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Global patterns of lake ice phenology and climate: Model simulations and observations

Sarah E. Walsh,[1] Stephen J. Vavrus,[2] Jonathan A. Foley,[2] Veronica A. Fisher,[2]
Randolph H. Wynne,[3] and John D. Lenters[4]

Abstract. Lake ice phenology parameters (dates of ice onset and thaw) provide an integrative climatic description of autumn to springtime conditions. Interannual variations in lake ice duration and thickness allow estimates of local climatic variability. In addition, long-term changes in lake ice phenology may provide a robust indication of climatic change. The relationship between lake ice and climate enables the use of process-based models for predicting the dates of freeze-up and thaw. LIMNOS (Lake Ice Model Numerical Operational Simulator) is one such model, which was originally designed to simulate the ice phenology of several lakes in southern Wisconsin. In this study, LIMNOS is modified to run globally on a 0.5° by 0.5° latitude-longitude grid using average monthly climate data. We initially simulate the ice phenology for lakes of 5- and 20-m mean depths across the northern hemisphere to demonstrate the effects of lake depth, latitude, and elevation on ice phenology. To evaluate the results of LIMNOS we also simulate the ice phenology of 30 lakes across the northern hemisphere which have long-term ice records. LIMNOS reproduces the general geographic patterns of ice-on and ice-off dates, although ice-off dates tend to occur later in the model. Lakes with extreme depths, surface areas, or precipitation are simulated less accurately than small, shallow lakes. This study reveals strengths and weaknesses of LIMNOS and suggests aspects which need improving. Future investigations should focus on the use of geographically extensive lake ice observations and modeling to elucidate patterns of climatic variability and/or climate change.

1. Introduction

Previous studies of lake ice have mainly focused on its role in the heat budget of lakes [*Birge*, 1915; *Juday*, 1940; *Scott*, 1964; *Adams and Lagenby*, 1978; *Hamblin and Carmack*, 1990; *Oppenheimer*, 1997], its relationship to aquatic ecosystems [*McLain et al.*, 1994], and its use as an indicator of climatic variability and climate change [*Scott*, 1964; *Palecki and Barry*, 1986; *Schindler et al.*, 1990; *Hanson et al.*, 1992; *Robertson et al.*, 1992; *Assel and Robertson*, 1995; *Wynne et al.*, 1996; *Anderson et al.*, 1996; *Wynne et al.*, 1998]. Early work in these areas was mainly conceptual; recording and comparing data from different lakes and lake districts [e.g., *Birge*, 1915; *Bryson and Bunge*, 1956; *Scott*, 1964]. More recently, however, lake ice research has focused on the creation of geographically extensive lake ice data sets (based both on in situ measurements and satellite measurements) and the development of process-oriented models of lake ice physics. These developments have significantly advanced our understanding of the physics of lake ice and greatly expanded the possibilities of future investigations.

[1]Department of Fisheries and Wildlife, Michigan State University, East Lansing.
[2]Center for Climatic Research and Climate, People, and Environment Program, Institute for Environmental Studies, University of Wisconsin, Madison.
[3]Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg.
[4]Center for Limnology, University of Wisconsin, Madison.

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Quantitative measures of lake ice phenology (i.e., date of ice onset and date of ice thaw) can provide a powerful, integrative description of wintertime and springtime climatic conditions. For example, year-to-year changes in the duration and thickness of lake ice cover furnish an estimate of local climatic variability and its potential impact on aquatic ecosystems. In addition, long-term changes in lake ice phenology may provide an early indication of climatic change. Global warming scenarios, for example, suggest that warmer conditions will be greatest over high-latitude land masses during winter, which would have important implications for lake ice phenology [*Vavrus et al.*, 1996]. Similarly, historical lake ice records, which often date back hundreds of years, may help us to depict past climatic variations [e.g., *Palecki and Barry*, 1986; *Vavrus et al.*, 1996].

In this study, we attempt to describe the global-scale patterns of lake ice phenology in relation to climate. First, we use a numerical model of lake ice physics (Lake Ice Model Numerical Operational Simulator (LIMNOS)) to simulate the phenology of lake ice for lakes across the entire globe. Second, the model is applied to a 0.5° by 0.5° latitude-longitude grid and is driven by long-term average (30-year; 1931–1960) climatic data. Third, in each 0.5° by 0.5° grid cell we simulate lake ice development over hypothetical lakes of 5- and 20-m mean depths to help quantify the role of lake morphometry. Fourth, we compare model simulations against a compilation of 30 long-term lake ice phenology records spanning the northern hemisphere. By comparing the model simulations against these observations we evaluate the potential skill of using computer models to describe the physical relationships between lake ice and climate across continental and global scales.

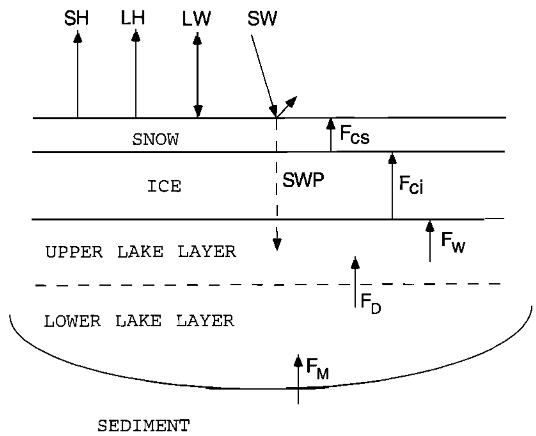


Figure 1. Lake Ice Model Numerical Operational Simulator (LIMNOS) schematic. SH, sensible heat flux; LH, latent heat flux; LW, net longwave radiation flux; SW, net solar radiation flux; SWP, penetrative solar radiation flux; F_{ci}, conductive heat flux through ice; F_{cs}, conductive heat flux through snow; F_W, basal heat flux (from lake to ice bottom); F_D, eddy-diffusion heat flux; F_M, heat flux from sediment. Adapted from *Vavrus et al.* [1996].

2. LIMNOS: Model Description

The links between lake ice and climate enable the use of mathematical models to understand and predict ice accretion and ablation. For example, the thermodynamics of small lakes have been accurately simulated by models, such as the Dynamic Reservoir Simulation Model (DYRESM) [*Patterson and Hamblin*, 1988], Minnesota Lake Model (MINLAKE) [*Gu and Stefan*, 1990], and Lake Ice Model Numerical Operational Simulator (LIMNOS) [*Vavrus et al.*, 1996]. These models are generally similar to each other, but they have been used in different ways. For example, studies using DYRESM and MINLAKE have concentrated mainly on model development and validation [*Patterson and Hamblin*, 1988; *Gu and Stefan*, 1990], while *Vavrus et al.*, [1996] utilized LIMNOS in a sensitivity study of the importance of climate and lake depth in the thermodynamics of lake ice. In addition, Vavrus et al. successfully simulated the timing of ice onset and ice thaw (herein referred to as the "ice-on" and "ice-off" dates) for three different southern Wisconsin lakes.

In this study, we apply LIMNOS to the entire globe at a 0.5° by 0.5° latitude-longitude grid. While the original model was designed with only local and regional applications in mind, we have extrapolated its use broadly in an attempt to describe the general patterns of lake ice phenology that occur within different climatic regimes. The model is described by *Vavrus et al.* [1996] in detail; here we will only present the general features of the model.

LIMNOS is patterned after the thermodynamic sea ice models of *Maykut and Untersteiner* [1971] and *Parkinson and Washington* [1979], which numerically solve the vertical heat conduction equations for layers of ice and snow. The model (Figure 1) considers only bulk diffusive vertical energy transfer through the snow and ice layers, with an energy balance required at each of the vertical interfaces: air-snow or air-ice interface, snow-ice interface, and ice-water interface. When ice cover is present, this constraint means that at the frozen upper surface the sum of energy fluxes from the atmosphere must be balanced by vertical heat conduction through the ice and snow layers, plus energy used in melting.

LIMNOS uses *Semtner*'s [1976] "zero layer" parameterization to solve the energy balance equations, so that ice has zero heat capacity and therefore adjusts its temperature instantaneously to atmospheric forcing. This approximation results in at most only three temperatures in the model which dictate the heat conduction: that at the lower ice surface (set to the freezing point), the upper surface (snow or ice), and the snow-ice interface. The ice is assumed to form as a solid 1-cm slab instantaneously across the entire lake with no horizontal variation. When the simulated ice thickness drops below 1 cm, all of the ice is required to melt off. These assumptions are justified by the authors' own observations of the suddenness of ice formation on Madison-area lakes and by published accounts of Lake Mendota (Wisconsin), which show that complete freeze and breakup are rapid events that can usually be pinpointed to within 1 or 2 days [*Bunge and Bryson*, 1956]. However, on very extensive lakes, such as the Great Lakes, ice does not occur in this manner and instead forms initially along the shore and then spreads into the interior.

The model has two lake layers, whose variable thicknesses are determined by the amount of turbulent kinetic energy (TKE) going into the lake. The TKE is the sum of turbulent kinetic energy production from wind stirring and surface buoyancy effects. The upper layer deepens for TKE > 0 and shoals for TKE < 0, according to the Integral Model of *Niiler and Kraus* [1977]. During ice coverage the bottom layer is subjected to a heat flux from the lake sediments, utilizing estimates appropriate for a 12-m-deep midlatitude lake (Lake Mendota, Wisconsin) [*Scott*, 1964]. Because this heat flux is derived from a single lake, it may not be representative of lakes in other parts of the world. However, it is impossible to specify the appropriate heat flux for every (hypothetical) lake in the model, and sensitivity tests by the model show that the ice-on and ice-off dates are not strongly affected by this term.

During ice-free conditions, the sum of the energy fluxes at the lake surface (Q_0) dictates the time rate of changes of water temperature T_W, according to

$$\frac{dT}{dt} = \frac{Q_0}{C_W D_{\mathrm{MIX}}} \tag{1}$$

where C_W is the volumetric specific heat of the lake of depth D_{MIX}. When the lake is ice covered, the upper and lower layer lake temperatures are also calculated from (1), except that Q_0 is replaced by the net flux of heat coming into the layer (including the penetration of solar flux into the layers, heat exchange between layers, and heating of the lower layer from the underlying sediment). Solar radiation into the lake is attenuated by an extinction coefficient of 0.35 m^{-1}, as suggested by *Patterson and Hamblin* [1988].

When a thick snow cover causes hydrostatic sinking of the ice-snow boundary below the surface of the lake, the model converts some of the snow into grey ice, following *Ledley* [1985]. This conversion not only reduces the insulating capacity of the snow-ice slab by decreasing the snow depth but also causes a more opaque ice cover. The subsequent solar penetration through the ice pack is reduced when the snow cover melts off in the spring; thus less energy is available for bottom melting. The bottom melting is generated by the basal heat flux, which is assumed to occur as a strictly diffusive heat transfer process.

A major simplification made here is that lake depth is the only morphometric parameter addressed; no treatment of lake shape, fetch, or bathymetric variations is considered. Also, there is no provision for open water (leads) within the ice cover. The absence of leads and any aerial dependence on the ice cover means that potentially important processes are neglected. For instance, *Scott* [1964] suggests that during snow coverage, small lakes may "see" a different (warmer) climate than that of large ones, by virtue of their greater relative shoreline fraction allowing more solar radiation to be absorbed on nearby land and advected over the lake. This distinction is especially relevant to ice melting, as in reality an ice cover melts both vertically (as simulated here) and horizontally, the latter process being driven by preferential heating of open water within the ice pack. Although it would not be feasible to alter the meteorological input fluxes to account for the effect of differential solar absorption on adjacent land, a proper treatment of leads and their role in the decay of lake ice would be an appropriate next step.

LIMNOS was designed to simulate ice thermodynamics of small temperate lakes lacking extreme climatic or morphometric characteristics, but the absolute upper bound is not known yet. When applied to a suite of lakes in Minnesota, LIMNOS was found to be applicable up to at least a mean depth of 30 m and a surface area of 540 km^2 for the ice-off date. Other tests found that the model will not accurately simulate the ice phenology of Grand Traverse Bay on Lake Michigan (mean depth of 46 m).

3. Extending LIMNOS to the Global Scale

Within each 0.5° by 0.5° grid cell of the global array, the model simulates the physics of a hypothetical small inland lake. Rather than simulating each of the world's lakes individually, this technique allows us to examine the general patterns of lake behavior across broad climatic ranges. By comparing model simulations of small lakes that actually exist in a given grid cell, we can ascertain the accuracy of the simulations. Because LIMNOS is only designed to simulate the physics of small lakes, we exclude some large lakes such as the Great Lakes and Lake Baikal from the comparisons. In addition, the model is not designed to simulate the ice dynamics of rivers.

This version of LIMNOS operates on an hourly time step and is driven by the following atmospheric variables: air temperature, precipitation (snowfall is estimated as a function of air temperature when the air temperature is near or below freezing), solar radiation, longwave radiation, humidity, and wind speed. In order to provide these driving data sets to the model, we synthesize quasi-daily climatic conditions from monthly averaged climatic data (following the methods used by *Levis et al.* [1996]. In addition, daily climatic conditions are further decomposed to generate a simple diurnal cycle of solar radiation and temperature. The basic climatic data used in this study are based on the W. Cramer and R. Leemans (unpublished data, 1996) climatic data set (version 2) of monthly mean temperature, temperature range (maximum minus minimum temperature), precipitation, and cloudiness [*Leemans and Cramer*, 1990; W. Cramer, personal communication, 1996]. In addition, we use a monthly mean data set of relative humidity produced by *Levis et al.* [1996] that was generated from the world airfield summaries data set [*World WeatherDisc*, 1994]. From these primary data the model estimates quasi-daily values (by linearly interpolating the monthly mean values) of daily average temperature, temperature range, precipitation, humidity, and cloudiness. The downward longwave radiation fluxes are parameterized in terms of air temperature, humidity, and cloudiness; solar radiation is parameterized in terms of cloudiness and the Earth's orbital mechanics.

Because a global data set of observed wind speeds is not yet available, we use a constant wind speed of 5 m s^{-1} in these simulations (sensitivity tests show that this approximation may affect the ice-on date, but its effect on the thaw date is probably negligible). Using a constant wind speed to run the model made the stratification of the lakes which precedes freeze-up impossible to simulate, since this process requires periods of relatively weak winds. To parameterize stratification, the lakes were forced to shoal when the lake temperature reached 1°C, by prescribing a linear decrease in the depth of the upper water layer between the bottom of the lake and the surface as a function of the water temperature [*Vavrus et al.*, 1996].

4. Simulations of Lake Ice Phenology

The global LIMNOS simulations are run for 3 years to ensure that the lake thermodynamics are in equilibrium with the climatic forcing. Here we present the simulations of the last year of the simulation for lakes of 5- and 20-m mean depths (Plates 1 and 2).

Qualitatively speaking, the general patterns of lake ice phenology all appear reasonable. At the most basic level we can quickly see that lakes freeze in much of the northern United States, all of Canada, most of central and northern Europe, and most of Asia. Furthermore, by comparing Plates 1 and 2 we see that the southern border of lake ice varies according to the average depth of the lake. Deeper lakes require a colder climate in order to freeze owing to their greater heat storage capacity, whereas shallow lakes will cool more quickly and freeze in a shorter period of time. *McFadden* [1965] showed that shallow lakes require a 3-day running average below 0°C to freeze, while deep large lakes require a 40-day running average below 0°C for freeze to occur. The southern boundary of ice in the United States is within a few grid cells of anecdotal evidence in the Midwest and several cells too far south in the Rocky Mountain Range, but we currently do not have any other data on where the boundary is for most of the globe.

The general pattern of lake ice duration (Plates 1c and 2c, Figure 2, and Plate 3) reflects the effects of latitude and continentality on wintertime climate. There is a strong increase in lake ice duration with increasing latitude (Figure 2). This variation is strikingly linear north of 40°N, with topography introducing significant nonlinearities south of 40°N. Superimposed on the zonal mean is a pattern of increasing lake ice duration moving west to east across continental interiors (Plate 3). Taken together, this results in the longest ice duration in northeastern Siberia and northern Canada (Plates 1c and 2c).

To better understand the geographic patterns in lake ice, we can examine various factors such as topography, freezing degree days (FDD), and precipitation. For example, topography plays an important role in the ice dynamics of lakes: the Tibetan Plateau and the Rocky Mountains have much longer ice durations than those of other areas at these latitudes (Plate 3). By comparing the global map of FDD (Plate 4) with Plate 1, we can see that most areas where FDD is greater than zero are also areas where 5-m deep lakes freeze. Plate 4 also shows increasing FDD to the north and east, suggesting that temperature plays a role in the ice duration anomalies previously seen in (Figure 2 and Plate 3). (FDD are calculated by adding up

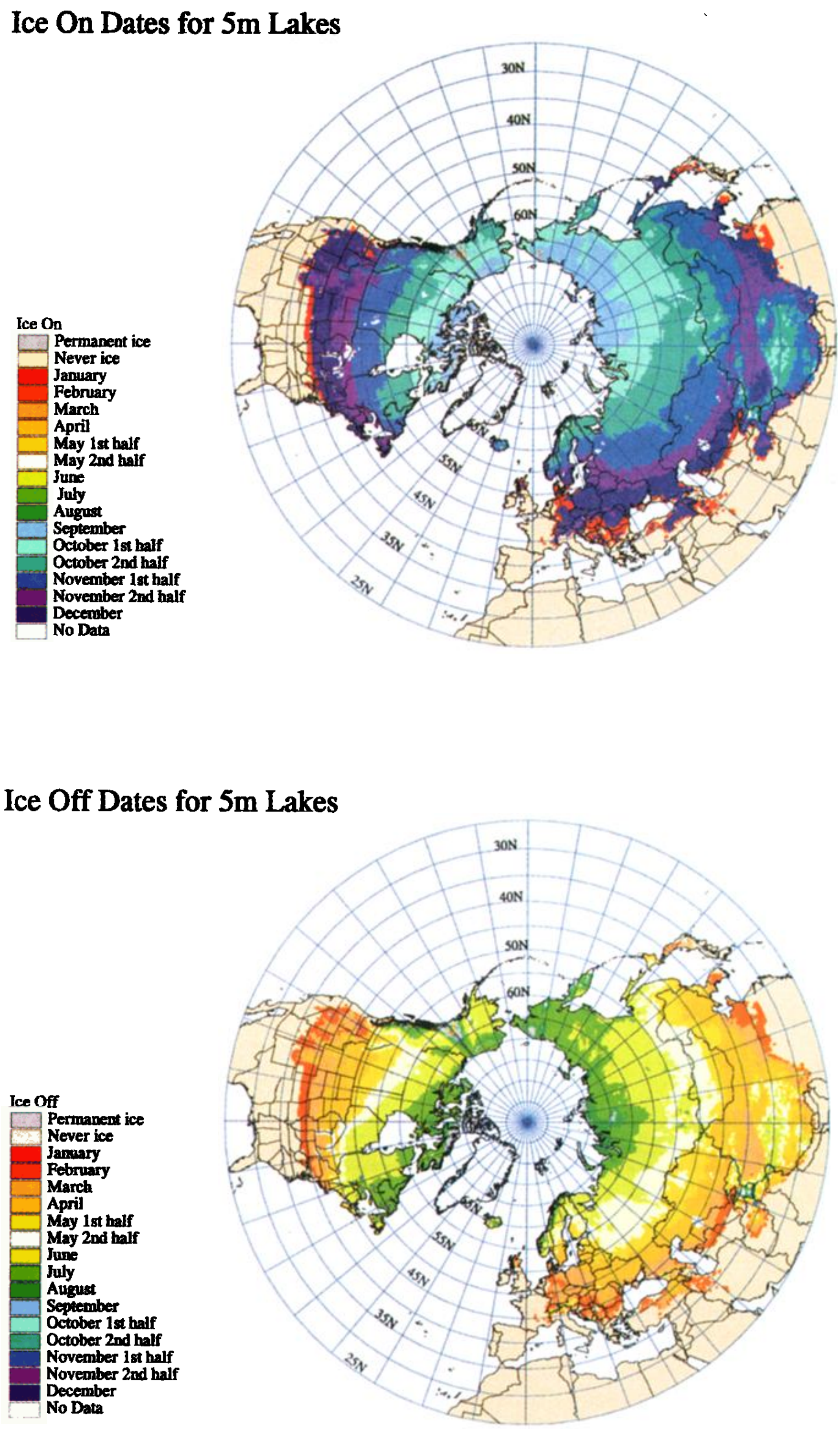


Plate 1. Global lake ice phenology simulations for 5-m lakes. Data are only presented for areas north of 20°N because the area south of this line had very few lakes freeze (only a few grid cells in the tip of South America). Shaded areas represent permanent ice cover. Ice-on and ice-off dates were calculated to the day in the model but are presented to the nearest month or half month to show regional patterns.

the number of degrees below zero (°C) that the average daily temperature is for every day of the year. The daily temperatures are approximated by interpolating long-term monthly mean values, as in the model simulations (see section 3).)

Another example of the effect of regional climate on ice is seen in areas of high snowfall (Plate 5) where the model simulates longer ice duration (Plate 3). This behavior follows the sensitivity studies of *Vavrus et al.* [1996], who attribute the dependence on the higher reflectivity of snow, enhanced creation of grey ice, and the added mass of the ice and snow layers. In some areas, such as the southern border between Alaska and Canada, this can even result in the development of

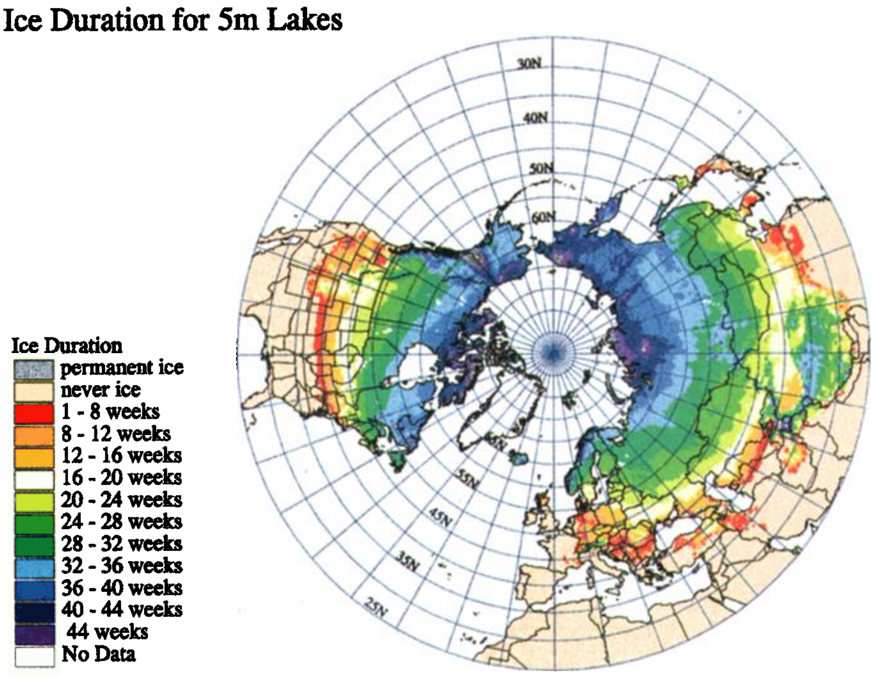


Plate 1. (continued)

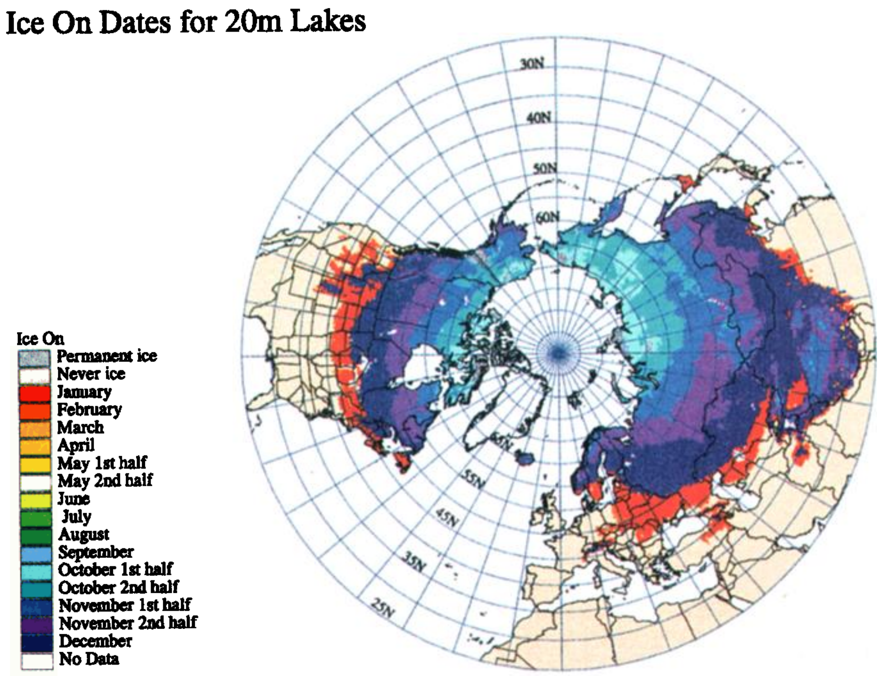
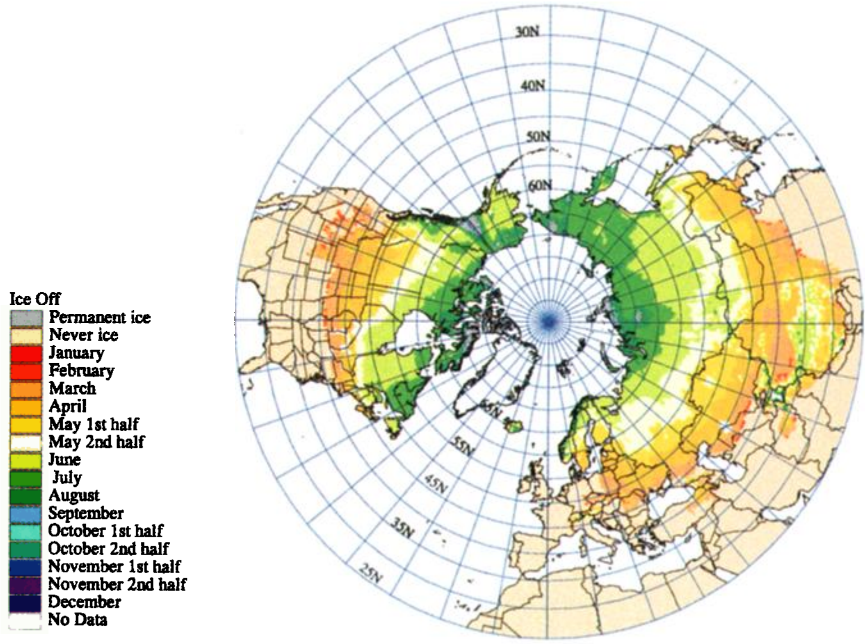


Plate 2. Global lake ice phenology simulations for 20-m lakes. Presentation of data is the same as in Plate 1.

permanent lake ice cover. The model prediction of permanent lake ice cover in this region seems realistic since glaciers exist in the region and annual snowfalls can exceed 22 m [*Bryson and Hare*, 1974]. However, the extreme annual snowfalls shown near the Alaska/Canada border (Plate 5) may be due in part to an overestimate of precipitation as snowfall (see section 3).

Across the northern hemisphere, contours of ice-off dates are much tighter than those for ice-on dates, suggesting that ice thaw is more sensitive to changes in climate. Others, including *Palecki and Barry* [1986], *Robertson et al.* [1992], and *Assel and Robertson* [1995], have noted the enhanced sensitivity of lake ice-off dates to climate. While performing sensitivity studies with an earlier version of LIMNOS, *Vavrus et al.* [1996] also noted that simulated ice-off dates were more sensitive to temperature perturbations than ice-on dates. Furthermore, Lake Mendota (Wisconsin) is known to have more variabil-

Ice Off Dates for 20m Lakes



Ice Duration for 20m Lakes

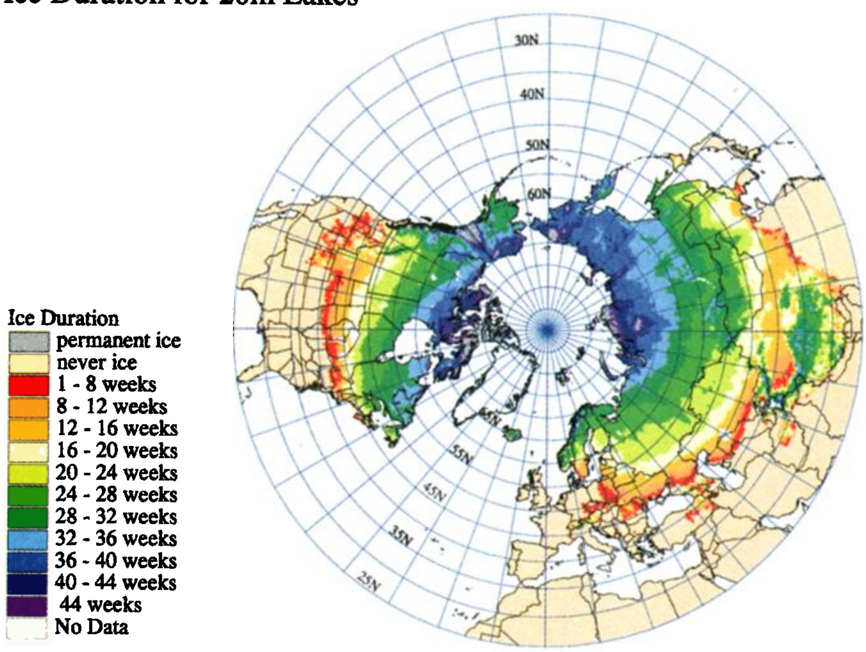


Plate 2. (continued)

ity in its ice-off records than in those for ice-on [*Robertson et al.*, 1992].

5. Global Lake Ice Phenology Data

Most studies of lake ice phenology have focused on individual lakes or lake districts. Some larger-scale analyses of lake ice phenology have been conducted but not at a global scale; *Wynne et al.* [1996], for example, described the temporal coherence of lake ice phenology data (as obtained from satellite) for 62 lakes across the Laurentian Shield. *Wynne et al.* [1998] assessed recent trends in lake ice breakup dates (as derived from satellite data) in the U.S. Upper Midwest and portions of Canada (60°N, 105°W to 40°N, 85°W).

Our ice data are from a global lake ice phenology data set for the northern hemisphere compiled by the Lake Ice Analysis Group (LIAG). LIAG is a multi-investigator, multi-institutional effort aimed at the analysis and interpretation of long-term ice records on lakes and streams in relation to climatic

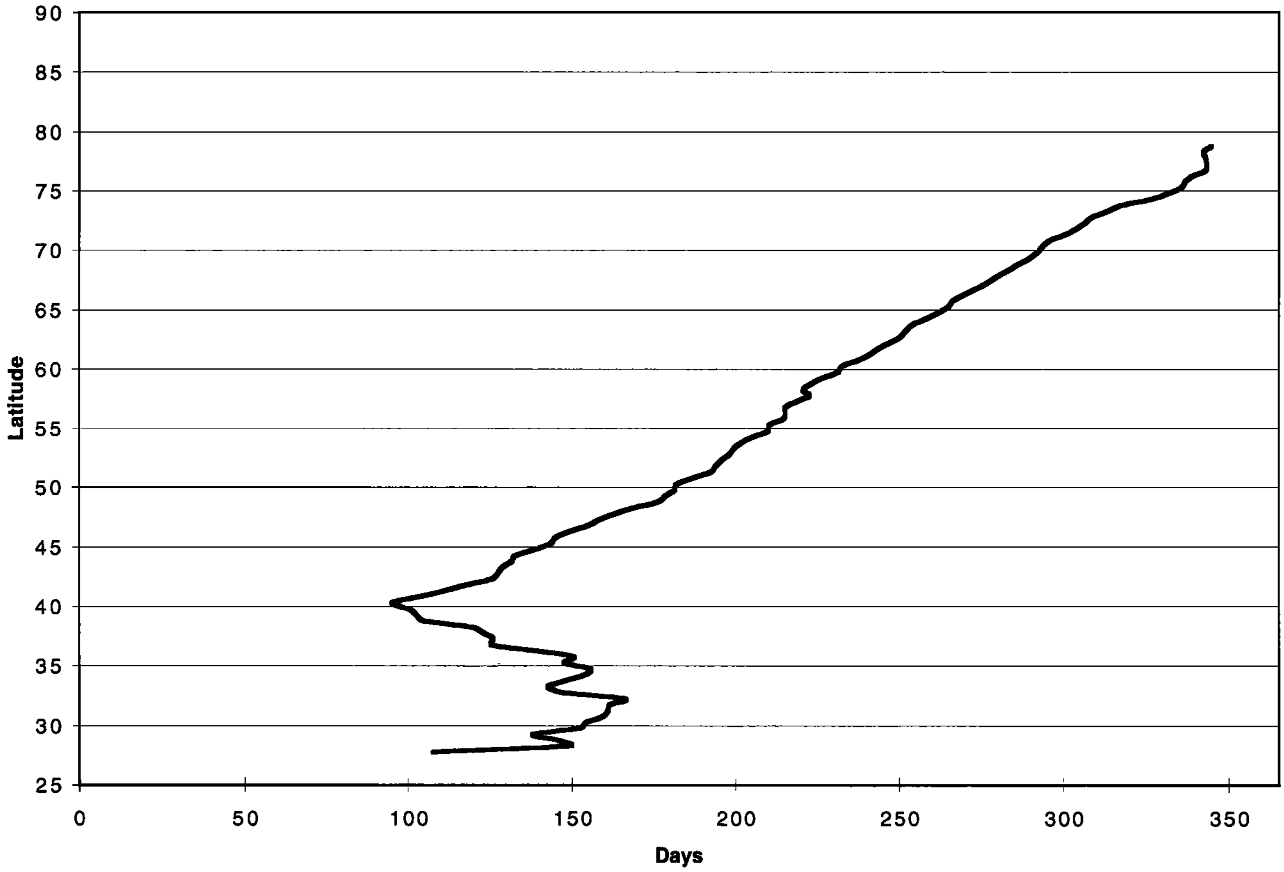


Figure 2. Zonal mean ice duration for 5-m lakes. Average lake ice duration was calculated for each half-degree latitude band.

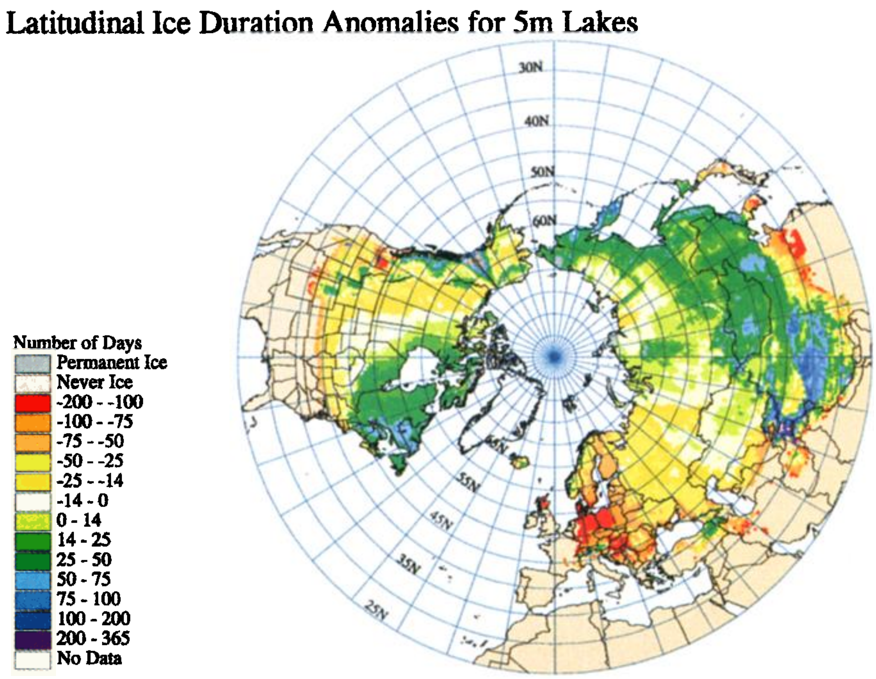


Plate 3. Latitudinal ice duration anomalies for 5-m lakes. The zonal mean ice duration was subtracted from the actual simulated value for each cell. Negative numbers signify fewer days with ice than that of the latitudinal average, while positive numbers indicate a longer ice duration than that of the average.

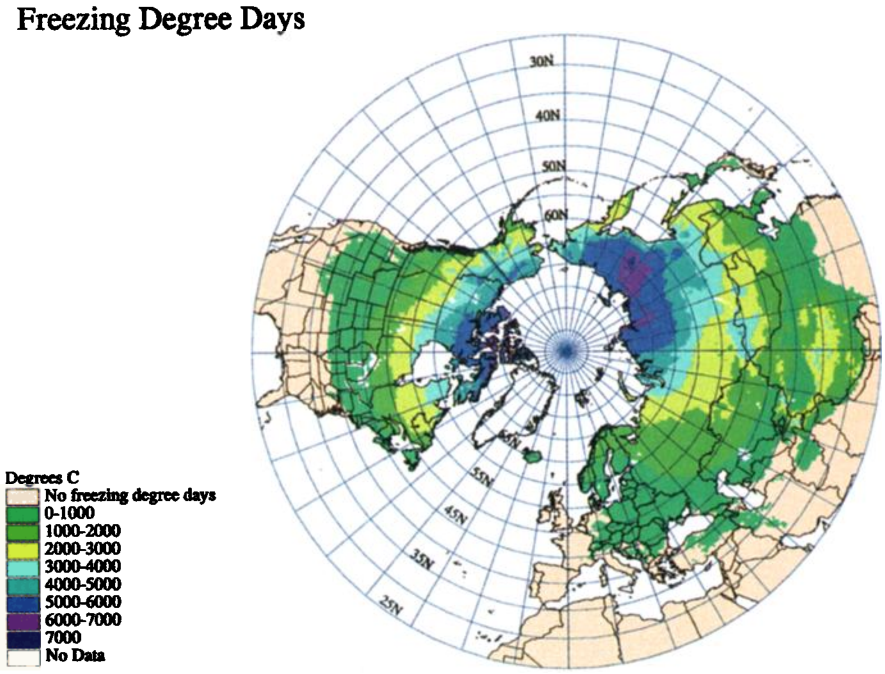


Plate 4. Freezing degree days. These data were calculated using the daily average temperature. The number of degrees below 0°C was totaled for the entire year to provide a regional picture of extremes in winter temperature.

and ecological systems (See http://limnosun.limnology.wisc.edu/~webadmin/ice/LIAGpage.html). LIAG activities are organized and maintained by the North Temperate Lakes Long-Term Ecological Research Program (LTER) site at the Center for Limnology, University of Wisconsin-Madison.

In this study, we selected a subset of the LIAG data set. First, we only selected lake records that reported the mean lake depth (as required by LIMNOS) and that provided at least 10 years of data for both ice-on and ice-off dates. In some regions, including Finland and areas in Russia, there were still

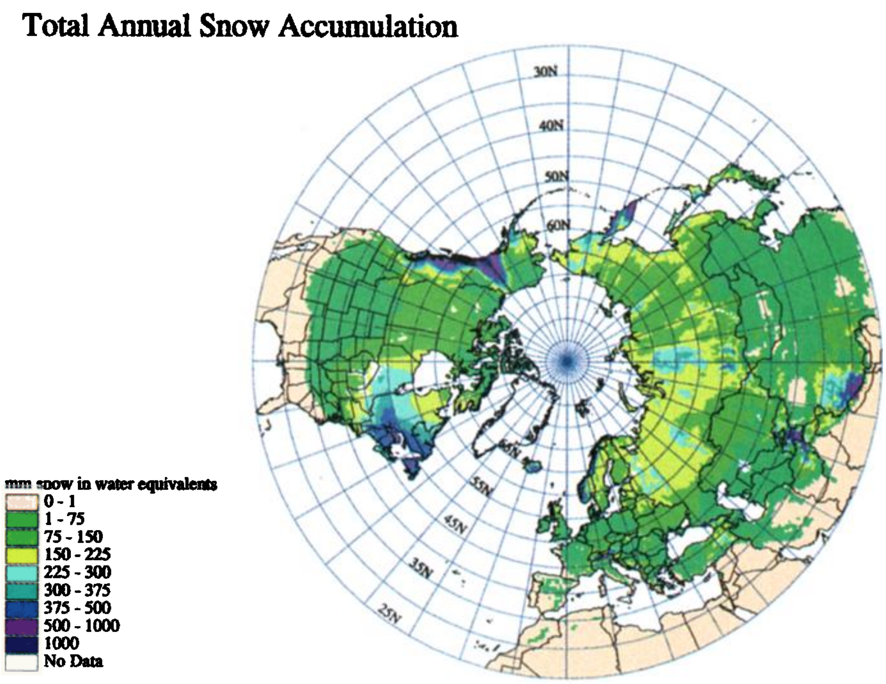


Plate 5. Total annual snow accumulation in water equivalent. These data were calculated by totaling the daily precipitation occurring as snow over an entire year.

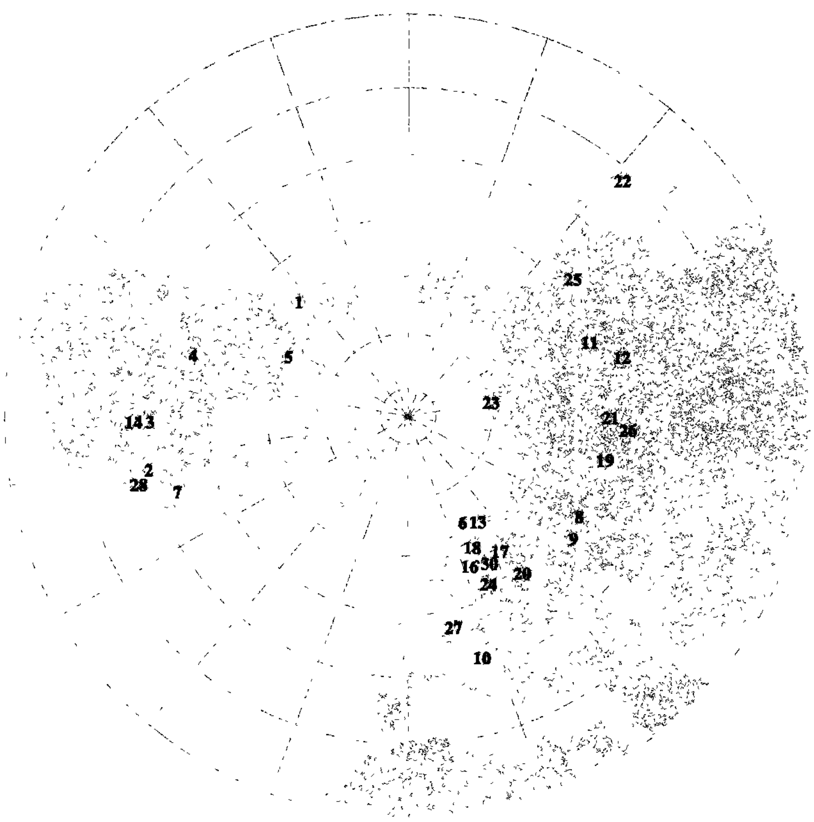


Figure 3. Distribution of observed lake ice phenology data. Numbers on this map are positioned at the location of the lakes used in the model comparison. The numbers refer to the identification numbers found in Table 1. Lakes 15 and 29, which are not mapped, are located near lakes 27 and 30, respectively.

a large number of lake records within relatively small regions. In these areas we only selected a random subset of the lakes so as not to bias the geographic representation of the data set to these regions. The resulting 30 lakes span much of the northern hemisphere (Figure 3 and Table 1).

The 30 lakes vary in mean depth from 2 to 174 m with an average of 19.0 m. The lakes are distributed throughout Eurasia in Russia, Finland, Germany, Hungary, and Japan. In North America the lakes are located in New York, Wisconsin, the Northwest Territories, Yukon, Saskatchewan, Ontario, and Quebec.

6. Comparing Simulated and Observed Lake Ice Phenology

Many interesting patterns appear in the global lake ice simulations, but without evaluating the accuracy of the model, patterns of lake ice phenology cannot be considered conclusive. Here we compare model simulations against the 30 lake ice phenology records presented in Table 1. In this case, we apply LIMNOS to each lake individually, by running the model with the observed lake depth and driving it with the atmospheric inputs for the 0.5° by 0.5° latitude-longitude cell that contains the lake. In cases where a lake is larger than a 0.5° by 0.5° grid cell, we use the location where the data were collected to determine which cell to use.

A preliminary comparison of simulated and observed lake ice phenology parameters (Table 1 and Figure 4) shows that the global-scale patterns of lake ice phenology are satisfactorily captured by the model. The linear regressions (Figure 4a) between simulated and observed lake ice phenology parameters are highly significant. Ice duration ($r^2 = 0.86$) is slightly more significant than the ice-on date ($r^2 = 0.83$) or ice-off date ($r^2 = 0.79$). It appears that the model is most accurately simulating ice-on dates, while simulated ice-off dates have a bias toward a later date. Overall, the results of these data-model comparisons show that it is possible to simulate lake ice phenology patterns on a global scale using very simple climatic and morphometric parameters.

In order to remove the strong latitudinal association between simulated and observed lake ice parameters, anomalies were calculated along five latitudinal bands and plotted simultaneously (Figure 4b). The five bands cover 43°–69°N, contain four to seven lakes each, and range in width from ~1°–5° latitude. After removing the effects of latitude the correspondence between observed and simulated dates continues to be very good. The remaining anomalies (Figure 4b) are not strongly dependent on depth but do show variations with longitude (not shown). In fact, the observed duration anomalies indicate a general eastward increase in lake ice across the continents, similar to those presented in the global simulation (Plate 3).

Several of the lakes were simulated to within 2–4 days for both ice-on and ice-off dates, while others were off by over a month. When the model output is within 2–4 days of the long-term average, it is considered to be within the observational error. An inherent source of error in these comparisons is that the definition of ice-off is somewhat subjective, possibly varying between the day when leads appear in the lake, when

Table 1. Summary Data on Comparison Lakes

Identification Number	Lake Name	Latitude, deg	Longitude, deg	Mean Depth, m	Surface Area, km^2	Ice-On Dates		Ice-Off Dates		Ice Duration	
						Observed	Simulated	Observed	Simulated	Observed	Simulated
1	Aishihik	61.65	−137.48	30.0	146.0	332.4	304.0	165.8	236.8	198.4	297.8
2	Boshkung	45.05	−78.75	23.3	7.2	357.1	372.2	114.4	122.6	122.2	115.4
3	Crystal	46.02	−89.62	10.4	0.4	332.8	338.5	112.8	118.6	145.0	145.1
4	Diefenbaker	51.28	−106.83	21.6	430.0	349.7	348.4	119.0	119.6	134.2	136.2
5	Great Bear	66.08	−118.03	71.7	31153.0	330.3	332.7	190.8	169.7	225.4	202.0
6	Inarie	69.05	28.40	14.4	8.0	319.8	315.8	157.9	156.5	203.1	205.7
7	Lac St. Jean	48.52	−72.27	11.4	1053.0	341.6	335.1	130.7	165.5	154.1	195.4
8	Argayash	55.33	60.54	5.0	7.0	308.7	307.0	117.8	140.5	174.1	198.5
9	Asli-kul	54.18	54.37	5.1	23.3	313.5	310.2	112.8	143.7	164.3	198.5
10	Balaton	46.83	17.67	3.0	596.0	345.3	363.0	80.5	52.8	91.2	54.8
11	Baunt	55.13	113.07	17.0	111.0	295.7	303.7	145.6	167.6	214.9	228.9
12	Gusinoye	51.07	106.17	15.0	163.0	325.1	314.4	126.4	142.8	166.3	193.4
13	Lovozero	67.59	35.05	5.8	223.0	296.3	296.2	154.9	162.6	223.5	231.5
14	Mendota	43.66	−89.45	12.4	39.4	357.2	356.2	92.6	93.6	100.4	102.4
15	Mueggelsee	52.43	13.65	4.9	7.4	376.4	366.0	84.9	60.7	73.5	59.7
16	Nasijarvi (3568)	61.53	23.75	14.0	257.0	347.7	324.3	130.4	133.8	147.8	174.5
17	Onega (Petrozavodsk)	61.30	35.45	30.0	9900.0	350.0	360.4	125.2	142.5	140.2	147.2
18	Oulujarvi (5932)	64.33	27.33	8.0	928.0	317.6	319.5	138.8	139.6	186.2	185.1
19	Sartlan	54.54	78.35	3.0	238.0	303.5	301.2	123.6	140.7	185.1	204.5
20	Senezhskoye	56.11	37.00	3.9	8.5	319.0	315.0	115.9	147.8	161.9	197.8
21	Shira	54.30	90.70	11.9	32.0	317.4	313.5	123.9	145.8	171.5	197.3
22	Suwa	36.15	138.08	4.7	12.9	372.7	364.9	58.6	63.7	51.0	63.8
23	Taymyr	74.40	101.36	11.9	4560.0	277.6	276.3	182.8	236.3	270.2	325.0
24	Tchudsko-Pskovskoye	57.51	26.57	7.1	3560.0	334.3	331.2	106.6	135.5	137.3	169.3
25	Tchukchagirskoye	52.00	130.36	2.0	366.0	298.9	294.2	133.9	135.8	200.0	206.6
26	Teletskoye	51.46	87.36	174.0	223.0	328.5	357.0	120.5	149.8	157.0	157.8
27	Nehmitzsee	53.17	13.03	6.4	1.7	362.3	367.3	78.4	70.8	81.1	68.5
28	Oneida	43.24	−76.14	6.8	206.7	357.4	354.2	93.1	88.8	100.7	99.6
29	Paijanne S	61.18	25.53	17.0	30.0	346.7	350.5	126.8	133.7	145.1	148.2
30	Saimaa S	61.08	28.27	17.0	15.0	333.1	351.7	125.1	133.8	157.0	147.1

Included here are the lake identification numbers used to locate the lake in Figure 3, lake name, morphometric data (depth and surface area), latitude-longitude position of lake, and observed and modeled ice-on and ice-off dates and duration.

50% of the lake is ice free, or when there is no ice left on the lake. The process of ice melting off a lake can take several days, and there is not a unified method to determine which is the ice-off date. The determination of the ice-on date is also not universally defined, but the time period over which ice-on occurs is typically shorter than that for ice-off. One possible problem in determining ice-on dates is if there is a short freeze early in the fall season, followed by a temporary thaw, and then a consequent refreeze for the rest of the winter. We do not know how this situation is dealt with by the different data collectors.

The lakes which were not modeled accurately were often found in extreme climate conditions or varied drastically from the stereotypical small, round-bottomed lake that the model was designed to simulate. For example, Lake Teletskoye in Russia (near Lake Baikal) has a mean depth of 174 m. The model simulated the lake to freeze on day 357 and thaw on day 149, but the long-term average freeze and thaw dates are 328 and 120, respectively. Similarly, the ice-off date of Great Bear Lake (mean depth of 71.7 m) in northern Canada is simulated to thaw 21 days too early (however, the ice-on date was within 2 days). Although these are poor simulations, with an error of up to 30 days in either direction, these lakes vary greatly from the type of lake for which the model was originally developed. We doubted whether the model would run successfully for a lake with a mean depth over 100 m because it cannot adequately reproduce the thin upper layer in deep lakes. The shoaling parameterization was designed for shallow Lake Mendota (Wisconsin).

Another lake which was poorly simulated is Aishihik Lake in northwestern Canada. The model predicted the ice-on date to be ~30 days too early, and it predicted the ice-off date to be over 50 days too late. This lake has an average depth of 30 m, which should not be too deep for the model, but it is in an area which receives a large amount of snow.

Along with depth and snow cover, one other variable which may be difficult for LIMNOS to account for is surface area. Several lakes which are known to have large surface areas are simulated poorly, including Lake Balaton in Hungary (mean depth of 3.0 m). Ice-on is within 10 days of the long-term record, but ice-off is simulated more than 25 days too early by the model. This may be a result of the lake having less edge effect than is appropriate for the model. Lake Balaton is ~80 km (50 miles) long and 16 km (10 miles) wide. If wind blows across the length of the ice-covered lake, it will cool and cause the lake to experience a climate colder than the ambient air temperature used in the model. The opposite is possible in the fall, when the water would warm any cool air and cause the lake to experience a different climate than that which the atmospheric forcings provide for the area. LIMNOS does not take this sort of complex wind dynamic into consideration. Great Bear Lake in northern Canada is another lake with a large surface area (31,153 km^2), one which is larger than both Lake Ontario and Lake Erie. This lake is also deep (mean depth of 71.7 m), but the surface area may be more problematic for the simulation than the depth.

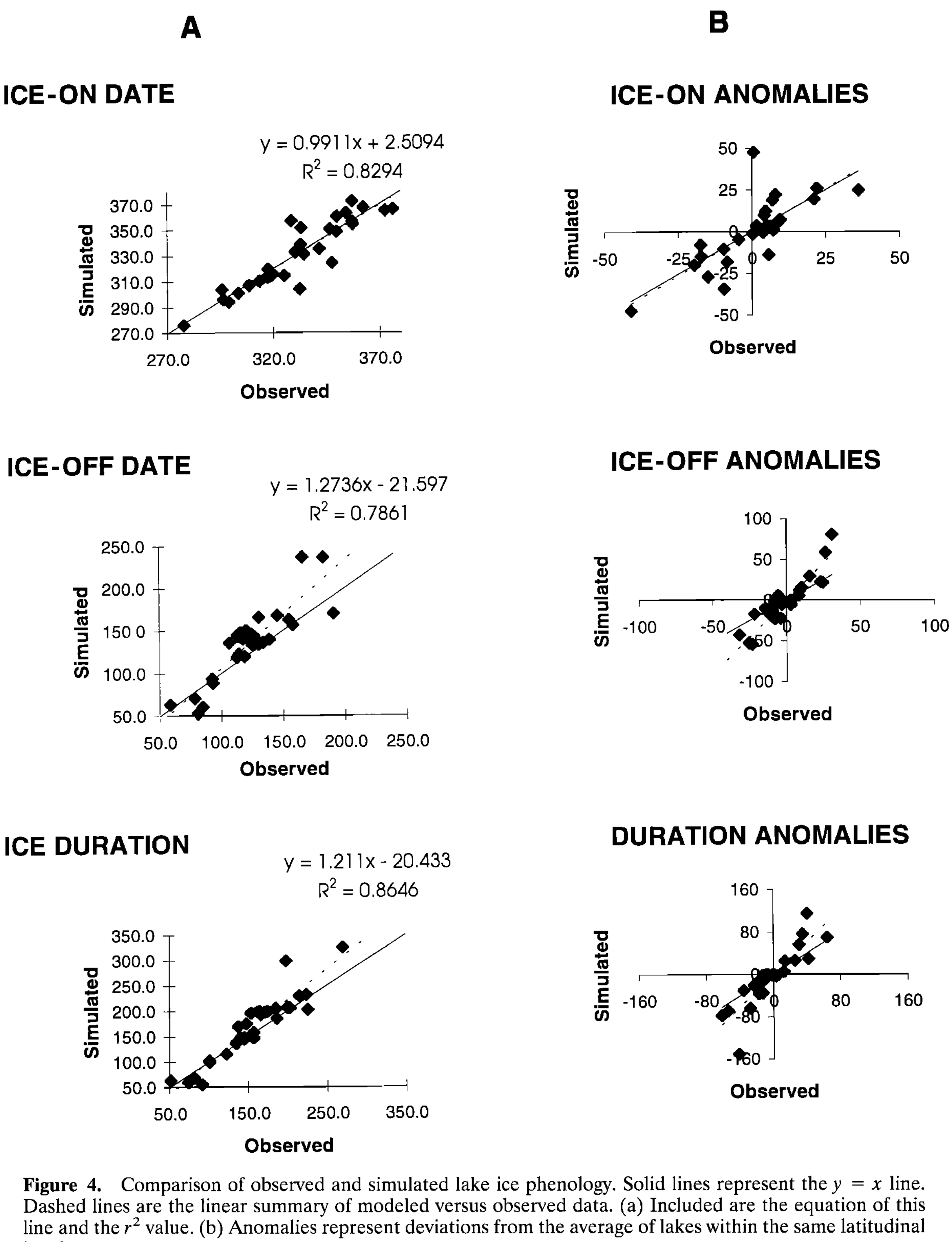


Figure 4. Comparison of observed and simulated lake ice phenology. Solid lines represent the $y = x$ line. Dashed lines are the linear summary of modeled versus observed data. (a) Included are the equation of this line and the r^2 value. (b) Anomalies represent deviations from the average of lakes within the same latitudinal band.

7. Conclusions

The phenological behavior of natural systems provides a robust assessment of climate variability and possibly climatic change. For example, several studies have examined the seasonal behavior of high-latitude snow cover [*Groisman et al.*, 1994] and sea ice [*Chapman and Walsh*, 1993] in order to detect climate variability or change in the northern hemisphere. Other studies have focused on the use of biological indicators to describe climatic variability, including seasonal variations in vegetation cover and atmospheric CO_2 concentration. For example, *Myneni et al.* [1997] examined a time series of satellite-derived vegetation indices and concluded that there has been an 8- to 16-day increase in the length of the summer growing season (mainly by advancing the onset of springtime conditions) over the northern high latitudes between 1981 and 1991. In addition, *Keeling et al.* [1996] and *Chapin et al.* [1996] discuss how changes in the seasonal fluctuations in atmospheric CO_2 concentration over the high latitudes may also be related to warmer spring and summer conditions during the 1990s.

Despite these findings, a systematic analysis of lake ice phenology across the entire northern hemisphere has never before been performed. It is likely that global-scale changes in lake ice phenology would provide a highly robust, integrative measure of climatic variability or climate change. This property is especially fruitful in efforts to detect anticipated future anthropogenic changes, which are expected to be most extreme during winter and spring in high latitudes. A wide variety of local- and regional-scale studies have already demonstrated the links between lake ice phenology and known modes of climatic variability, including El Niño-Southern Oscillation (ENSO) [e.g., *Anderson et al.*, 1996; *Robertson et al.*, 1992]. In addition, lake ice formation and melt off is often detectable from satellite sensors [*Wynne et al.*, 1993, 1996, 1998; *Jeffries et al.*, 1996], making it an ideal candidate for proxy monitoring of climatic variability by remote sensing.

Here we have depicted the phenological behavior of lake ice across the globe using a highly idealized numerical model and a compilation of historical lake ice observations. A comparison between model simulations and long-term lake ice phenology records indicates that in general the model successfully simulates lake ice processes across a wide geographic domain, but there are types of lakes which the model handles poorly. In particular, the model does not perform well for lakes of great depth, large surface area, or extreme snow conditions. These discrepancies help to bracket the applicability of LIMNOS and point to which processes need to be better simulated. Future efforts should therefore adapt this lake ice model to account for some of these conditions.

We have initially focused only on the long-term average behavior of lake ice. Using only average monthly climatic data and an idealized numerical model of lake physics, we have been able to explain the geographic variation in lake ice phenology across the globe. Future work should include the simulation of year-by-year onset and melt off of lake ice across the northern hemisphere, and it should compare these results to observational time series. In this way, we may be able to enhance the ability of using historical lake ice records as an indicator of global-scale climate variability and climatic change.

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V. A. Fisher, J. A. Foley, and S. J. Vavrus, Center for Climatic Research, Institute for Environmental Studies, University of Wisconsin, 1225 West Dayton Street, Madison, WI 53706. (e-mail: vavrus@phoebus.meteor.wisc.edu)

J. D. Lenters, Center for Limnology, University of Wisconsin, 680 North Park Street, Madison, WI 53706.

S. E. Walsh, Department of Fisheries and Wildlife, Michigan State University, 13 Natural Resources Building, East Lansing, MI 48824.

R. H. Wynne, Department of Forestry, Virginia Polytechnic Institute and State University, 319 Cheatham Hall, Blacksburg, VA 24061.

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