readily accessible atlas data can be used). For reasons of general applicability, therefore, a model based on annual mean air temperatures is preferable to one based on air temperatures integrated over a shorter time period.

[6] The observed ice breakup dates follow the predicted air temperature dependence surprisingly well across the whole temperature range (Figure 3a). In addition, the residuals are very small, although they include uncertainties in both the temperature and ice data, and although temperatures here are represented exclusively by annual means, which indicates that the control of ice breakup by factors other than the regional climate (e.g., local weather conditions or lake morphometry) is weak. Apart from areas under strong maritime influence and the warmest regions with irregular ice cover, residuals of the 30-yr medians from our regional model are usually less than 5 d. This illustrates the accuracy with which median ice breakup dates can be predicted from air temperature normals by using simple algorithms, even without accounting for local seasonality.

4. Temporal Patterns of Lake Ice Breakup

[7] The nonlinear temperature response of lake ice breakup on a spatial scale might possibly differ from that on a temporal scale. We therefore investigated the sensitivity of breakup dates to interannual variations in air temperature over 42 yr (1961–2002) within two climatically different geographical regions, one covering most of the north-east of Sweden (Region I in Figure 1; 61–67°N, $T_m \approx 0$–3°C) and the other covering the south of Sweden (Region II; 56–60°N, $T_m \approx 5$–7°C). Each of these regions was represented by median dates from 14 evenly distributed lakes and by annual mean temperatures (July–June) derived from the anomalies observed at six evenly distributed meteorological stations. Evaluations based on our data had shown that both air temperature and breakup dates were highly coherent within each of the regions, and that the influence of the selection and number of lakes and stations on the computed median values was negligible. We found that the dependence of the timing of ice breakup on air temperature derived from the temporal comparison (Figure 3b) was virtually identical to that derived from the spatial comparison (Figure 3a). Moreover, the residuals were only about twice as large (as would be expected because the number of observations included was four times less), although neither local nor seasonal deviations from the average regional temperature cycle had been taken into account.

5. Recent Patterns of Lake Ice Breakup

[8] The observed nonlinearity of the relationship between breakup dates and mean air temperature implies that long-term changes in air temperature will have a greater effect on the timing of lake breakup in warmer regions (air temperature reference normals: 5 to 7°C) than in colder regions (−2 to 2°C). This was tested with data from the period 1991–2002, when mean air temperatures over the whole of Sweden were homogeneously 0.8°C higher than during the period 1961–90. This recent temperature increase caused ice breakup to occur on average 17 d earlier in the warmer Region II but only 4 d earlier in the colder Region I (median of the 14 lakes in each region; Figure 3b).

6. Conclusions

[9] We conclude that, whereas increasing air temperatures may result in drastic shifts in the timing of lake ice breakup in temperate regions, such shifts are likely to be much less drastic in colder regions. As a consequence, any future increase in air temperature might result not only in generally earlier ice breakup, but also in a heterogeneous shift in the timing of breakup along regional temperature gradients. Since the timing of ice breakup determines the timing of many physical, chemical and biological lake processes, this may lead to an alteration in the diversity of lake types in many areas.

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