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Historical Trends, Drivers, and Future Projections of Ice Phenology in Small North Temperate Lakes in the Laurentian Great Lakes Region

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Abstract: Lake ice phenology (timing of ice breakup and freeze up) is a sensitive indicator of climate. We acquired time series of lake ice breakup and freeze up, local weather conditions, and large-scale climate oscillations from 1981–2015 for seven lakes in northern Wisconsin, USA, and two lakes in Ontario, Canada. Multiple linear regression models were developed to understand the drivers of lake ice phenology. We used projected air temperature and precipitation from 126 climate change scenarios to forecast the day of year of ice breakup and freeze up in 2050 and 2070. Lake ice melted 5 days earlier and froze 8 days later over the past 35 years. Warmer spring and winter air temperatures contributed to earlier ice breakup; whereas warmer November temperatures delayed lake freeze. Lake ice breakup is projected to be 13 days earlier on average by 2070, but could vary by 3 days later to 43 days earlier depending upon the degree of climatic warming by late century. Similarly, the timing of lake freeze up is projected to be delayed by 11 days on average by 2070, but could be 1 to 28 days later. Shortened seasonality of ice cover by 24 days could increase risk of algal blooms, reduce habitat for coldwater fisheries, and jeopardize survival of northern communities reliant on ice roads.

Keywords: climate change; lake ice phenology; weather; climate oscillations; climate change projections; ice breakup; ice freeze; ice loss

1. Introduction

Temperate regions of the Northern Hemisphere have undergone faster warming trends in the past three to four decades than over the last 1300 years [1]. Lake ice phenology (the timing of ice breakup, freeze up and duration) is highly sensitive to changes in climate [2,3] and therefore, long-term ice phenological records can serve as indicators of climate dynamics over time, both in the past and into the future. Over a 150-year period, ice has melted earlier, frozen later, and ice duration has become shorter in lakes and rivers across the Northern Hemisphere [2,4]. Specifically within the Great Lakes region, Jensen et al. [5] found that on average, lake ice melted 6.3 days earlier ($n = 64$ lakes and 1 river) and froze 9.9 days later ($n = 33$ lakes) from 1975 to 2004. Shorter periods of lake ice cover can lead to earlier stratification and warmer summer surface water temperatures [6,7], earlier spring

phytoplankton blooms [8], and alterations in fish feeding behaviour such that in warmer years lake trout eat smaller prey from deeper, offshore regions [9]. Ice phenology is also important to terrestrial mammals; such as the Isle Royale wolves that require lake ice for gene flow into their population [10].

Observed historical trends in lake ice phenology have been associated with changes in local weather and large-scale climate oscillations [11–14]. For example, air temperature, precipitation, wind, cloud cover, and solar radiation have been correlated with ice phenology [4,14–20]. Air temperature has consistently been found to be the most important driver of lake ice phenology [4,15,16,21–25]. For example, Assel and Robertson [22] found that a 1 °C change in air temperatures resulted in ice breakup occurring 8.4 days earlier and ice freeze up occurring 7.1 days later in Grand Traverse Bay, Michigan. Interestingly, air temperature has been found to be a more important driver of ice phenology in lakes south of 61° N, whereas solar radiation is a more influential driver than air temperatures at latitudes north of 61° N [19]. A decrease in snowfall by 50% corresponded to breakup dates that were 4 days earlier in Southern Wisconsin, whereas a 50% increase in snowfall resulted in ice breakup occurring six days later [23]. However, spring rainfall can either accelerate the physical process of ice melting or delay ice breakup by decreasing the amount of solar radiation input to a lake's surface [16,21,23,26].

In addition to relatively long-term changes in climate and weather, large-scale climate oscillations, including the Quasi-biennial Oscillation (QBO), El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and the solar sunspot cycle, have been shown to explain variation in lake ice phenology [4,11–13,15,16,18,27–33]. For example, Anderson et al. [27] found significantly earlier breakup dates during the mature warm phase of the ENSO than the average breakup dates in Wisconsin lakes. Further, NAO's influence on winter air temperature [34], snowfall [15], and southerly and westerly wind strength [12] may affect ice breakup dates. In Lake Mendota, Wisconsin, for example, ice duration and breakup were primarily affected by NAO and PDO; NAO influenced lake ice dynamics through snowfall rates and PDO through local air temperatures [15]. In south-central Ontario, Canada, ice breakup dates were affected by solar activity, ENSO, NAO and the Arctic Oscillation [32].

Few studies have explored the impact of future climatic change on lake ice phenology and duration of ice cover in the winter. For example, in Dickie Lake, Ontario, warmer air temperatures, increased snowfall, and reduced wind speed were important drivers of earlier lake ice breakup, whereas warmer air temperatures, reduced wind speed, and increased heat storage corresponded to delayed lake freeze up [17]. Projections on Dickie Lake using regression and physically-based models suggested that lake ice duration may decrease by 50 days, from approximately 130 days in 2010 to 80 days by the year 2100 [17]. There appear to be differences in lake ice response to future climate change, owing to lake type, surface area, depth or volume [35]. For example, a study on three lakes in southern Wisconsin suggested that deep lakes, both small (Fish Lake) and large (Lake Mendota), could experience no lake ice cover in multiple years with increases in daily mean air temperature as little as 4 °C [36]. However, a small, shallow lake would continue to freeze with increases in daily mean air temperatures up to 10 °C, suggesting that ice cover in shallow lakes may be more resilient to climatic change [36].

The overall goal of our study is to expand our understanding of the impacts of future climatic changes on lake ice phenology for north temperate lakes in the Laurentian Great Lakes region of North America. The Laurentian Great Lakes watershed is home to tens of thousands of small north temperate lakes similar to the nine lakes that we studied over the past 35 years. Specifically, we are interested in addressing the following questions: (1) What are the historical trends in the timing of lake ice breakup and freeze up in nine small north temperate lakes in the Laurentian Great Lakes region of Wisconsin, USA and Ontario, Canada between 1981 and 2015? (2) What are the local weather and large-scale climate drivers of lake ice breakup and freeze up over this time period based on multiple regression models? and (3) What is the projected timing of lake ice breakup and freeze up in 2050 and 2070 based on coupling regression models with the suite of downscaled Global Circulation Models

(GCM) projections across a range of greenhouse gas emission (RCP) scenarios? We aim to contribute to the scant literature on the effects of future climatic change on lake ice phenology by further exploring the influence of climatic projections on future predictions of lake ice.

2. Materials and Methods

2.1. Data Acquisition

2.1.1. Ice Breakup and Freeze up Dates

Lake ice breakup and freeze up dates for nine north temperate lakes in Wisconsin, United States and Ontario, Canada, were acquired for the period between 1981/1982 and 2014/2015 (Figure 1). Lake ice data for seven northern Wisconsin lakes (Allequash Lake, Big Muskellunge Lake, Crystal Bog, Crystal Lake, Sparkling Lake, Trout Bog, and Trout Lake) were acquired from the North Temperate Lakes Long Term Ecological Research Program (NTL-LTER; Table 1) [37,38]. The timing of lake ice breakup for the northern Wisconsin lakes was defined as the day a boat could be driven from the dock to the deepest point of the lake without encountering ice. The day the lake froze was defined as the day the deepest point of the lake was ice covered.

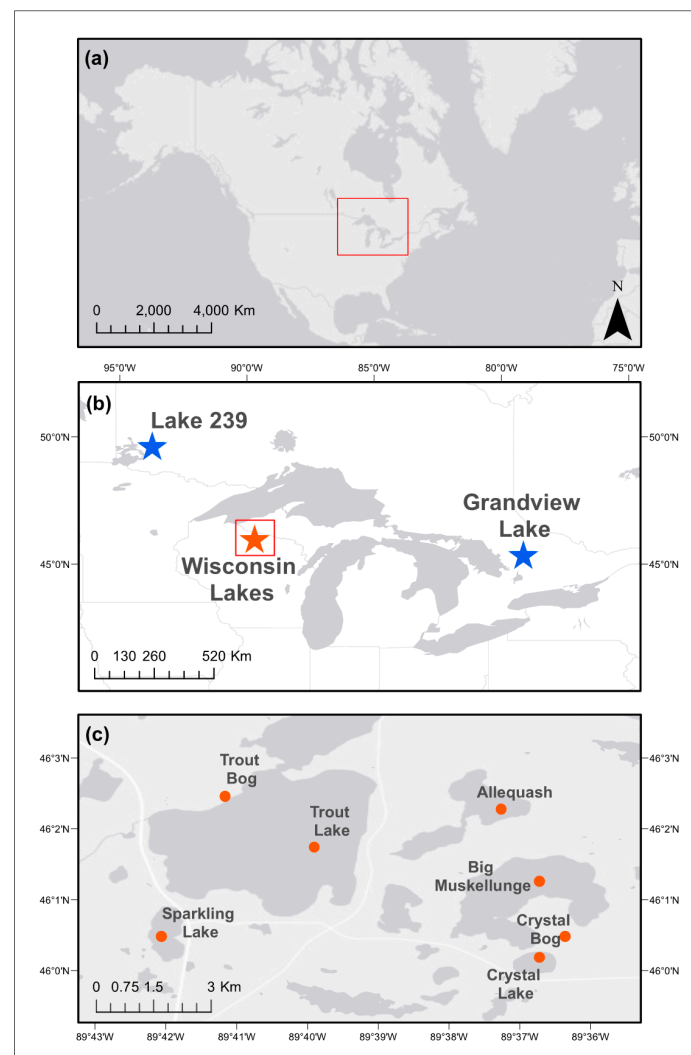


Figure 1. Maps of (a) North America (the red box indicates the location of the study regions); (b) the study regions in Ontario, Canada (blue stars) and Wisconsin, USA (orange star); and (c) a close up of the seven study lakes in northern Wisconsin.

We obtained lake ice phenological data for Grandview Lake in south-central Ontario from the Ontario Ministry of Environment and Climate Change and Lake 239 in north-western Ontario from the IISD Experimental Lakes Area. Lake ice breakup date in Grandview Lake was defined as the date it was less than ~15% ice covered and frozen when it was more than 85% ice covered. Lake 239 was considered thawed when 90% of the lake was ice-free and considered frozen when 90% of the lake was ice covered. Importantly, each site defined ice breakup and freeze up in the same manner every year, although each source of data defined ice breakup and freeze up slightly differently. Trends analyses were conducted on each lake separately and therefore consistency in data measurements between years within a lake is imperative.

Table 1. Morphometric and geographic characteristics of the nine north temperate study lakes.

Region	Lake	Latitude (°)	Longitude (°)	Elevation (m)	Surface Area (km ²)	Mean Depth (m)	Maximum Depth (m)
Wisconsin	Allequash Lake	46.04	−89.62	494	1.64	2.9	8.0
Wisconsin	Big Muskellunge Lake	46.02	−89.61	500	3.63	7.5	21.3
Wisconsin	Crystal Bog	46.01	−89.61	503	0.01	1.7	2.5
Wisconsin	Crystal Lake	46.00	−89.61	502	0.38	10.4	20.4
Wisconsin	Sparkling Lake	46.01	−89.70	495	0.64	10.9	20.0
Wisconsin	Trout Bog	46.04	−89.69	499	0.01	5.6	7.9
Wisconsin	Trout Lake	46.03	−89.67	492	15.65	14.6	35.7
Ontario	Grandview Lake	45.20	−79.05	335	0.74	10.0	28.0
Ontario	Lake 239 (Rawson Lake)	49.66	−93.72	387	0.54	10.5	30.4

2.1.2. Historical Meteorological and Large-Scale Climate Oscillation Data

We obtained monthly weather data for the historical period (1981–2015) in the form of air temperature, precipitation, and cloud cover from the University of East Anglia’s Climatic Research Unit. The weather data were derived from meteorological station measurements that were interpolated into 0.5° latitude/longitude gridded datasets [39]. Seasonal averages of fall, winter, and spring were calculated using monthly values. We defined fall as September, October, and November; winter as December plus January and February of the following year; and spring as March, April, and May. As lake ice breakup in the nine lakes ranged from 18 to 28 April on average, we also calculated the average of March and April temperatures and precipitation, to include as predictor variables. Large-scale climate oscillations including monthly and annual index values of the North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), Arctic Oscillation (AO), and Quasi-biennial Oscillation (QBO), as well as sunspot numbers were obtained from online open source databases (Table 2). In the case of climate drivers with monthly index values, an annual average was calculated.

Table 2. Large-scale climate oscillations and local weather data used to identify drivers of lake ice phenology.

Climate Variable	Source	Length of Record	Scale
Total Sunspot Number (SS)	Sunspot Index and Long-term Solar Observations (SILSO) http://www.sidc.be/silso/	1700–2015	Annual
North Atlantic Oscillation Index (NAO)	National Center for Atmospheric Research (NCAR) https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based	1865–2015	Annual
El Nino Southern Oscillation (ENSO)-(SOI)	National Climate Center, Australia (Bureau of Meteorology) http://www.bom.gov.au/climate/enso/#tabs=SOI	1876–2016	Monthly
Quasi-Biennial Oscillation Index (QBO)	National Oceanic and Atmospheric Administration (NOAA) http://www.esrl.noaa.gov/psd/data/climateindices/list/	1948–2016	Monthly
Arctic Oscillation (AO)	National Oceanic and Atmospheric Administration (NOAA) http://www.esrl.noaa.gov/psd/data/climateindices/list/	1950–2016	Monthly
Local Air Temperature and Precipitation	University of East Anglia’s Climatic Research Unit (CRU) https://crudata.uea.ac.uk/cru/data/hrg/	1901–2015	Monthly

2.1.3. Projected Climate Data

We acquired projected climate data for mid-century (2050; average of 2041–2060) and late-century (2070; average of 2061–2080) from the Intergovernmental Panel on Climate Change 2013 fifth assessment report [40]. We extracted projected monthly air temperature and precipitation from all 19 general circulation models (GCMs) for both 2050 and 2070 (Supplementary Table S1). Each GCM consisted of one to a maximum of four representative concentration pathways (RCP) of greenhouse gas emissions including RCP 2.6, 4.5, 6.0 and 8.5. RCP 2.6 represents the most conservative estimate of forecasted greenhouse gas concentrations, in which an aggressive mitigation strategy is implemented and temperatures are kept below 2 °C above pre-industrial temperatures [40]. In contrast, RCP 8.5 represents the “business-as-usual” scenario and forecasts the highest emissions of greenhouse gases. RCP 4.5 and RCP 6.0 are greenhouse gas emissions scenarios which forecast intermediate increases in greenhouse gas emissions [40]. The north temperate region is projected to become warmer and wetter (Supplementary Table S1).

We used the full suite of 19 GCMs and corresponding 4 RCPs for mid and late century totalling 126 climate change scenarios in our projections of climate change on lake ice phenology. We used all scenarios available to incorporate the uncertainty and variability in forecasted air temperatures and precipitation among the GCMs and RCPs. Differences in projections of future air temperature and precipitation stem from variations in spatial and vertical resolution of GCMs, modelling of several processes such as ocean mixing and terrestrial processes, and climate feedback mechanisms [41]. Incorporating all of the climate change scenarios has been suggested to account for this variability and uncertainties among GCMs [40].

2.2. Data Analyses

2.2.1. Trends in Lake Ice Phenology

We used Sen’s slopes to calculate trends in lake ice breakup and freeze up between 1981 and 2015 using the “openair” package in R [42]. Sen’s slopes are a nonparametric method of statistically testing trends. The Sen’s slope is the median of the slopes calculated between each pair of points [43,44]. This analysis has previously been used to discern temporal trends in ice phenology [4,45].

2.2.2. Drivers of the Timing of Lake Ice Breakup and Freeze up

We used multiple linear regression models on the time series of lake ice phenology, local weather, and large-scale climate oscillations, to identify significant local weather and large-scale climate oscillations explaining the timing of lake ice breakup and freeze up. We ran a forward selection procedure with dual criterion, such that each predictor variable was potentially included in the model if it was significant at $\alpha = 0.05$ and explained significant amounts of variation (R^2_{adj}) using the “packfor” package in R [46]. We assessed multicollinearity among predictor variables using Spearman correlations. Correlations between predictor variables that had a rho value greater than 0.70 and with a p -value less than 0.05 were considered multicollinear and removed from the models. For lake ice breakup, we developed a linear regression model for all lakes in our dataset using year as a covariate in the model. For lake ice freeze up, we developed individual linear regression models for each lake. The freeze up process is more heavily influenced by individual lake characteristics such as mean depth, than climate drivers [36,47,48]. Therefore, we found that developing individual models for lake ice freeze up explained substantially more variation than a generalized model. In addition, we ran linear regressions to examine the relationships between ice breakup and freeze up (trends and average day of breakup/freeze up) and lake morphometric characteristics including volume, surface area, and mean depth. Models were selected using the Akaike Information Criterion (AIC), such that the most parsimonious model yielded the lowest AIC value [49].

2.2.3. Projections in Lake Ice Phenology

We forecasted the timing of lake ice breakup and freeze up date for 2050 and 2070 under all 126 climate change scenarios for 9 north temperate lakes (Supplementary Table S1). The aforementioned linear models were extrapolated using projected air temperatures and precipitation to forecast the day of year (DOY) the ice would breakup or freeze in 2050 (2041–2060) and 2070 (2061–2080). The change in the timing of lake ice breakup and freeze from forecasted to historical was calculated by subtracting the forecasted average DOY of 126 climate change scenarios from the historical average DOY (1981–2015).

3. Results

3.1. Trends in Lake Ice Phenology

Lake ice breakup was 5 days earlier between 1981/2 and 2014/5. The average rate was 1.5 days per decade in northern Wisconsin lakes. There were no trends in ice breakup in the Ontario lakes (Figure 2; Supplementary Figures S1–S9). All trends for lake ice breakup in both regions were nonsignificant ($p > 0.05$), perhaps because of high inter-annual variation and shorter nature of the time series. Lake ice freeze up was 7.8 days later between 1981/2 and 2014/5. The average change was 2.2 days per decade in all lakes. Only the two Ontario Lakes, Grandview Lake and Lake 239, had significant trends in lake ice freeze. Notably, Grandview Lake froze 12 days later and experienced the greatest rate of change in the timing of freeze during the study period (Figure 2; Supplementary Figures S1–S9).

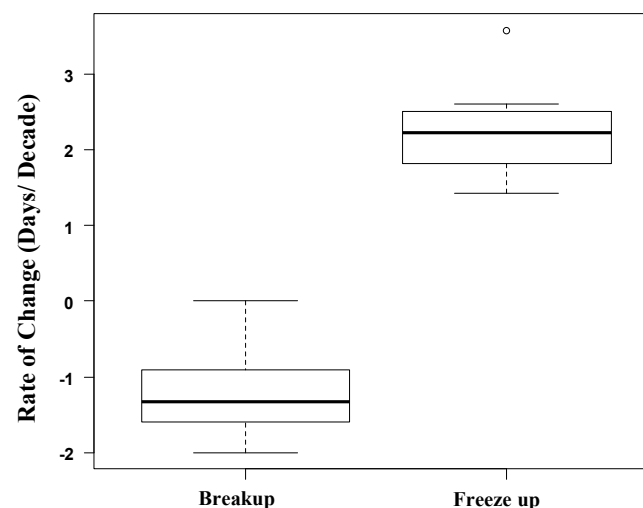


Figure 2. Rate of change of lake ice breakup and freeze up (day of year) in nine north temperate lakes between 1981/2 and 2014/5.

3.2. Drivers of the Timing of Lake Ice Breakup and Freeze up

The most important predictor variables of the timing of lake ice breakup in all study lakes between 1981/2 and 2014/5 were the combined mean of March and April air temperature, winter air temperature, and winter precipitation. March and April were the months including and preceding the timing of lake ice breakup. We found that with increases in spring and winter air temperatures, lake ice broke earlier in the year. Increases in winter precipitation led to later ice breakup date. No large-scale climate oscillation was significant. The model explained 91% variation and was significant at $p < 0.05$ (Table 3).

Table 3. Multiple linear regression model results for the timing of lake ice breakup and freeze up. The most parsimonious models with their respective R^2_{adj} , AIC, and p -values are displayed.

Response Variable	Region	Lake	Model Equation ¹	R^2_{adj}	AIC	p -Value
Break-up Day of Year	All	All lakes	$DOY_b = 99.28 - 2.79(\text{MarAprTemp}) - 1.13(\text{WinTemp}) + 0.06(\text{WinPrecip})$	0.91	1643.22	<0.001
Freeze-up Day of Year	Wisconsin	Allequash Lake	$DOY_f = 344.90 + 2.85(\text{NovTemp})$	0.60	226.85	<0.001
Freeze-up Day of Year	Wisconsin	Big Muskellunge Lake	$DOY_f = 344.11 + 3.42(\text{NovTemp})$	0.70	223.60	<0.001
Freeze-up Day of Year	Wisconsin	Crystal Bog	$DOY_f = 327.14 + 2.75(\text{NovTemp})$	0.63	220.52	<0.001
Freeze-up Day of Year	Wisconsin	Crystal Lake	$DOY_f = 343.63 + 3.06(\text{NovTemp})$	0.69	218.02	<0.001
Freeze-up Day of Year	Wisconsin	Sparkling Lake	$DOY_f = 345.66 + 2.88(\text{NovTemp})$	0.58	230.42	<0.001
Freeze-up Day of Year	Wisconsin	Trout Bog	$DOY_f = 328.31 + 2.65(\text{NovTemp})$	0.66	212.26	<0.001
Freeze-up Day of Year	Wisconsin	Trout Lake	$DOY_f = 352.61 + 3.24(\text{NovTemp})$	0.61	233.86	<0.001
Freeze-up Day of Year	Ontario	Grandview Lake	$DOY_f = 338.57 + 3.22(\text{NovTemp})$	0.39	242.32	<0.001
Freeze-up Day of Year	Ontario	Lake 239	$DOY_f = 308.67 + 3.93(\text{FallTemp})$	0.63	209.38	<0.001

Notes: ¹ Model variables include DOY_b = breakup day of year, MarAprTemp = mean air temperature during the March–April period, WinTemp = mean air temperature from December to February, WinPrecip = mean precipitation from December to February, DOY_f = freeze day of year, NovTemp = mean November air temperature, and FallTemp = mean air temperature from September to November.

Mean November air temperature (i.e., the month including and preceding lake freeze up) was the most important predictor variable explaining the timing of lake ice freeze up for eight of the nine lakes in our study. The only exception was Lake 239, which was influenced by fall air temperature instead of November air temperature. No large-scale climate oscillations were significant for any lake. The mean variation explained for all models was 61% with a range of 39–70% variation explained (Table 3).

We found a significant linear relationship between lake ice freeze up date and mean depth ($p < 0.05$), such that deeper lakes froze later. However, there were no other significant relationships between lake ice phenology and lake morphology within our study sites (Supplementary Table S2).

3.3. Forecasted Lake Ice Loss

Mean ice duration is forecasted to decrease by 20 days in northern Wisconsin lakes, 15 days in Grandview Lake in south-central Ontario, and 19 days in Lake 239 in northwestern Ontario by 2050 (Figure 3a). By 2070, ice duration is projected to decrease even further by a total of 25 days on average in northern Wisconsin lakes, 21 days in Grandview Lake, and 25 days in Lake 239 (Figure 3b). Concurrently, mean annual air temperatures are forecasted to increase between 1.6 and 2.9 °C in mid century, and by 1.5–4.6 °C in late century. Mean annual precipitation is projected to increase by 1 mm to 2 mm by 2050 and from 1.5 mm to 3.5 mm by 2070 (Supplementary Table S1). We forecast that this will result in, on average, 15 to 23 days shorter ice duration by 2050, and 14 to 34 days shorter ice duration by 2070 (Supplementary Table S1).

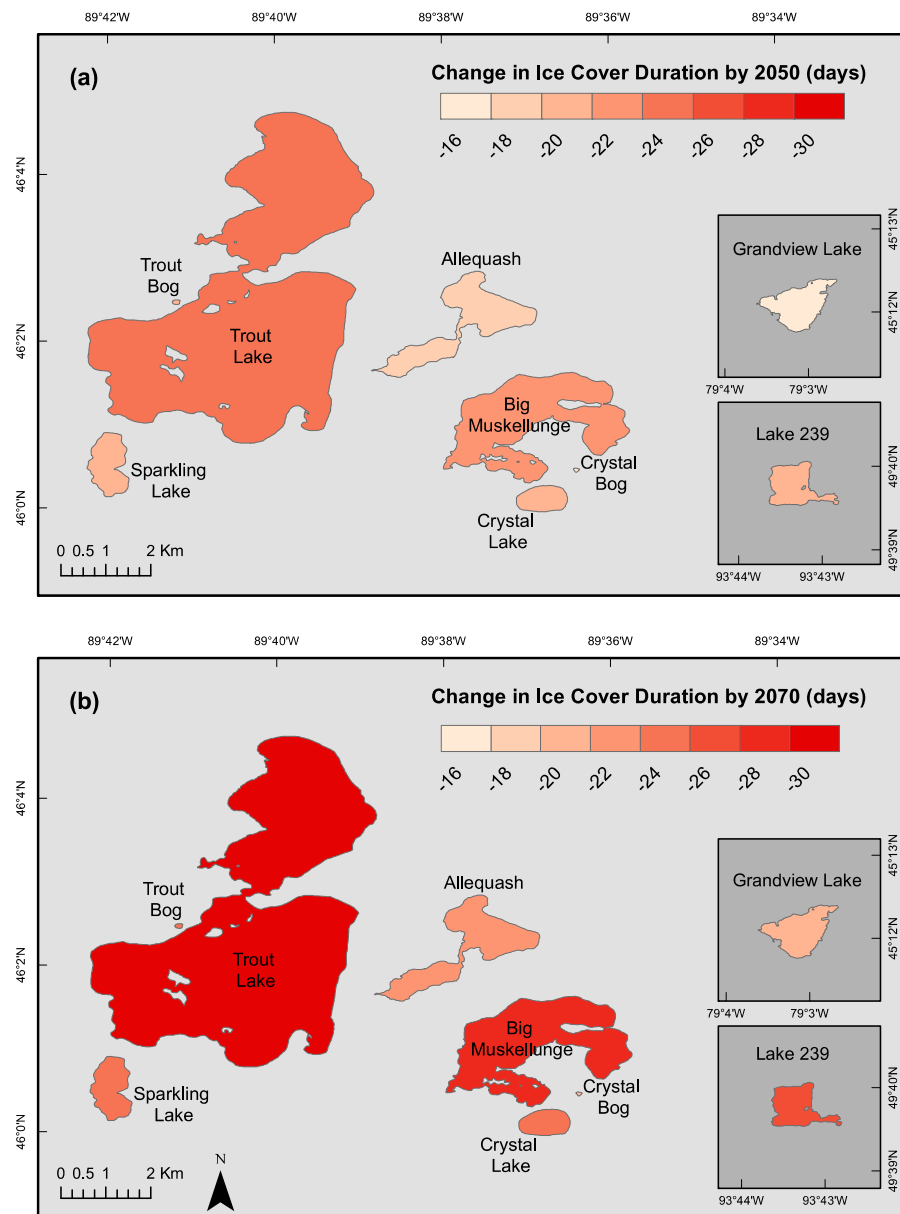


Figure 3. Projected mean loss of ice duration in nine north temperate study lakes by the year (a) 2050 and (b) 2070. The seven northern Wisconsin lakes are featured in the main map layout; Grandview Lake and Lake 239 in Ontario are featured in the darker insets.

We predict that lake ice breakup will be on average 10 days earlier by 2050 and 13 days by 2070 in these nine north temperate lakes (Supplementary Table S1). In the past 34 years, lake ice breakup occurred between 21 March to 18 May. However, by 2050, lake ice breakup is projected to occur earlier between 20 March and 2 May and between 13 March and 30 April by 2070 (Figure 4a). With a 1 °C increase in forecasted spring air temperature we calculated earlier ice breakup by 2.5 days (Equation (1); $R^2 = 0.93$; $p < 0.05$; Figure 4b).

$$\text{Change in ice breakup date} = 0.97 - 3.45 * \text{Forecasted mean March and April air temperature} \quad (1)$$

For example, an increase in spring air temperatures by 2 °C could translate to ice breakup occurring between 0 and 12 days earlier. An increase in spring air temperatures by 5 °C could correspond to earlier ice breakup by 9 and 24 days (Figure 4b).

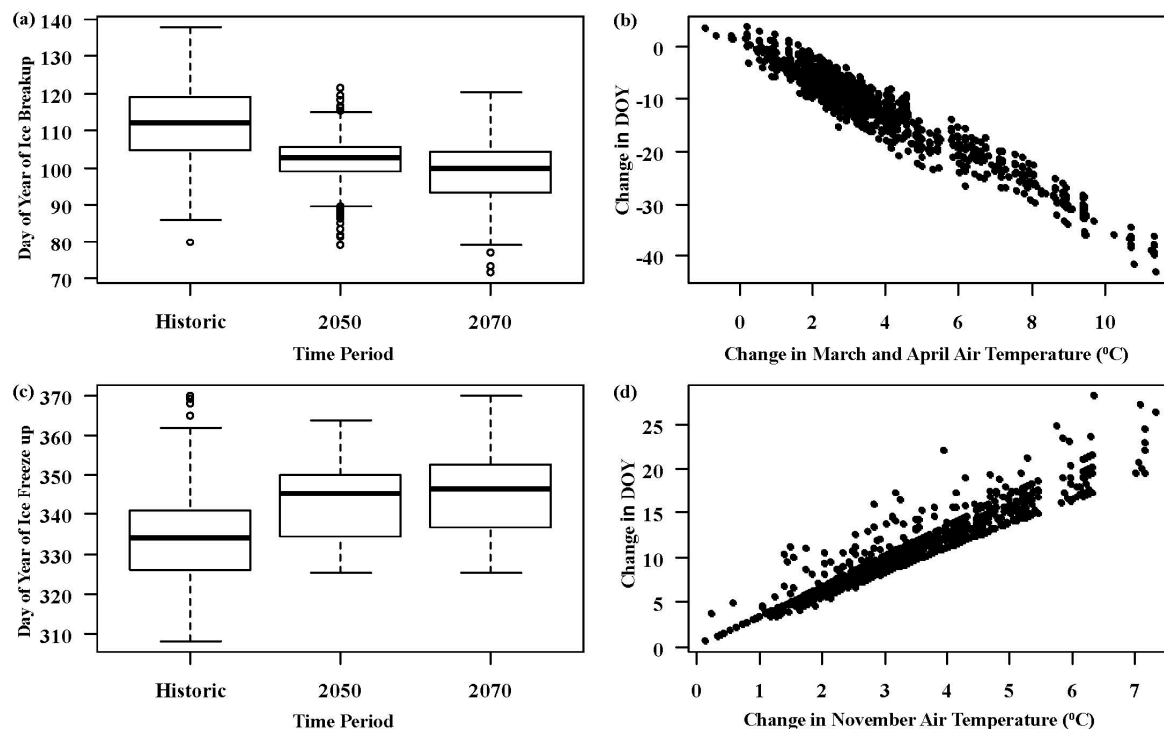


Figure 4. (a) The timing of lake ice breakup (day of year) for the historic period (1981/2–2014/5), and forecasted in 2050, and 2070; (b) Forecasted change in the day of ice breakup with the corresponding change in mean March–April air temperature under 126 projected climate scenarios; (c) The timing of lake ice freeze up (day of year) for the historic period (1981–2015), 2050, and 2070; (d) Forecasted change in the day of ice freeze up with the corresponding change in mean November air temperature under 126 projected climate scenarios.

We forecast that lake ice freeze up will be 9 days later by 2050 and 11 days later by 2070 (Supplementary Table S1). Over the past 35 years, lake ice freeze up occurred between 4 November and 5 January. However, by 2050, lake ice freeze up is projected to occur between 21 November and 30 December and between 21 November and 5 January by 2070 (Figure 4c). With a 1 °C increase in forecasted November air temperature, we calculated later ice freeze up by 3.3 days (Equation (2); $R^2 = 0.89$; $p < 0.05$; Figure 4d). An increase in November air temperatures by 2 °C could translate to ice freeze up occurring between 4 and 11 days later. An increase in November air temperatures by 6 °C could correspond to later ice freeze up by 16 to 28 days (Figure 4d).

$$\text{Change in ice freeze up date} = 0.28 + 3.02 * \text{Forecasted mean November air temperature} \quad (2)$$

The variability in forecasted breakup and freeze up dates arises from the assumptions of varying Global Circulation Models (GCMs) and corresponding greenhouse gas emissions scenarios (RCPs). For example, the business-as-usual greenhouse gas emissions scenario (RCP 8.5) forecasted that by 2070, lake ice breakup could occur 18 days earlier with a range of 4 to 41 days earlier. Lake ice freeze up could be 16 days later (6 to 28 days later), depending upon the GCM (Supplementary Table S1). Intermediate greenhouse gas emissions scenarios (e.g., RCP 4.5) project that lake ice breakup could occur 12.5 days earlier on average, with a range of 0.5 to 33.5 days earlier by 2070 and lake ice freeze up could be delayed by 11 days on average, ranging between 1 and 23 days later (Supplementary Table S1). The best case greenhouse gas emissions scenario, which assumes stabilization of greenhouse gases by mid-century (RCP 2.6), forecasts ice breakup to be 1 week earlier on average with a range of 2 days later to 24 days earlier, and ice freeze up to be on average 1 week later with a range of 2 to 14 days later by 2070 (Supplementary Table S1).

4. Discussion

4.1. Trends in Lake Ice Phenology

In northern Wisconsin, lake ice breakup became earlier at a rate of 1.5 days per decade between 1981/2 and 2014/5. There were no trends in ice breakup in Grandview Lake and Lake 239. Unsurprisingly, none of the trends were significant, at the $p < 0.05$ level. This is likely attributed to the high inter-annual variation and shorter nature of the time series as longer ice records have shown significant trends (e.g., [2,4,44,45]). For example, Hodgkins [50] calculated trends in ice breakup for lakes in New England for varying record lengths from 25 to 150 years. He found nonsignificant trends in the shorter 25-year period, although trends were significant for the same lakes with records extending 50 to 150 years [50]. A second possible explanation for the nonsignificant trends in ice breakup might be an off-set or compensation among several drivers; the role of increased air temperatures may be off-set by the effects of increased snowfall and reduced wind locally [17]. However, for lakes across the Northern Hemisphere, lake ice trends are becoming faster in recent decades [4,16]. Ice melted 0.88 days per decade earlier over a 150-year period spanning 1854 to 2004 for lakes across the Northern Hemisphere. In the most recent 30-year time period (1974–2004), ice melted twice as fast at a rate of 1.86 days per decade earlier [4].

All nine study lakes showed a trend towards later freeze up over the past 35 years. Rates of warming in recent decades are much higher than what has been recorded in the North America historically [5,17]. For example, Jensen et al. [5] found that the lakes froze an average of 3.3 days per decade later, concomitantly with an increase of average fall-spring air temperature of 0.7 °C per decade in 65 waterbodies in the Great Lakes Region recording ice phenology from 1975–2004. The nine lakes we studied in Wisconsin and Ontario have been freezing at a rate approximately 4 times faster than rates of lakes across the Northern Hemisphere over a 150-year period between 1846 and 1995, where the average freeze up date warmed by 0.58 days per decade [2]. Dickie Lake and Lake Utopia, both within the Great Lakes region, have been warming especially fast [17,45]. Freeze up date was delayed in Dickie Lake (close in proximity and similar characteristics to Grandview Lake) by 4.9 days per decade between 1975 and 2009 [17] and 12.3 days per decade later between 1971 and 2000 in Lake Utopia [45].

4.2. Drivers of the Timing of Lake Ice Breakup and Freeze up

The most important predictors for lake ice breakup were weather variables, specifically spring and winter air temperatures, and winter precipitation. Air temperature has been suggested to be the most prominent driver of lake ice breakup timing in lakes and rivers across the Northern Hemisphere [4,15,16,21–23]. For example, in Lake Mendota in Wisconsin, a 1 °C increase in early spring and winter temperatures resulted in ice break-up occurring 6.4 days earlier [51], at a rate much faster than projected for the nine study lakes here under future climatic change. Warming of early spring temperatures may result in the premature arrival of the 0 °C isotherm and thereby earlier ice breakup date [45]. Likewise, warmer winter temperatures can limit ice growth throughout the winter and therefore ice may be more easily melted in the spring [52]. In contrast, increased winter snowfall has been associated with later ice breakup dates monotonically as greater snow cover on lake ice can increase the albedo and generally results in thicker lake ice [23]. However, a nonlinear relationship exists between snowfall decreases and ice decay partly in response to a positive feedback because of decreased albedo and increased solar penetration [23].

Air temperature was also the most important driver of lake ice freeze up in these nine north temperate lakes in the Laurentian Great Lakes watershed over the past 35 years. We found that November or fall air temperature was the only significant predictor of lake ice freeze date, explaining up to 70% of the variation in freeze date across all nine lakes. Air temperature during the fall is consistently one of the most important influences on freeze up date [4,17,53,54], because warmer temperatures prevent the lake from releasing sensible heat and dropping to a temperature where it can

freeze [53]. For example, over a 150-year period, fall air temperatures were correlated strongly ($r = 0.6$) with freeze up date in lakes across the Northern Hemisphere [4].

We did not find any significant relationships between lake ice phenology and large-scale climate oscillations in our lakes between 1981/2 and 2014/5, although many previous studies have suggested the importance of climate oscillations on lake ice phenology and ice cover across the Northern Hemisphere [11–13,33,55]. However, our study is consistent with findings from Dickie Lake, south-central Ontario, for which NAO and ENSO did not explain significant variation in freeze up date [17]. There are several reasons large-scale climate oscillations may not have a direct influence on ice breakup and freeze up in our study lakes. First, several climate indices have been shown to affect temperature and precipitation across the Northern Hemisphere [11,33,56–58] and these relationships may have already been embedded in our models by the inclusion of temperature and precipitation variables. Second, although climate oscillations may play an important role in explaining temporal fluctuations (i.e., ice, local climate, water quality), their contribution to overall trends may be weak within our study period. Third, the influence of large-scale climate oscillations with longer cycle lengths, such as NAO [59], may be underestimated because these cycles would not have occurred repeatedly within our study period [16].

Morphometric characteristics of lakes such as volume, surface area, and depth are known to impact lake ice phenology [53,60]. We found that deeper lakes tend to freeze later, but no other morphometric characteristics were significantly related to lake ice breakup or freeze up trends. However, mean depth is known to be an important physical characteristic of a lake, specifically in relation to lake ice formation [60]. Deeper lakes can store more heat and will take longer to cool to a temperature where it can freeze [61]. In contrast, lake morphometry has been shown to have little effect on lake ice breakup as it is more influenced by climatic and geographic variables such as air temperature and latitude [62].

4.3. Forecasted Lake Ice Loss

The seasonal duration of lake ice cover is projected to decline in north temperate lakes on average by 24 days, but estimates of ice loss range between 0 to 63 days in late century depending upon the degree of climatic warming. Several studies have predicted similar reductions in ice cover days under future climate change. For example, Yao et al. [17,63] predicted a 50-day decline in the ice duration of Dickie and Harp Lakes located in south-central Ontario between 2010 and 2100 under a single climate projection estimated by the Canadian Regional Climate Model (CRCM V4.2) (The Ouranos Consortium, Montreal, QC, Canada). Shuter et al. [53] also expected similar changes for 19 lakes across Canada where ice breakup was estimated to occur 0–20 days earlier and freeze up was projected to be 4–23 days later by the years 2041–2070.

Although the seasonality of ice cover is projected to decline by an average of 24 days under mean climatic projections, there have already been extreme warm years over the past 34 years that may foreshadow ice seasonality in the future. For example, the earliest date lake ice melted within our study region was 21 March in 2012 within the past 34 years. By 2050, the earliest date of ice breakup is projected to be 20 March and 13 March by 2070 under projected changes in mean climatic conditions. Extreme warm events in the future may contribute to even shorter periods of ice cover on lakes in the north temperate region of North America. With breakup dates becoming earlier and freeze up dates becoming later under future climate change some studies have suggested that not only will the ice cover season shorten but there will likely be more ice free years. Magee and Wu [36] simulated future changes in daily air temperatures and lake ice thickness for 3 lakes in Madison, Wisconsin. Over the simulated 100-year period an increase in air temperatures by 4 °C to 10 °C would lead to several no-freeze years for these lakes. Similarly, Robertson et al. [51] predicted that increases in daily air temperatures by 5 °C would result in two no-freeze years in a 30-year period for Lake Mendota in Wisconsin.

4.4. Implications for Losing Lake Ice

Projected loss of lake ice in north temperate lakes by an average of 24 days, ranging from 0–63 days, by 2070 under scenarios of climate change will have far-reaching ecological and socio-economic implications for north temperate lakes. As ice cover duration declines, summer thermal habitat will be greatly altered including a longer thermal stratification period and warmer surface water temperatures [7]. The longer open water season may increase evaporation, resulting in lower lake levels with negative consequences for water quality and littoral habitat availability [4]. Earlier spring lake ice breakup has been shown to shift the timing and abundance of plankton [64,65], promoting a higher risk of toxic algal blooms in nutrient-rich lakes [66]. As many species rely on a combination of photoperiod and thermal cues as triggers for critical life history events (e.g., spawning, larval emergence), changes in ice cover phenology may produce detrimental ecological mismatches [65]. For example, fall spawning fish species may be vulnerable to a warmer incubation period, promoting earlier spring hatching and potential starvation if the spring production pulse is not similarly responsive [67]. During warmer, longer summers, cold-water species will be increasingly squeezed between warming surface waters and deep anoxic habitats [67]. As winter conditions become less severe, aquatic communities will shift from being dominated by winter specialists to species that thrive in warmer, brighter, and more productive environments [4,67].

In addition to its ecological importance, consistent year-to-year lake ice cover has extensive socio-economic implications. More frequent algal blooms and the loss of large-bodied cold-water fishes will negatively impact important ecosystem services such as clean drinking water, fisheries, and summer recreational activities. In addition, lake ice supports multi-billion-dollar recreation and tourism opportunities in north temperate regions including ice fishing, snowmobiling, ice skating, and associated winter festivals [63,68–70]. Northern transportation is predicted to be heavily impacted by climate, as ice roads spanning frozen waterways are relied upon as lifelines to remote northern communities and industrial sites [71]. The decreasing predictability of lake ice already has shown signs of undermining food security, human safety, and economic vitality in northern regions [71,72]. Results from this study suggest an alarming risk to north temperate regions within this century and stress the importance of mitigating greenhouse gas emissions to curb the ecological and socio-economic impacts of climate change in response to reduced seasonality of ice cover.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/10/01/70/s1, Tables S1 and S2, Figures S1–S9. Table S1: The change in climatic variables (mean annual temperature and mean annual precipitation), day of ice breakup, and day of ice freeze up under each climate change scenario for 2050 and 2070. Table S2: Slope, explained variation, and significance of linear regressions examining the relationship between lake ice breakup and freeze up and lake morphometric characteristics, including volume (m³), surface area (km²), and depth (m). Figures S1–S9: Lake ice (a) breakup and (b) freeze up trends for each lake during the study period.

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