Effects of climate change on lake ice freeze up across the Northern Hemisphere: Historical patterns and future predictions

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ABSTRACT

Shifts in freeze up dates signal climatic change. We examined nine lakes in the Great Lakes region to forecast freeze up dates into the future. We also examined 75 lakes around the Northern Hemisphere to understand how and why freeze up has changed historically. Freeze up was later by an average of eight days in the Great Lakes region and nine days around the Northern Hemisphere in recent decades, with air temperatures being the primary driver of change in both studies. Date of freeze up on lakes in the Great Lakes region is expected to advance by an additional average of 11 days by the late 21st century. We highlight the importance of not only focusing on linear trends, but also examining the time series for potential abrupt shifts. Overall, winter ice seasons are becoming shorter which emphasizes the importance of mitigating climate change to protect our freshwater ecosystems.

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GENERAL INTRODUCTION

Since the Industrial Revolution, anthropogenic emissions have played a major role in increasing global temperatures. Between 1880 and 2012, land and ocean surface temperatures warmed by an average of 0.85°C with a range of 0.65°C to 1.06°C (IPCC 2014). Since the mid-20th century, most of the warming the Earth has experienced was a direct result of human activity (IPCC 2014). Observing changes in lake ice phenology is an effective way to detect climate change. Lake ice phenology is the study of the timing of freeze up, breakup, and ice cover duration (Benson *et al.* 2012). Changes in lake ice phenology are well known to be a reliable indicator of changes in climate (Robertson *et al.* 1992; Assel and Robertson 1995; Magnuson *et al.* 2000; Sharma and Magnuson 2014; Sharma *et al.* 2016).

Warming trends in lake ice freeze up and breakup dates have been documented to have started at the beginning of the Industrial Revolution (Sharma *et al.* 2016). Timing of freeze up and breakup exhibit strong relationships with air temperatures (Assel and Robertson 1995; Magnuson *et al.* 2000; Benson *et al.* 2012). In the Northern Hemisphere, over the last 150 years there are significant trends for later freeze up, earlier lake ice breakup, and shorter duration of full ice cover (Magnuson *et al.* 2000; Benson *et al.* 2012; Sharma and Magnuson 2014; Magee and Wu 2016). These trends have become more rapid in recent decades (Jensen *et al.* 2007; Benson *et al.* 2012) and the decline in ice cover duration is expected to continue into the future as a result of climatic changes (Shuter *et al.* 2013; Yao *et al.* 2013; Hewitt *et al.* 2018).

The change in timing of lake ice freeze up and breakup and the resulting decline in ice cover duration can have a number of consequences. Lake ice cover is a seasonally occurring event on most lakes in the Northern Hemisphere and is tied to many aspects of a lakes' ecosystem. For example, the summer surface water temperatures of seasonally ice-covered lakes have been warming at notably higher rates than those that do not experience seasonal ice cover (O'Reilly *et al.* 2015). A change to one phenological variable can have a cascading effect on others. In this case, studies show that as breakup becomes earlier the spring phytoplankton peak will advance (Weyhenmeyer 2001; Adrian *et al.* 2006). As well, shorter ice cover seasons may reduce the anoxic conditions typically experienced during the winter in shallow lakes (Magnuson *et al.* 1997). There is even evidence that shorter ice seasons can have an impact on the fauna around ice covered lakes. Hedrick *et al.* (2014) suggested that ice bridges on Lake Superior were likely used by wolves to travel from the mainland to the population on Isle Royal. This movement would have helped maintain gene flow and therefore the genetic health of the population.

In addition to ecological implications, diminishing ice seasons have the potential to affect the culture and economy of many communities. Many people rely on ice cover for activities ranging from cultural events and recreation to transport and tourism (Yao *et al.* 2013; Magnuson and Lathrop 2014). For example, on Lake Superior, ecotourists use the ice to travel along the Apostle Islands National Lakeshore to visit the ice caves filled with frozen stalactites, stalagmites, and ice falls (Magnuson and Lathrop 2014). Further, shorter ice seasons could impact commercial and sport fishing opportunities. In Lake Michigan, there is evidence to suggest that decreased ice cover duration has led to smaller population sizes of whitefish, which are an important part of the fishing industries in the Great Lakes (Assel and Robertson 1995).

Lake ice phenology is both a barometer for climatic change as well as an ecological response to climate warming. In this thesis we focus specifically on the process of lake ice freeze up and we use two studies to examine how this process has changed historically and how it will continue to change in the future. Our first study examines nine lakes in the Great Lakes region and uses historical patterns and climate projections to forecast lake ice freeze up dates over the next fifty years (Hewitt *et al.* 2018). Our second study expands the scope of the first by examining the changes in lake ice freeze up on lakes around the Northern Hemisphere with a focus on understanding drivers of long-term historical changes. Improving our understanding of the patterns and drivers of lake ice phenology will highlight the importance of mitigating climate change in order to protect our culture, our economy, and our freshwater ecosystems.

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Chapter 1

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

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I am a first author on a manuscript entitled “Historical Trends, Drivers, and Future Projections of Ice Phenology in Small North Temperate Lakes in the Laurentian Great Lakes Region” that was published in the journal *Water* in January 2018. The manuscript was written about lake ice freeze up and breakup, which are two processes that occur on a lake during the winter season. I was primarily in charge of freeze up and my co first author Lianna Lopez was primarily in charge of breakup. Overall, my contributions to the manuscript included collecting data, managing half of the dataset, running half of the statistical analyses, assisting in/developing figures and tables, writing a large portion of the manuscript (including parts of the introduction/methods/results/discussion), making revisions at all stages (pre and post submission), and assisting in finalizing proofs for the journal. My contributions to the manuscript were substantial and therefore I have submitted the full manuscript as the first chapter of my thesis upon the recommendation of my MSc. examining committee.

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.

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.

METHODS

Data Acquisition

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.

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.

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.

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].

Data Analyses

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].

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].

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).

RESULTS

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).

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).

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).

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).

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).

Change in ice breakup date = 0.97 – 3.45 * Forecasted mean March and April air temperature (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).

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).

Change in ice freeze up date = 0.28 + 3.02 * Forecasted mean November air temperature (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).

DISCUSSION

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].

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].

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.

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.

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TABLES

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

Region	Lake	Latitude	Longitude	Elevation (m)	Surface Area (km2)	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

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

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

FIGURES

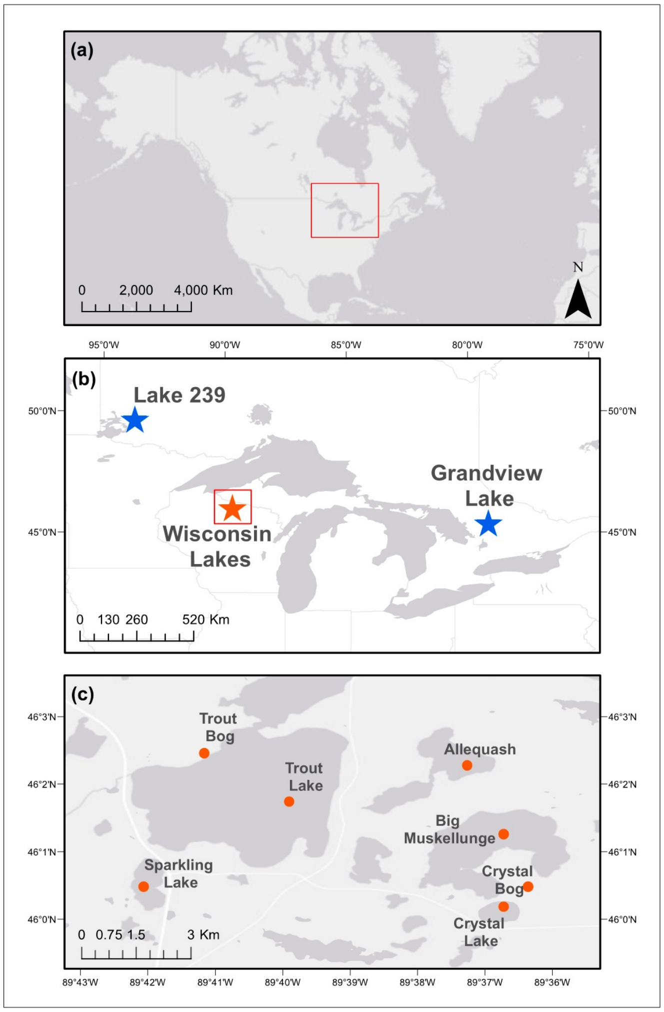

Figure 1: Maps of (**a**) North America (the red box indicates the location of the study regions); (**b**) the study regions in Ontario, Canada (blue stars) and Wisconsin, USA (orange star); and (**c**) a close up of the seven study lakes in northern Wisconsin.

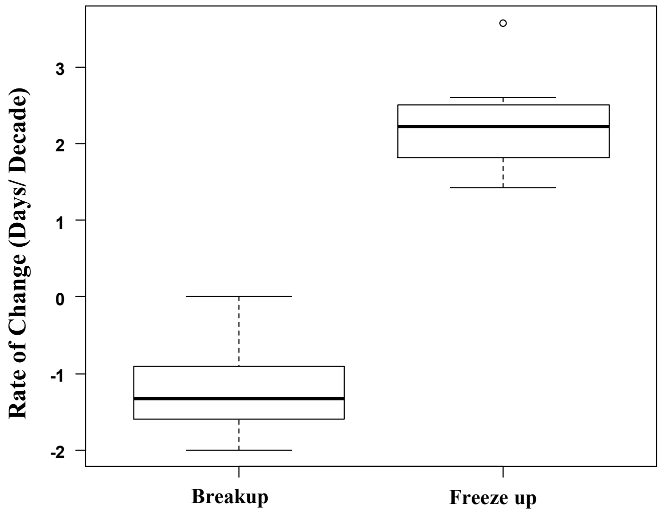

Figure 2: Rate of change of lake ice breakup and freeze up (day of year) in nine north temperate lakes between 1981/2 and 2014/5.

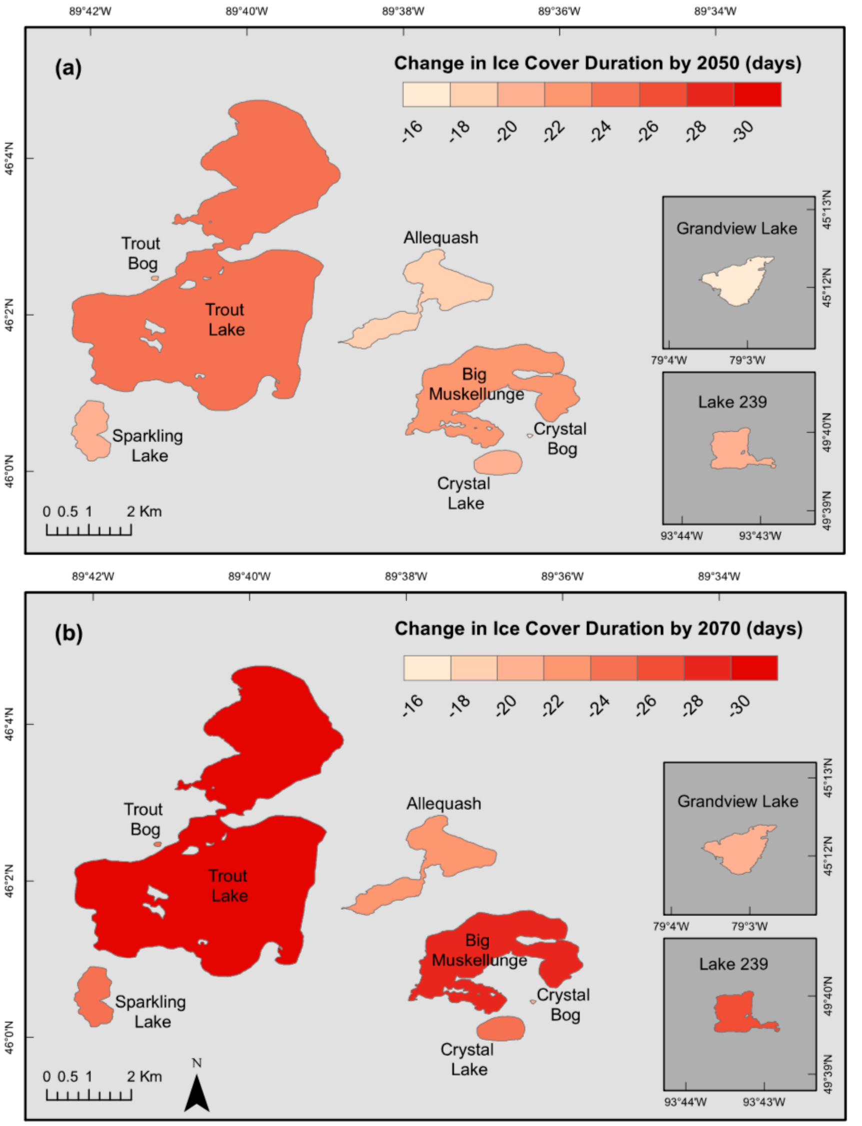

Figure 3: Projected mean loss of ice duration in nine north temperate study lakes by the year (**a**) 2050 and (**b**) 2070. The seven northern Wisconsin lakes are featured in the main map layout; Grandview Lake and Lake 239 in Ontario are featured in the darker insets.

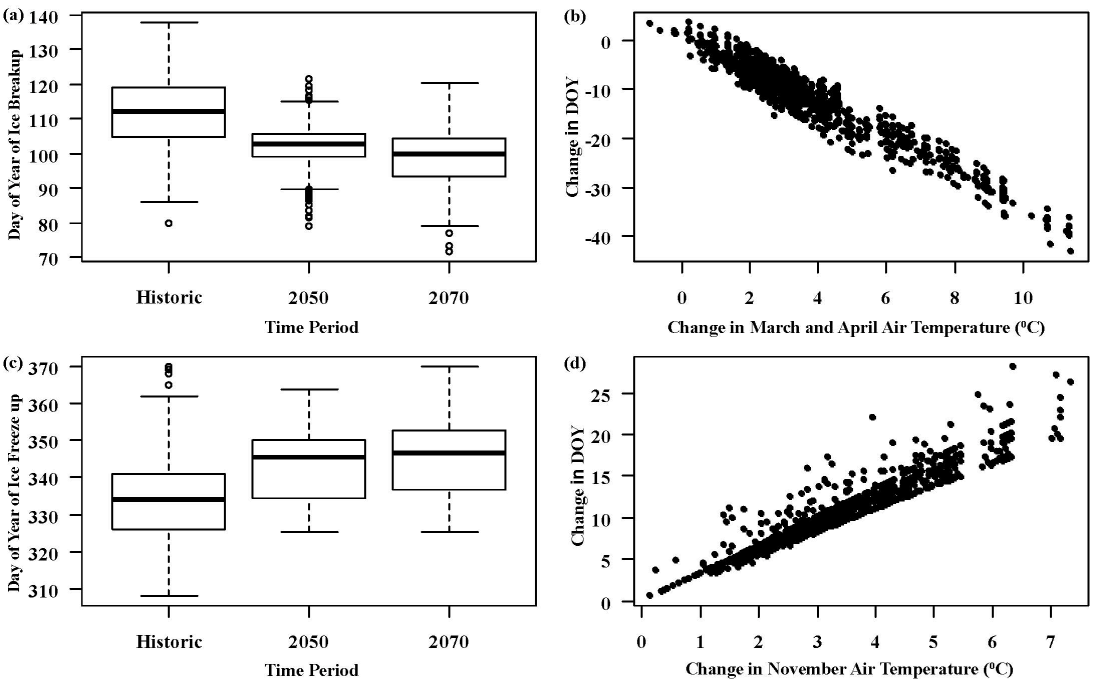

Figure 4: (**a**) The timing of lake ice breakup (day of year) for the historic period (1981/2–2014/5), and forecasted in 2050, and 2070; (**b**) Forecasted change in the day of ice breakup with the corresponding change in mean March–April air temperature under 126 projected climate scenarios; (**c**)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

SUPPLEMENTARY MARTERIALS

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. RCP = Representative Concentration Pathway, *n* = number of models, MAT = mean annual temperature, MPPT = mean annual precipitation, DOYb = breakup day of year, DOYf = freeze up day of year.

Region	Year	RCP	*n*	*Δ*MAT	*Δ*MPPT	*Δ*DOY$_b$ (min *Δ*DOY,max *Δ*DOY)	*Δ*DOY$_f$ (min *Δ*DOY, max *Δ*DOY)
Wisconsin	2050	2.6	15	2.63	4.01	−8.34 (−27.61, 2.20)	7.58 (3.48, 12.43)
		4.5	19	3.23	4.56	−10.80 (−29.65, −2.15)	9.56 (5.28, 15.51)
		6.0	12	2.76	4.50	−8.98 (−26.98, 3.79)	8.28 (3.34, 12.09)
		8.5	17	3.91	4.93	−13.03 (−35.80, 1.21)	10.93 (4.73, 17.73)
	2070	2.6	15	2.61	5.09	−8.01 (−24.95, 2.83)	7.74 (3.34, 12.60)
		4.5	19	3.94	4.39	−13.15 (−35.31, 0.51)	10.97 (4.46, 20.97)
		6.0	12	3.68	4.19	−13.05 (−35.79, −1.32)	10.40 (5.56, 17.04)
		8.5	17	5.63	5.99	−19.09 (−43.16, −3.59)	15.62 (8.85, 24.39)
Ontario	2050	2.6	15	0.51	−2.07	−6.56 (−23.72, 1.23)	6.65 (1.20, 13.77)
		4.5	19	1.13	−1.85	−9.07 (−25.01, −2.32)	8.72 (3.30, 17.50)
		6.0	12	0.68	−1.62	−7.19 (−22.61, 3.28)	7.85 (1.85, 13.64)
		8.5	17	1.84	−0.96	−11.63 (−30.86, 1.25)	10.89 (1.37, 17.96)
	2070	2.6	15	0.47	−0.96	−5.81 (−22.83, 1.98)	6.81 (1.53, 14.30)
		4.5	19	1.82	−1.17	−11.52 (−31.00, −1.23)	10.80 (0.56, 23.01)
		6.0	12	1.58	−1.18	−10.94 (−27.95, −3.19)	10.30 (4.43, 19.40)
		8.5	17	3.50	0.93	−17.39 (−38.93, −4.49)	16.43 (6.04, 28.23)
Regional	2050	2.6	15	1.57	0.97	−7.94 (−27.61, 2.20)	7.37 (1.20, 13.77)
		4.5	19	2.18	1.36	−10.41 (−29.65, −2.15)	9.38 (3.30, 17.50)
		6.0	12	1.72	1.44	−8.58 (−26.98, 3.79)	8.18 (1.85, 13.64)
		8.5	17	2.87	1.98	−12.72 (−35.80, 1.25)	10.92 (1.37, 17.96)
	2070	2.6	15	1.54	2.06	−7.52 (−24.95, 2.83)	7.54 (1.53, 14.30)
		4.5	19	2.88	1.61	−12.78 (−35.31, −0.51)	10.94, (0.56, 23.01)
		6.0	12	2.63	1.51	−12.58 (−35.79, −1.32)	10.37 (4.43, 19.40)
		8.5	17	4.57	3.46	−18.71 (−43.16, −3.59)	15.80 (6.04, 28.23)

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 (m^3), surface area (km^2), and depth (m). DOY = day of year.

Ice Variable	Morphometric Variable	Slope	R^2_{adj}	*p*-value
Breakup Trend	Volume	−0.44	0.10	0.21
Breakup Trend	Surface Area	−0.01	0.14	0.17
Breakup Trend	Mean Depth	0.00	−0.14	0.97
Breakup Avg. DOY	Volume	16.17	0.03	0.31
Breakup Avg. DOY	Surface Area	0.23	0.01	0.32
Breakup Avg. DOY	Mean Depth	0.46	0.28	0.08
Freeze Trend	Volume	0.00	−0.11	0.65
Freeze Trend	Surface Area	−0.02	−0.11	0.66
Freeze Trend	Mean Depth	−0.02	−0.12	0.70
Freeze Avg. DOY	Volume	0.00	0.23	0.11
Freeze Avg. DOY	Surface Area	1.08	0.25	0.10
Freeze Avg. DOY	Mean Depth	1.64	0.49	0.02

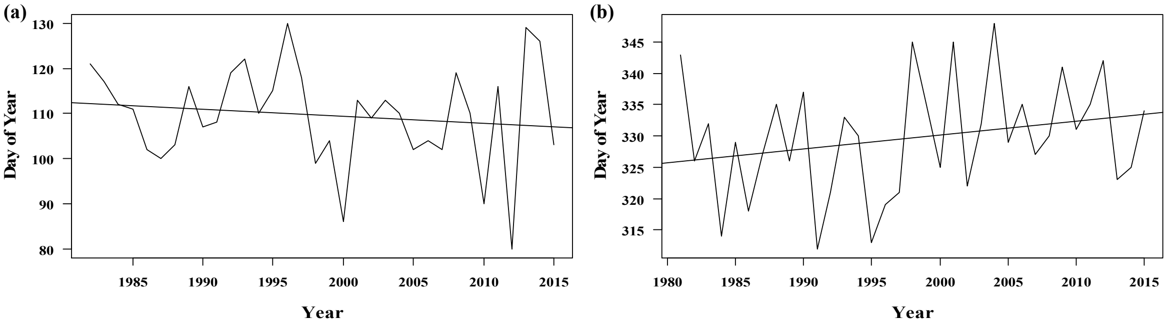

Figure S1: Lake ice **a**) breakup and **b**) freeze up trends for Allequash Lake during the study period.

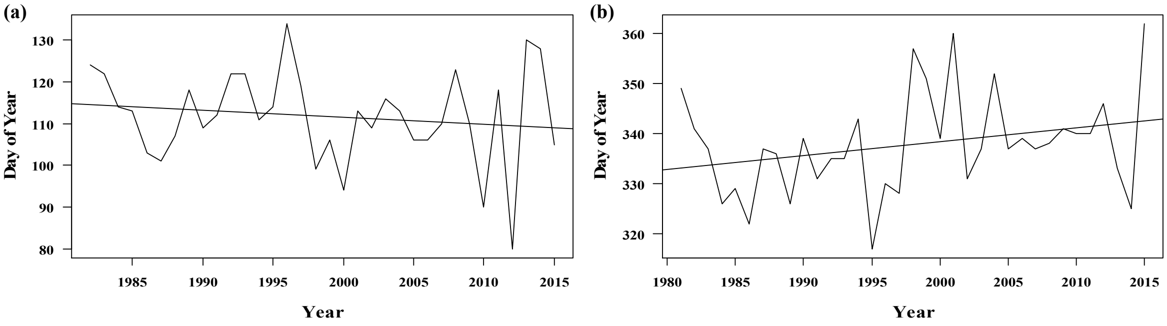

Figure S2: Lake ice **a**) breakup and **b**) freeze up trends for Big Muskellunge Lake during the study period.

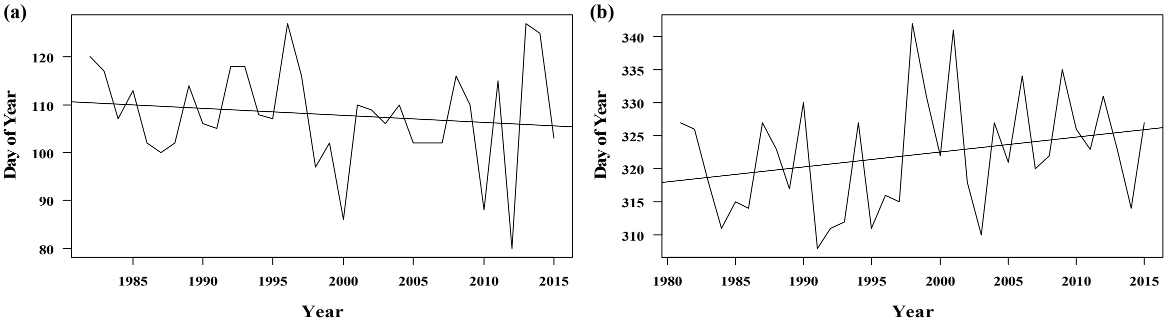

Figure S3: Lake ice **a**) breakup and **b**) freeze up trends for Crystal Bog during the study period.

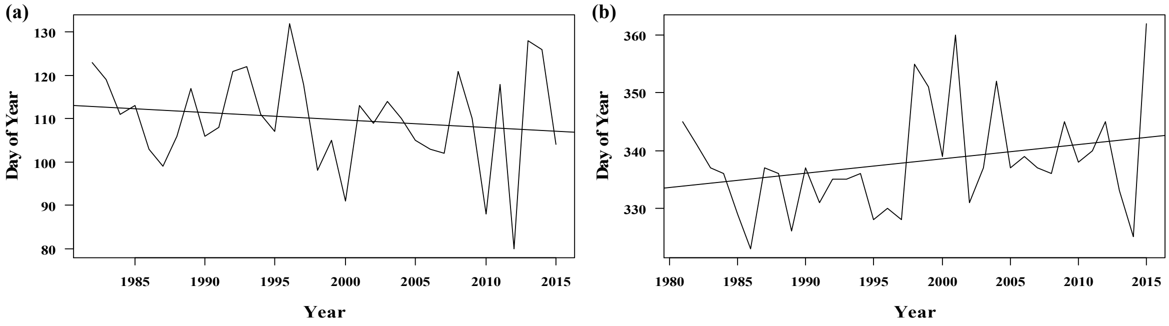

Figure S4: Lake ice **a**) breakup and **b**) freeze up trends for Crystal Lake during the study period.

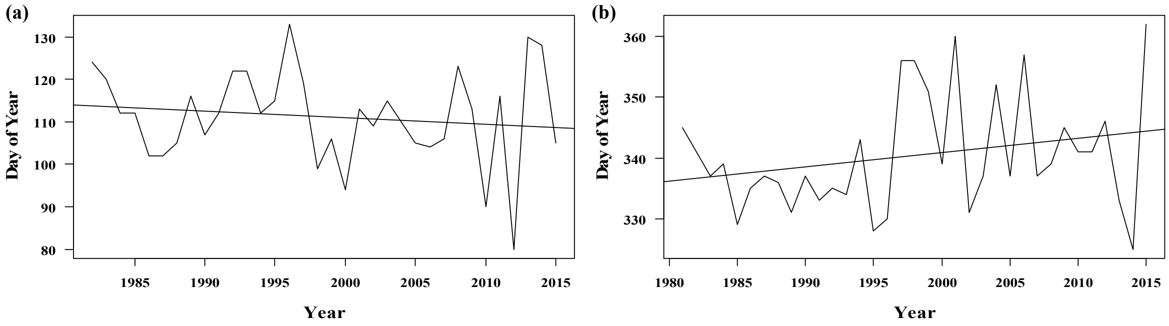

Figure S5: Lake ice **a**) breakup and **b**) freeze up trends for Sparkling Lake during the study period.

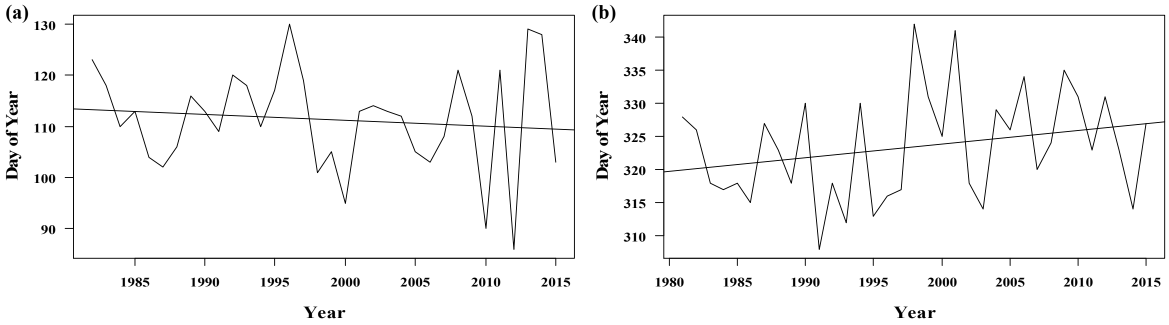

Figure S6: Lake ice **a**) breakup and **b**) freeze up trends for Trout Bog during the study period.

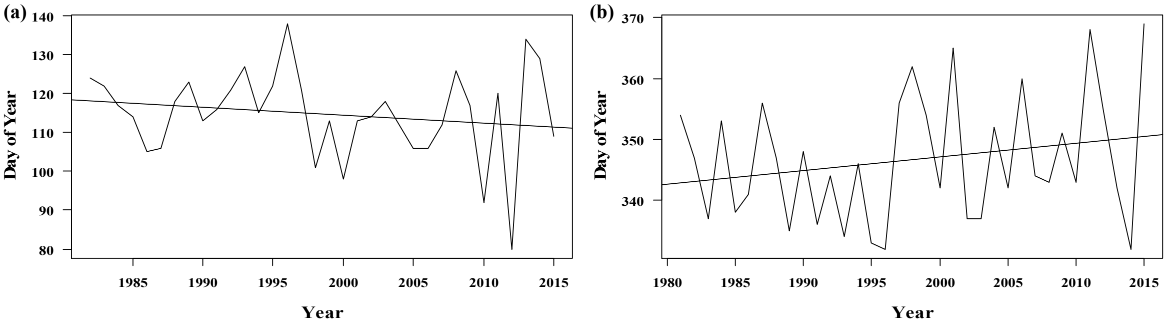

Figure S7: Lake ice **a**) breakup and **b**) freeze up trends for Trout Lake during the study period.

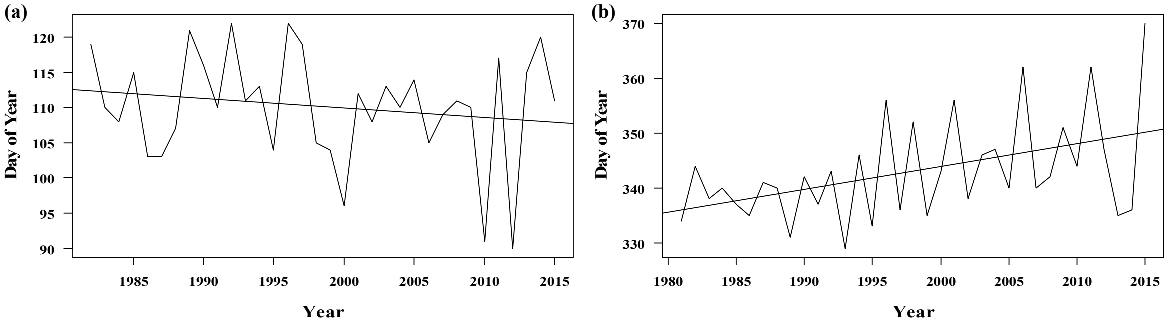

Figure S8: Lake ice **a**) breakup and **b**) freeze up trends for Grandview Lake during the study period.

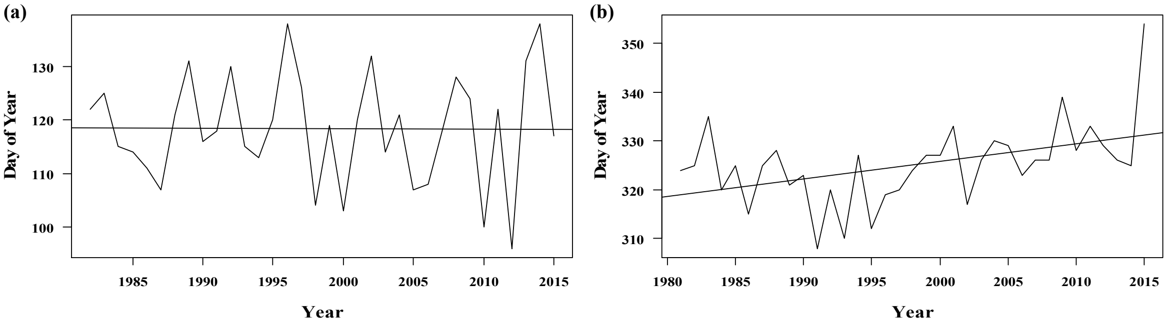

Figure S9: Lake ice **a**) breakup and **b**) freeze up trends for Lake 239 (Rawson Lake) during the study period.

Chapter 2

Impacts of climate change on lake ice freeze up across the Northern Hemisphere

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Keywords: climate change, lake ice freeze up, trends, abrupt shifts, Northern Hemisphere

ABSTRACT

Long-term changes in lake ice freeze up are indicative of climatic change. We examined the changes in lake ice freeze up on 75 lakes across the Northern Hemisphere between 1950 and 2013 as well as identified the drivers of change. Lake ice freeze up became later on about 90% of the study lakes, with an average delay of 1.5 days per decade (range: 2.1 days per decade earlier to 3.7 days per decade later). Trends in lake ice freeze up are primarily driven by the air temperature during the month of/before freeze up, lake surface area, and elevation. Changes in lake ice freeze up may sometimes be described as abrupt shifts rather than monotonic trends. Of the 75 study sites, 33 experienced abrupt shifts towards later freeze up dates. Advancement of lake ice freeze up and the resulting decline in ice cover duration may have consequences for our culture, economy, and freshwater ecosystems around the world.

INTRODUCTION

The Earth's surface temperature has warmed by approximately 0.85°C between 1880 and 2012 (IPCC 2014). One of the most visible early-warning indicators of climate change is the loss of ice in northern freshwater systems, which has been significantly declining over the past 150 years (Magnuson *et al.* 2000; Shuter *et al.* 2013; Magee and Wu 2016). Notably, the rate at which lake ice freeze up is delayed has started to accelerate in recent decades (Jensen *et al.* 2007; Benson *et al.* 2012). Changes to lake ice have been shown to have wide-reaching and cascading consequences for lake ecosystems. For example, we may see declines in winter-dependent species as a result of shorter ice seasons (Benson *et al.* 2012).

Changes in ice cover have frequently been attributed to local weather, large-scale climate oscillations, and climatic change. Air temperature is one of the most important factors influencing lake ice freeze up (Williams *et al.* 2004; Benson *et al.* 2012). For lakes across the Northern Hemisphere, an increase in air temperature of around 0.2°C is needed to shift freeze up by one day (Magnuson *et al.* 2000). In addition to local weather, large-scale climate oscillations such as the El Niño Southern Oscillation and the North Atlantic Oscillation have been linked to changes in the freeze up date (Robertson *et al.* 2000; Wrzesinski *et al.* 2015). An analysis of 22 lakes in Poland over a 50-year period demonstrated that freeze up was positively correlated with the North Atlantic Oscillation (Wrzesinski *et al.* 2015). Although the impacts of large-scale climate oscillations have been demonstrated, they are not always consistent across regions as local factors such as lake geography may counter effects (Sánchez-López *et al.* 2015).

While changes in lake ice freeze up frequently appear to follow monotonic linear trends, some of the changes in freeze up can also occur as abrupt shifts (Magnuson *et al.*

2000). Several lakes, including Lake Mendota (Wisconsin, US), Grand Traverse Bay, (Michigan, US), and Lake Superior have experienced abrupt shifts in freeze up date that may be attributed to shifts in climatic variables (Assel and Robertson 1995; Van Cleave *et al.* 2014). For example, Lake Superior experienced a shift in lake ice freeze up that was concurrent with an abrupt shift in the Pacific Decadal Oscillation in 1998 (Van Cleave *et al.* 2014). Although abrupt shifts may play an important role in long-term ice phenology trends, few studies have attempted to detect them.

This study examined the changes in lake ice freeze up over six decades on lakes across the Northern Hemisphere. There are currently gaps in our understanding of how lake ice phenology has changed globally and this study aims to take a comprehensive approach at investigating this issue. The objectives of our study were to: (1) examine the trends in lake ice freeze up between 1950 and 2013, (2) identify the morphometric, geographic, and meteorological drivers of lake ice freeze up trends, and (3) determine if there are abrupt shifts in the time series of lake ice freeze up and how this may coincide with abrupt shifts in air temperature and large-scale climate oscillations.

METHODS

Data Acquisition

Lake physical characteristics and ice freeze up dates were acquired from the National Snow and Ice Data Center (Table S1; Benson *et al.* 2000). Lakes were included in this study if they had data beginning in the 1950-1955 winter seasons and ending at the earliest in the 2000-2001 winter season, after having been updated by records provided by collaborators. Lakes were also removed if they did not freeze in more than 5% of the years in their time series. The final data set included 75 lakes from four countries: United States, Sweden, Finland, and Russia (Figure 1). Freeze dates were converted into day of year using January 1st as day zero, January 2nd as day one, and December 31st as day negative one and so on. These day of year values were chosen to keep a one day time step between consecutive days whether freeze up occurred in the first or second year of the winter season. Leap years were taken into consideration when converting the dates to day of year. For each of the 40 lakes that were missing data within their time series, we used the average freeze up day of year for that lake. Six of the remaining lakes experienced years where the lake did not freeze over. For years where freezing did not occur, we used the latest day of year that the lake froze to replace the missing value (Benson *et al.* 2012).

We acquired weather data including measures of air temperature, precipitation, and cloud cover from the University of East Anglia's Climatic Research Unit. The data were taken from 0.5° latitude/longitude gridded datasets which were developed using monthly observations at meteorological stations across the world (CRU TS4.01; Harris *et al.* 2014). Time series of total sunspot number and large-scale climate oscillations including El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO), and CO_2 were acquired from various open source databases online (Table 1). We took annual averages of all large-scale climate oscillation indices that were given on a monthly timescale as well as a winter (Dec-Feb) and a summer (Jun-Aug) average of the PDO index (PDO_w, PDO_s).

Data Analysis

Trends in Lake Ice Freeze up

We used non-parametric Sen's slopes to test for temporal trends in lake ice freeze up. Sen's slope estimates are the median of the slopes between all pairs of points (Theil 1992, Sen 1968). We used this method from the "openair" package in R to test for a trend over the duration of each lake's time series (R Core Team, 2018). Each time series began between 1950/51 and 1955/56 and ended between the 2000/01 and 2013/14 winter seasons.

Predictors of Lake Ice Freeze up Trends

We ran linear regressions to look for potential relationships between lake ice freeze up trends and morphometric, geographic, and meteorological predictors. In addition, we used locally weighted (loess) regression lines to visually explore for potential nonlinear trends. Loess is a method of developing a regression surface by smoothing the dependent variable as a function of the independent variable using a moving window (Devlin and Cleveland 1988). Meteorological variables included trends in air temperature, precipitation, and cloud cover calculated using Sen's slopes at three timescales: (1) 'month' being the month preceding freeze up or the month of freeze up depending on whether the average freeze up date falls up to or after the 15th of the month respectively, (2) 'season' calculated based on the two months leading up to freeze up including the 'month' variable, and (3) 'fall' calculated as the Sep-Nov period. For example, if the average freeze up date for a lake is November 15th the 'month' would be October but if the average freeze up date was November 16th it would be November. Lake morphometric and geographic predictors included mean depth, maximum depth, surface area, and elevation. All of the morphometric and geographic predictors were log transformed to meet the assumptions of normality.

As a result of the significant linear regression relationships, we used multiple linear regression models to identify the meteorological, morphometric, and geographic predictors of lake ice freeze up trends. We developed multiple linear regression models using a dual criterion forward selection approach from the "packfor" package in R. Predictors that were significantly related to freeze up at $\alpha=0.05$ level and explained significant amounts of variation (R^2_{adj}) were included in the final model (Blanchet *et al.* 2008). We tested for multicollinearity using Spearman correlations with the "Hmisc" package in R and removed any predictors that were highly correlated. Predictors that remained were selected based on the individual linear regression results and prior knowledge of the system. Predictors were considered highly correlated if the rho value was above 0.7 and it was significant at $p < 0.05$.

To account for potential nonlinear relationships apparent in the loess curves, we also developed a regression tree and a generalized additive model (GAM). Regression trees are developed by splitting the data into two homogenous groups at each step by minimizing the sum of squares within the groups and maximizing it between them (De'ath 2002). The most parsimonious tree was chosen based on the complexity parameter that minimized the cross-validation error (Sharma *et al.* 2012). The regression tree was developed using the "rpart" package in R. GAMs build on the generalized linear model by replacing the linear predictor with an additive predictor (Hastie and Tibshirani, 1990). We developed GAMs using the select=TRUE variable selection method from the "mgcv" package in R. We applied the same method for assessing multicollinearity in the GAM model as we did for the multiple linear regression model. As a result of missing data, the total number of lakes used in the multiple linear regression model and the GAM was 64.

Abrupt Shifts in the Timing of Lake Ice Freeze up, Air Temperature, and Large-Scale Climate Oscillations

We used the sequential *t*-test analysis of regime shifts (STARS), breakpoints, and continuous segmented regression to detect abrupt shifts in the time series of lake ice freeze up, air temperature during the freeze up month, and large-scale climate oscillation indices. The STARS method detects shifts using a moving window approach and was the only test used to detect significant shifts in the mean of each variable (Rodionov 2004). The STARS method was run using a VBA program in excel. The breakpoints test detects shifts from one stable linear regression model to another (Bai and Perron, 2003) and it was run using the “strucchange” package in R. Continuous segmented regression is similar to breakpoints in that it detects abrupt shifts in linear regression models (Muggeo, 2008). A main difference between the breakpoints and continuous segmented regression methods is that continuous segmented regression is constrained such that the regression lines representing the end of one segment and beginning of the next must be touching (Muggeo, 2008). Continuous segmented regression detected shifts using the “segmented” package in R. All of our analyses are provided in a workflow in Figure 2.

RESULTS

Trends in Lake Ice Freeze up

Lake ice freeze up was delayed by an average of nine days between 1950 and 2013. This equates to a rate of change of 1.5 days per decade later (range: 2.1 days per decade earlier to 3.7 days per decade later) over the 64-year study period (Figure 3 and 4). Approximately 90% of the study sites experienced delays in the timing of freeze up, although only a quarter of them were significant (Table S2). Lake Superior's freeze up date changed the fastest, becoming later at a rate of 3.7 days per decade (Sen's slope $p < 0.05$), which equates to a loss of 24 ice-covered days since 1950 (Table S2).

Predictors of Lake Ice Freeze up Trends

We ran linear regressions and plotted loess curves to better understand the relationship between lake ice freeze up trends and each individual predictor variable. There were significant linear relationships between lake ice freeze up trends and maximum depth, surface area, and elevation, as well as air temperature, precipitation, and cloud cover (linear regressions $p < 0.05$; Table 2). Loess curves also demonstrated possible nonlinear associations between some variables. Due to the apparent relationships between lake ice freeze up trends with individual morphometric and meteorological variables, both linear and nonlinear multiple predictor analyses were tried to develop the best model of this relationship.

Of the three modelling techniques used, the GAM explained the highest amount of variation in the relationship between lake ice freeze up trends and the morphometric and meteorological predictors (Table 3). The GAM improved on the multiple linear regression model as it was able to account for nonlinear relationships. The regression tree was most parsimonious with only one node, suggesting no significant relationships between the predictor variables and freeze up trends. The GAM also had a higher R^2_{adj} than any of the single variable linear regression models.

Based on the GAM results, lake ice freeze up trends were related to air temperature trends from the freeze up month, surface area, and elevation (GAM $R^2_{adj} = 0.4$). Overall, lakes located in regions where air temperatures are warming faster, lakes with larger surface areas, and lakes situated at below-average elevations (approximately 90-180 m above sea level) have been experiencing the most significant delays in freeze up date (Figure 5).

Abrupt Shifts in the Timing of Lake Ice Freeze up, Air Temperature, and Large-Scale Climate Oscillations

A total of 42 of the 75 study sites (56%) experienced abrupt shifts in the timing of lake ice freeze up (Table 4). The STARS method detected an abrupt shift in 33 of the study lakes. All of the abrupt shifts detected by the STARS method were towards later lake ice freeze up dates with a delay of 14 days on average (range: 6 days later to 25 days later). The breakpoints method detected an abrupt shift in 26 lakes. The breakpoints method detected similar abrupt shift years to the STARS method (Figure 6), although it predicted trends towards earlier freeze up after the abrupt shift over 50% of the time (Table 4). No lake had more than one abrupt shift detected in its time series using either of these methods.

Forty-five lakes (60%) were found to have abrupt shifts in freeze up date using the continuous segmented regression method (Table S3, Figure S1). Not only was this higher than what was detected using either the STARS or breakpoints methods but individual lakes were also found to have up to four abrupt shifts in their time series. The “segmented” package in R cautioned that the automatic selection procedure for this analysis may overestimate the number of abrupt shifts in a time series. The number of shifts appear to have been overestimated and therefore we did not compare these results to the other methods.

The STARS method detected an abrupt shift in air temperatures from the freeze up month in 1998 in eight lakes in the midwestern United States. At these shifts, the average increase in temperature was 2°C. The only other shift that was detected by STARS was an abrupt 2°C increase in mean air temperature in 1999 at lake Gouta in Sweden. The breakpoints method detected no abrupt shifts in air temperature trends.

When assessing abrupt shifts in large-scale climate oscillations, the STARS and breakpoints methods detected the same shift year and magnitude for only one oscillation, the PDO_s index increased in 1998. The STARS method detected abrupt shifts in the ENSO, PDO_w, AO, and PDO_s whereas the breakpoints method detected shifts in the PDO_w, CO_2, PDO, and PDO_s (Table 5). As a result of the mismatches in the years and the magnitude of change between the STARS and breakpoints methods, the discussion will only be in reference to the results of the STARS method.

DISCUSSION

Lake ice freeze up has been delayed by an average of nine days over the last six decades across the Northern Hemisphere. Lakes located in regions with warming air temperatures, at lower elevations, and with larger surface areas experienced the greatest delays in lake ice freeze up. Thirty-three of the 75 study lakes experienced an abrupt shift towards later freeze up dates. These results provide novel insights into the ways lake ice freeze up has changed and what morphometric, geographic, meteorological, and climate predictors may be impacting freeze up across the Northern Hemisphere.

The freeze up rate of change identified in this recent 64-year period is significantly higher (>2x) than what was found on lakes across the Northern Hemisphere in earlier periods. Magnuson *et al.* (2000) found that between 1846 and 1995, 14 of 15 study lakes experienced delays in lake ice freeze up at an average rate of 0.6 days per decade. Similarly, in a study of 40 lakes across the Northern Hemisphere, lake ice freeze up was delayed by an average of 0.3 days per decade between 1905 and 2004 (Benson *et al.* 2012). Benson *et al.* (2012) also examined lake ice freeze up dates on 38 lakes between 1975 and 2004 and found that the rate of change had increased to 1.6 days per decade. This rate increase in recent decades is also reflected in regional studies. For example, Jensen *et al.* (2007) found that on 33 waterbodies in the Great Lakes region, lake ice freeze up became later by an average of 3.3 days per decade between 1975 and 2004. Our results correspond with these increased rates of change. We found that lake ice freeze up was delayed by an average of 1.5 days per decade on 75 lakes between 1950 and 2013.

Air temperature during the freeze up month was one of the most important predictors of lake ice freeze up trends between 1950 and 2013. Specifically, the lakes that experienced the greatest delays in lake ice freeze up were those in regions where air temperatures from the freeze up month were warming the fastest. Air temperature in the months leading up to freeze up is well documented as one of the most important predictors of lake ice freeze up (e.g., Palecki and Barry 1986; Assel and Robertson 1995; Magnuson *et al.* 2000; Williams *et al.* 2004; Benson *et al.* 2012; Shuter *et al.* 2013; Yao *et al.* 2013; Hewitt *et al.* 2018). For example, a study of 162 lakes across Canada found that lake ice freeze up was primarily driven by the arrival of freezing air temperatures in the fall, mean lake depth, and fall air temperature (Shuter *et al.* 2013). Further, Assel and Robertson (1995) identified that for Lake Mendota, one of the lakes in our study, an increase in fall and early winter air temperature of 0.2°C delays freeze up by 1 day. This rate is similar to that of other lakes around the world (Magnuson *et al.* 2000).

Freeze up trends are also influenced by morphometric variables including surface area and elevation. The lakes with the largest surface areas as well as those with below-average elevations between approximately 90-180 m experienced the most significant delays in freeze up date. Lakes with larger surface areas have longer fetches and therefore result in increased wind shear impacting the lake. Strong wind shear can both break up ice that has begun to form as well as increase the cooling rate of the lake (Williams *et al.* 2004). Although these are opposing forces, larger lake surface area has been related to later freeze up dates which is consistent with our results (Magee and Wu 2016). In general, air temperatures are lower at higher elevations (Jensen *et al.* 2007) and it would be expected that lakes at higher elevations have earlier freeze up dates (Williams *et al.* 2004). This temperature difference could have an effect on freeze up trends, and in our case freeze up dates did change less at higher elevations but the pattern was not linear. The nonlinear relationship between lake ice freeze up and elevation may also be a result of other variables such as proximity to the ocean (Williams *et al.* 2004). The impacts of larger surface areas and lower elevations on lake ice freeze up have also been identified to impact lakes across the Great Lakes region (Jensen *et al.* 2007).

Forty-four percent of our study lakes experienced an abrupt shift towards later lake ice freeze up dates. These abrupt shifts often occurred simultaneously with changes in air temperature and large-scale climate oscillations. For example, six of our study lakes in the midwestern United States experienced abrupt shifts in freeze up date in 1998 which was the same year that air temperature in these regions rose abruptly by an average of 2°C. There was also an abrupt shift detected in the PDO$_s$ in 1998. This shift in the Pacific decadal oscillation may have also attributed to the abrupt delay in lake ice freeze up dates in the lakes in the Great Lakes region. Van Cleave *et al.* (2014) detected this same shift in the PDO$_s$ and determined that it may have contributed to the 1998 abrupt shift in Lake Superior ice cover because a downward shift in PDO results in warmer winters in the Great Lakes region.

Abrupt shifts towards later lake ice freeze up were detected in 1999 and 2003 in many of our study sites in Finland and Sweden. Although these years do not correspond to shifts in the climatic variables that we tested, there is evidence to suggest that the winter NAO index may have influenced this shift. NAO is known to be strongly related to the weather and climate in Europe (Hurrell and Deser 2010; Wang *et al.* 2017). For example, air and water temperatures during winter/December were elevated at lakes in Poland during the positive phase of the NAO (Ptak *et al.* 2018). The winter NAO index remained mostly in the positive phase during the 1990s and this may have played a part in the shifts we found in lake ice at the end of this time period (Hurrell and Deser 2010).

Delayed freeze up and the resulting decrease in ice duration may have far-reaching cultural, socioeconomic, and ecological consequences. In areas that rely on winter tourism, such as the District of Muskoka region of Ontario, Canada, shorter ice seasons could be highly damaging to the local economy (Yao *et al.* 2013). In areas where communities rely on ice roads as a means of transportation, delayed freeze up would negatively effect the transportation of goods and people too and from these communities, potentially further isolating them (Magnuson and Lathrop 2014). Further, later lake ice freeze up and shorter ice duration can impact the local ecosystem in many ways. For example, decreases in ice cover can threaten winter-dependent species and impact the photosynthetic processes that occur in lakes throughout the year (Benson *et al.* 2012). In addition to the impacts on aquatic ecosystems, lake ice supports terrestrial ecosystems as well. For example, the population of wolves on Isle Royal has likely been supported by the gene flow of wolves being able to move in and out of the population via an ice bridge on Lake Superior (Hendrick *et al.* 2014).

Lakes across the Northern Hemisphere have lost an average of nine days of lake ice between 1950 and 2013. While this study focuses on lake ice freeze up, the potential consequences of ice cover loss will be further compounded by earlier ice breakup in the spring (Sharma and Magnuson 2014). As a result of warming air temperatures, lake ice freeze up is projected to continue to become even later and ice-covered seasons will increasingly shrink over time (Shuter *et al.* 2013; Hewitt *et al.* 2018). Later freeze up and shorter ice cover duration will have consequences for the ecosystems as well as the communities surrounding north temperate lakes.

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TABLES

Table 1: Large-scale climate oscillations and local weather variables used to determine the drivers of lake ice freeze up.

Climate Variable	Source	Length of Record	Scale
Total Sunspot Number (SS)	Sunspot Index and Long-term Solar Observations (SILSO) http://www.sidc.be/silso/datafiles	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
Pacific Decadal Oscillation Index (PDO)	Joint Institute for the Study of the Atmosphere and Ocean (JISAO) http://research.jisao.washington.edu/pdo/	1900-2016	Monthly
El Niño Southern Oscillation (ENSO)	National Climate Center, Australia (Bureau of Meteorology) http://www.bom.gov.au/climate/enso/#tabs=SOI	1876-2016	Monthly
Arctic Oscillation (AO)	National Oceanic and Atmospheric Administration (NOAA) http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml	1950-2016	Monthly
Carbon Dioxide (CO_2)	National Oceanic and Atmospheric Administration (NOAA) https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html	1959-2017	Annual
Local Air Temperature, Precipitation, and Cloud Cover	University of East Anglia's Climatic Research Unit (CRU) http://www.cru.uea.ac.uk/data	1901-2016	Monthly

Table 2: Slope, R^2_{adj}, and *p*-value of the linear regression models demonstrating the relationships between freeze up trends and each of the meteorological, morphometric, and geographic predictor variables. All of the meteorological variables are trends of one of the following; the month of/preceding freeze up (Month), an average of the two months leading up to freeze up including the 'month' variable (Season), or an average of September, October, and November (Fall).

Predictor	**Slope**	R^2_{adj}	***p*-value**
log(Elevation)	-0.05	0.09	0.005
log(Mean Depth)	0.02	0.00	0.268
log(Max Depth)	0.03	0.07	0.016
log(Surface Area)	0.02	0.14	0.001
Air Temperature (Month)	5.44	0.20	0.000
Air Temperature (Season)	5.61	0.19	0.000
Air Temperature (Fall)	3.01	0.03	0.069
Precipitation (Month)	-0.17	0.03	0.090
Precipitation (Season)	-0.43	0.12	0.002
Precipitation (Fall)	-0.32	0.11	0.003
Cloud (Month)	-0.31	0.01	0.191
Cloud (Season)	-0.37	0.04	0.052
Cloud (Fall)	-0.50	0.04	0.040

Table 3: Three models developed to describe the relationship between freeze up trends and candidate meteorological, morphometric, and geographic variables. Model R^2_{adj}, Akaike Information Criterion (AIC), and *p*-values are reported. As a result of missing data, the total number of lakes used in the multiple linear regression model and generalized additive model was 64. "Air temp month" is the rate of change of the air temperatures during the month of/preceding freeze up. For the regression tree: $R^2_{adj} = 1$ - cross validation error.

Model	**Predictors**	$\mathbf{R^2_{adj}}$	**AIC**	***p*-value**
Multiple Linear Regression Model	Air Temp Month log(Elevation)	0.21	-119.65	0.0003
Regression Tree	None	-0.03	-	-
Generalized Additive Model	Air Temp Month log(Surface Area) log(Elevation)	0.4	-128.79	-

Table 4: The timing and magnitude of abrupt shifts in freeze up date detected by the STARS or breakpoints test. The "abrupt shift year" is the first year in the segment following the shift. Statistical significance: $p < 0.05$ (*).

		STARS		Breakpoints	
Lake	**Country**	**Abrupt Shift Year**	**Change in Mean (days)**	**Abrupt Shift Year**	**Slope of the Second Segment (days/decade)**
AHTARINJARVI	FINLAND	2003	16*	1992	17.3*
ALA-RIEVELI (1468)	FINLAND	2000	14*	1987	12.8*
JAASJARVI - HARTOLA (1457)	FINLAND	2003	22*	1992	20*
KILPISJARVI	FINLAND	1999	8*	1966	3.3*
KUIVAJARVI	FINLAND			2005	-16.6
KUKKIA - PUUTIKKALA (3512)	FINLAND	2003	25*		
LAKE KALLAVESI (4079)	FINLAND			2005	-13
LAKE NASIJARVI (3568)	FINLAND	1999	17*		
LAKE PAIJANNE (1463)	FINLAND	1999	18*		
LAKE VESIJARVI (1462)	FINLAND	2003	19*		
LAPPAJARVI - HALKOSAARI (4703)	FINLAND	2003	22*	1992	21.4*
MUTUSJARVI	FINLAND	1999	10*		
MUURASJARVI (1401)	FINLAND	2003	20*	2005	-26
PAAJARVI - KARSTULA (1415)	FINLAND	2003	17*		
REHJA	FINLAND	2000	15*	2000	6.7
SAAKSJARVI - SAAKSKOSKI	FINLAND			1992	20*
SAANIJARVI (1403)	FINLAND	2003	18*	1968	6.5*
SIMPELEJARVI	FINLAND			1997	24.6*
SUMMASJARVI (1419)	FINLAND	2003	19*	1992	18.7*
YLA-KIVIJARVI - JURVALA (1488)	FINLAND	2003	25*	2005	-16.1
LAKE BAIKAL	RUSSIA	1977	6*		

JUKKASJARVI	SWEDEN	1999	9*		
NACKTEN	SWEDEN	1999	16*		
ORSASJON	SWEDEN	2003	12*		
RUNN	SWEDEN	1999	15*		
BIG GREEN LAKE	UNITED STATES			1995	47.5*
CAZENOVIA	UNITED STATES	1996	9*	1996	-23.3*
DETROIT	UNITED STATES	1998	8*		
DEVILS LAKE	UNITED STATES	1979	12*		
EAST OKOBOJI LAKE	UNITED STATES	1997	11*	1997	-22
FAIR LAKE	UNITED STATES	1986	9*		
GREEN	UNITED STATES	1998	6*	1998	-6.5
LAKE ESCANABA	UNITED STATES	1998	12*	1998	-6.9
LAKE MENDOTA	UNITED STATES	1997	9*		
LAKE SUPERIOR AT BAYFIELD	UNITED STATES	1997	25*	1997	-5.4
MAPLE LAKE	UNITED STATES			1998	-40
MEDICINE	UNITED STATES	1998	9*	1998	-10
PIERZ	UNITED STATES	1998	10*	1998	-6.2
SHELL LAKE	UNITED STATES	1998	8*		
SPIRIT LAKE	UNITED STATES			1998	-6.7
WACONIA	UNITED STATES			1998	-3.3
WASHINGTON	UNITED STATES			1991	16.7*

Table 5: The timing and magnitude of abrupt shifts in climate oscillations detected by the STARS or breakpoints test. The "abrupt shift year" is the first year in the segment following the shift. Statistical significance: $p < 0.05$ (*).

	STARS		Breakpoints	
Climate Oscillation	**Abrupt Shift Years**	**Change in Mean**	**Abrupt Shift Years**	**Slope of the Second Segment**
ENSO	1977	⇩*	-	-
NAO	-	-	-	-
PDO (Winter)	1976	⬆*	1976	-0.3*
AO	1988	⬆*	-	-
CO_2	-	-	1967, 1976, 1993, 2001	11.3*, 15.5*, 18.5*, 20.5*
PDO (Annual)	-	-	1980	-0.5*
PDO (Summer)	1979, 1998	⬆*, ⇩*	1998	-0.6
Sunspot	-	-	-	-

FIGURES

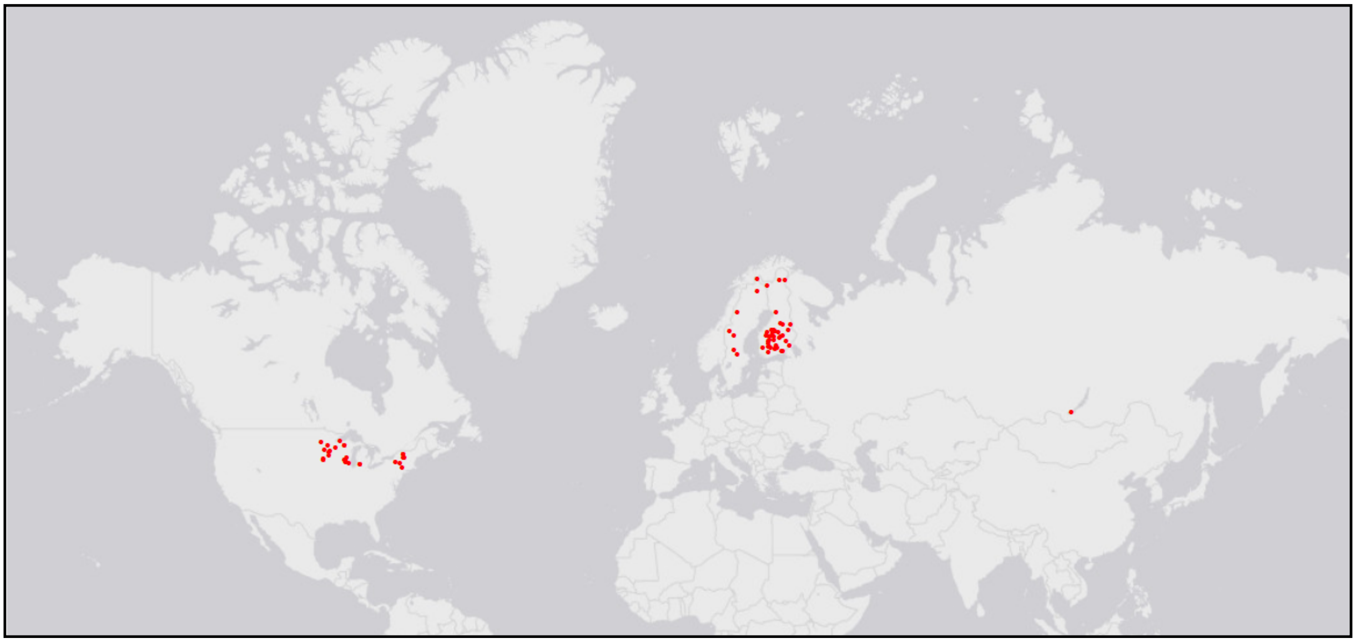

Figure 1: Map of all 75 study lakes located in four countries: United States, Sweden, Finland, and Russia.

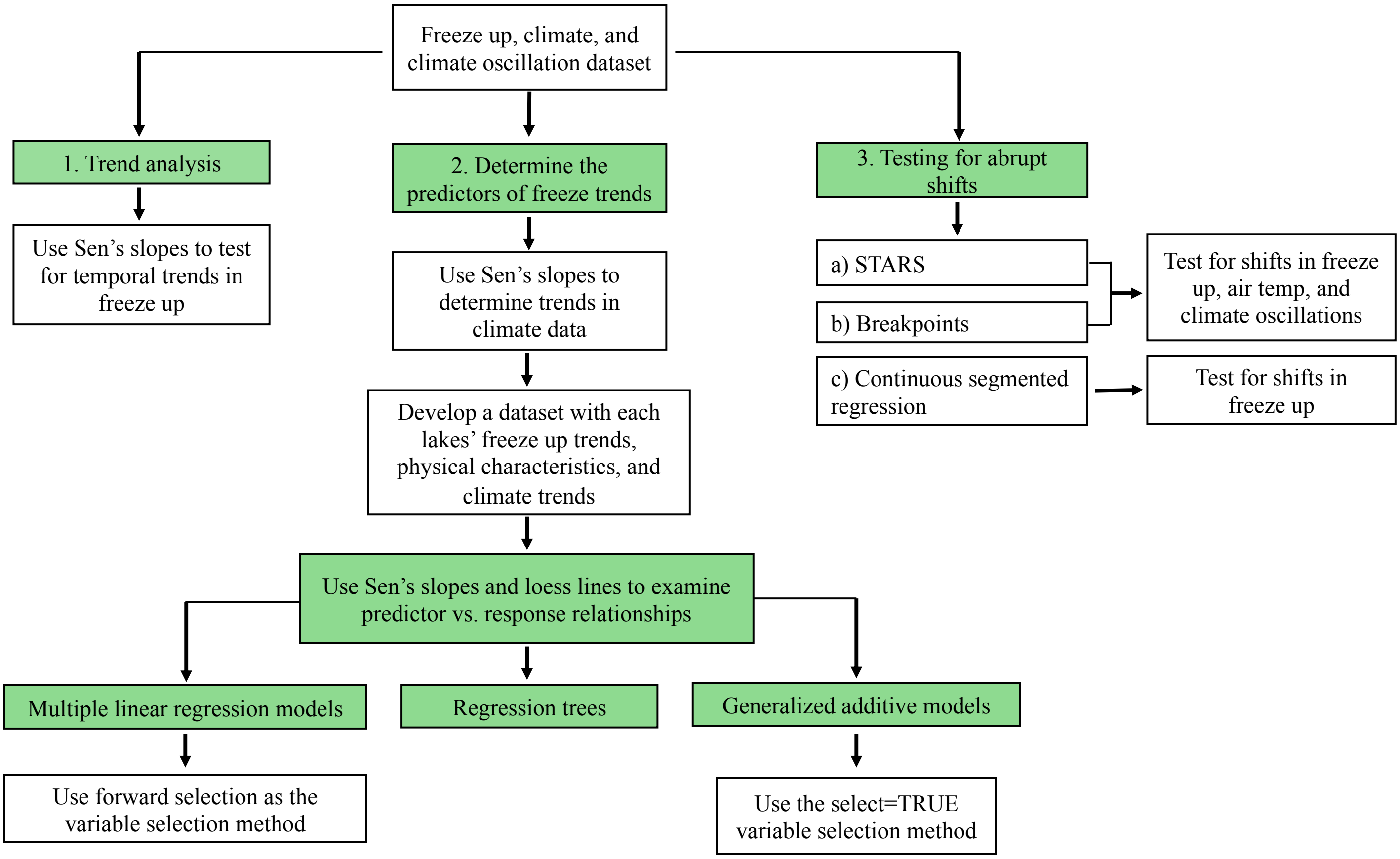

Figure 2: Methodological workflow demonstrating all steps taken during analyses. Blue boxes are the primary analysis steps and white boxes are further descriptions.

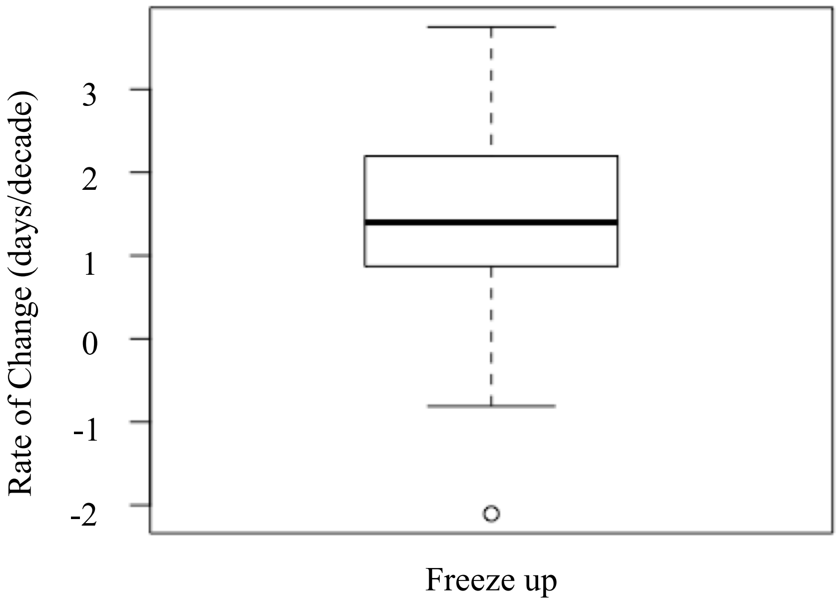

Figure 3: Rate of change of lake ice freeze up date on 75 lakes across the Northern Hemisphere between 1950 and 2013.

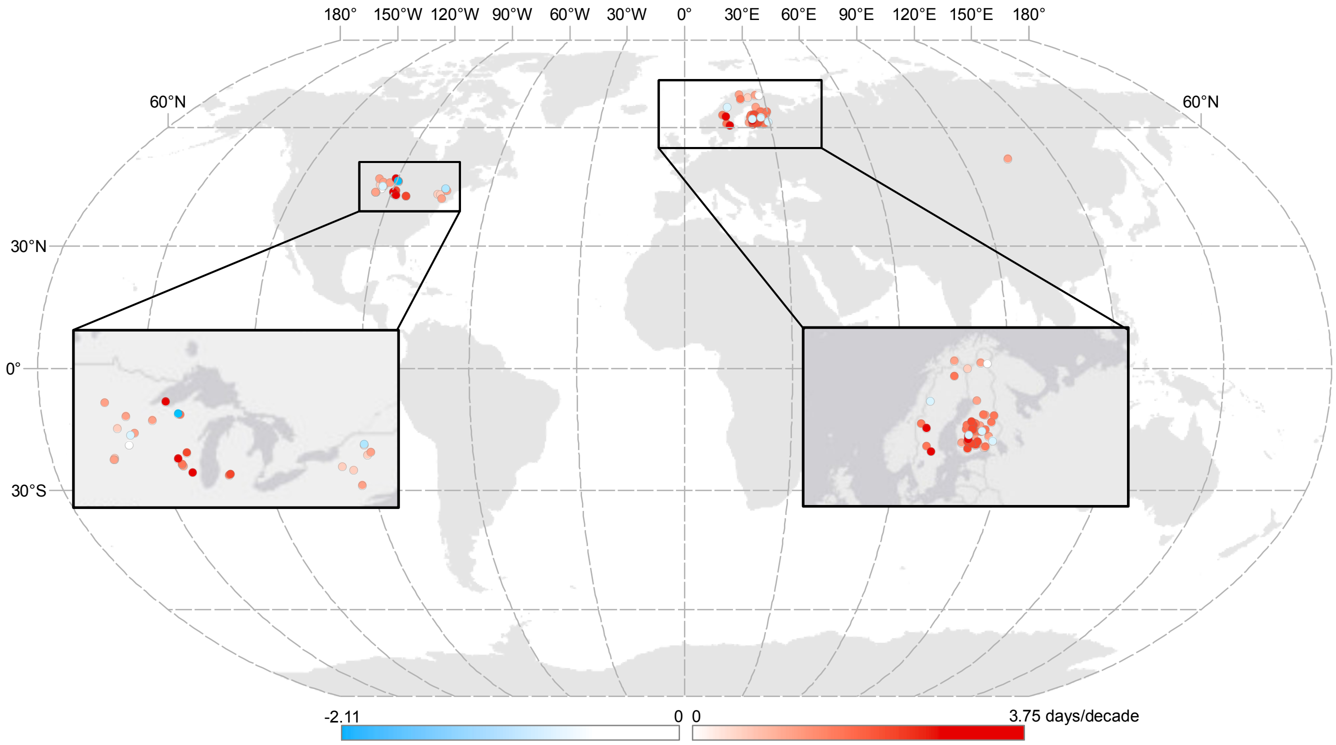

Figure 4: Map of the 75 study lakes with colours that represent the rate of change of lake ice freeze up. Dark red indicates lakes with the strongest warming trends and dark blue indicates lakes with the strongest cooling trends. The average rate of change was a delay of 1.5 days per decade (range: 2.1 days per decade earlier to 3.7 days per decade later) between 1950 and 2013.

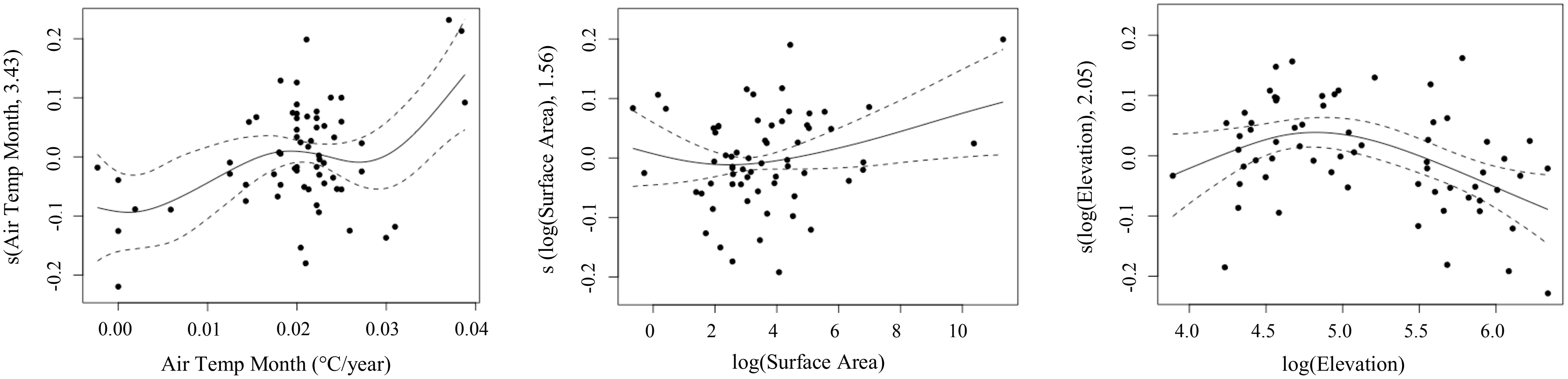

Figure 5: Partial plots of the relationships between lake ice freeze up trends and the predictor variables from the generalized additive model (R^2_{adj}= 0.4). Dashed lines represent the 95% confidence interval. “Air temp month” is the rate of change (Sen’s slope) of the air temperature in the month of/preceding freeze up.

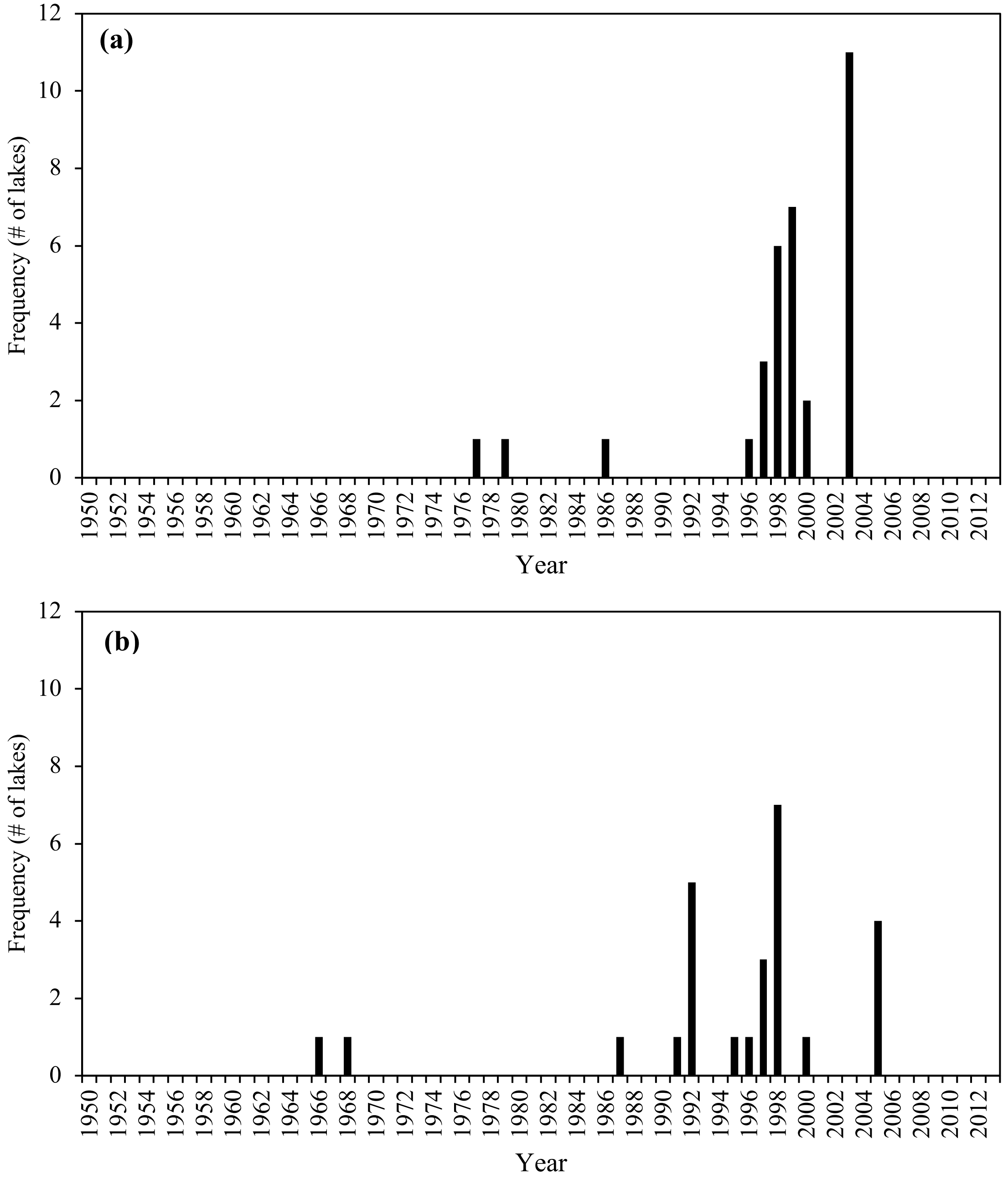

Figure 6: Number of lakes in which lake ice freeze up abrupt shifts were detected using the (a) STARS or (b) breakpoints analysis on lakes across the Northern Hemisphere between 1950 and 2013.

SUPPLEMENTARY MATERIALS

Table S1: Geographic and morphometric characteristics of the 75 study lakes across the Northern Hemisphere.

Lake	**Country**	**Latitude (°)**	**Longitude (°)**	**Elevation (m)**	**Mean Depth (m)**	**Max Depth (m)**	**Surface Area (km^2)**
AHTARINJARVI	FINLAND	62.70	24.05	153.5	5.2	27.0	39.9
ALA-KINTAUS (1449)	FINLAND	62.28	25.34	154.4	5.2	19.0	7.2
ALA-KIVIJARVI - YLA-MUNNI (1489)	FINLAND	60.94	27.51	75.1	4.8	19.0	91.9
ALA-RIEVELI (1468)	FINLAND	61.33	26.20	77.8	11.3	46.9	13.0
HANKAVESI - RAUTALAMPI (1436)	FINLAND	62.62	26.83	96.1	7.0	49.0	18.2
HAUKIVESI	FINLAND	62.09	28.57	75.8	9.1	55.0	560.0
IISVESI (1433)	FINLAND	62.76	26.89	97.9	17.2	34.5	164.5
INARI - NELLIM	FINLAND	68.85	28.30	118.7			1.0
JAASJARVI - HARTOLA (1457)	FINLAND	61.57	26.07	92.3	4.6	28.2	81.1
KALMARINJARVI (1417)	FINLAND	62.78	25.00	129.8	5.7	22.0	7.1
KILPISJARVI	FINLAND	69.03	20.80	472.8	19.5	57.0	37.3
KITUSJARVI (3548)	FINLAND	62.28	24.05	116.2			0.5
KIVIJARVI - SAARENKYLA (1407)	FINLAND	63.27	25.14	130.8	8.4	43.8	154.0
KUIVAJARVI	FINLAND	60.78	23.86	96.6	2.2	9.9	8.2
KUKKIA - PUUTIKKALA (3512)	FINLAND	61.33	24.62	86.6			43.4
KUORTANEENJARVI	FINLAND	62.86	23.41	75.8	3.3	16.2	14.9
LAKE KALLAVESI (4079)	FINLAND	62.83	27.77	81.8	9.7	75.0	316.0
LAKE NASIJARVI (3568)	FINLAND	61.53	23.75	95.4	13.0	61.0	256.0
LAKE PAIJANNE (1463)	FINLAND	61.37	25.51	78.3	15.0	94.5	1080.0
LAKE VESIJARVI (1462)	FINLAND	61.10	25.52	81.4	6.6	40.0	107.6
LANGELMAVESI - KAIVANTO (3506)	FINLAND	61.42	24.15	84.2	6.8	59.3	133.0
LAPPAJARVI - HALKOSAARI (4703)	FINLAND	63.26	23.64	69.5	6.9	39.0	145.5
LENTUA	FINLAND	64.23	29.59	167.9	7.4	52.0	77.8

LESTIJARVI	FINLAND	63.58	24.72	140.7	3.6	6.9	64.5
MUTUSJARVI	FINLAND	68.99	26.81	146.2	8.5	74.0	50.5
MUURASJARVI (1401)	FINLAND	63.47	25.34	112.2	9.0	35.7	21.1
OIJARVI	FINLAND	65.62	25.93	89.8	1.1	2.4	21.1
OULUJARVI	FINLAND	64.30	27.30	122.7	7.0	38.0	887.0
OUNASJARVI	FINLAND	68.38	23.64	286.9	6.6	31.0	6.9
PAAJARVI - KARSTULA (1415)	FINLAND	62.88	24.78	144.4	3.8	14.9	29.5
PALOVESI	FINLAND	61.90	23.94	96.0	9.6	61.0	25.5
PIELAVESI - SAVIA (1427)	FINLAND	63.20	26.67	102.3			110.0
PIELINEN	FINLAND	63.27	29.69	93.7	10.0	61.0	894.0
REHJA	FINLAND	64.21	27.88	137.9	8.5	42.0	96.4
SAAKSJARVI - SAAKSKOSKI	FINLAND	61.39	22.45	49.0	3.7	9.1	33.2
SAANIJARVI (1403)	FINLAND	63.40	25.58	114.0	2.0	6.0	12.6
SIMPELEJARVI	FINLAND	61.60	29.49	68.8	9.3	25.5	58.6
SUMMASJARVI (1419)	FINLAND	62.64	25.38	108.5	6.8	41.0	21.9
VISUVESI	FINLAND	62.12	23.93	96.1	7.0	62.0	46.2
YLA-KIVIJARVI - JURVALA (1488)	FINLAND	60.96	27.75	75.2	5.3	27.0	76.4
LAKE BAIKAL	RUSSIA	51.73	104.91	450.0	730.0	1637.0	31924.6
GOUTA	SWEDEN	65.67	15.40	438.6	17.2	58.0	31.6
JUKKASJARVI	SWEDEN	67.80	20.81	322.4			13.5
KALLSJON	SWEDEN	63.57	12.98	380.5	40.1	102.8	156.4
NACKTEN	SWEDEN	62.91	14.57	324.0	15.5	44.0	84.2
ORSASJON	SWEDEN	61.08	14.55	159.9	17.3	92.2	52.8
RUNN	SWEDEN	60.53	15.68	106.8	8.3	29.5	64.7
BIG GREEN LAKE	UNITED STATES	43.80	-89.00	242.9	31.7	71.9	29.7
BRANT	UNITED STATES	43.71	-73.71	243.0	9.1	18.3	5.5
CAZENOVIA	UNITED STATES	42.95	-75.87	363.0	7.2	14.5	4.8
DETROIT	UNITED STATES	46.79	-95.82	406.6	4.5	25.0	13.0
DEVILS LAKE	UNITED STATES	43.42	-89.73	293.5	9.1	14.3	1.5

EAST OKOBOJI LAKE	UNITED STATES	43.39	-95.10	426.0	3.0	6.7	7.5
FAIR LAKE	UNITED STATES	42.49	-85.33	280.1		11.9	0.9
GEORGE	UNITED STATES	43.62	-73.56	97.0		57.0	115.3
GREEN	UNITED STATES	45.25	-94.90	352.4	6.4	35.1	23.6
GULL LAKE	UNITED STATES	42.40	-85.41	268.2	11.6	33.5	8.3
LAKE ESCANABA	UNITED STATES	46.07	-89.58	502.9	4.3	7.9	1.2
LAKE GENEVA	UNITED STATES	42.57	-88.50	263.4	18.6	41.1	20.7
LAKE KEGONSA	UNITED STATES	42.97	-89.25	257.0	5.2	9.5	13.0
LAKE MENDOTA	UNITED STATES	43.10	-89.40	259.1	12.8	25.3	39.4
LAKE MONONA	UNITED STATES	43.07	-89.36	257.5	8.2	22.5	13.2
LAKE SUPERIOR AT BAYFIELD	UNITED STATES	46.81	-90.81	182.9	147.0	406.0	82100.0
MAPLE LAKE	UNITED STATES	46.14	-89.73	497.7		4.3	0.2
MEDICINE	UNITED STATES	45.01	-93.42	271.0	4.8	14.9	4.0
MIRROR	UNITED STATES	44.29	-73.98	565.0	4.3	18.3	0.5
MOHONK	UNITED STATES	41.77	-74.16	380.0			
OTSEGO	UNITED STATES	42.76	-74.90	363.0	24.9	50.6	17.1
PIERZ	UNITED STATES	45.96	-94.15	337.6	6.0	10.4	0.8
PLACID	UNITED STATES	44.32	-73.99	566.0	15.8	42.7	8.8
SHELL LAKE	UNITED STATES	45.73	-91.90	370.9	7.0	11.0	10.5
SPIRIT LAKE	UNITED STATES	43.46	-95.10	427.0		3.2	4.3
WACONIA	UNITED STATES	44.87	-93.78	293.6	4.0	13.0	13.0
WASHINGTON	UNITED STATES	44.25	-93.88	299.2	3.4	15.5	6.5
WEST OKOBOJI LAKE	UNITED STATES	43.39	-95.16	426.0		41.5	15.7

Table S2: Lake ice freeze up trends determined by Theil-Sen or linear regression analyses for all 75 study lakes. Trends are reported in days per decade.

		Theil-Sen		Linear Regression	
Lake	**Country**	**Slope**	***p*-value**	**Slope**	***p*-value**
AHTARINJARVI	FINLAND	1.0	0.331	1.6	0.113
ALA-KINTAUS (1449)	FINLAND	0.9	0.491	1.0	0.366
ALA-KIVIJARVI - YLA-MUNNI (1489)	FINLAND	0.7	0.439	1.1	0.233
ALA-RIEVELI (1468)	FINLAND	1.4	0.175	1.8	0.045
HANKAVESI - RAUTALAMPI (1436)	FINLAND	1.7	0.058	2.0	0.030
HAUKIVESI	FINLAND	1.4	0.210	1.6	0.083
IISVESI (1433)	FINLAND	-0.2	0.831	0.1	0.937
INARI - NELLIM	FINLAND	0.0	0.940	-0.2	0.819
JAASJARVI - HARTOLA (1457)	FINLAND	2.7	0.035	3.3	0.003
KALMARINJARVI (1417)	FINLAND	2.5	0.015	2.9	0.007
KILPISJARVI	FINLAND	1.2	0.112	1.3	0.045
KITUSJARVI (3548)	FINLAND	-0.2	0.875	-0.5	0.690
KIVIJARVI - SAARENKYLA (1407)	FINLAND	2.5	0.005	2.6	0.005
KUIVAJARVI	FINLAND	2.5	0.082	3.3	0.007
KUKKIA - PUUTIKKALA (3512)	FINLAND	2.8	0.030	3.6	0.004
KUORTANEENJARVI	FINLAND	1.8	0.058	2.4	0.011
LAKE KALLAVESI (4079)	FINLAND	2.2	0.058	2.8	0.003
LAKE NASIJARVI (3568)	FINLAND	2.6	0.065	2.9	0.012
LAKE PAIJANNE (1463)	FINLAND	2.7	0.017	3.1	0.004
LAKE VESIJARVI (1462)	FINLAND	2.1	0.137	2.4	0.023
LANGELMAVESI - KAIVANTO (3506)	FINLAND	1.6	0.249	2.2	0.051
LAPPAJARVI - HALKOSAARI (4703)	FINLAND	2.2	0.062	2.7	0.010
LENTUA	FINLAND	1.7	0.068	2.2	0.013
LESTIJARVI	FINLAND	2.5	0.017	2.5	0.005
MUTUSJARVI	FINLAND	1.4	0.065	1.5	0.018
MUURASJARVI (1401)	FINLAND	1.7	0.120	2.2	0.023
OIJARVI	FINLAND	1.2	0.401	1.2	0.229
OULUJARVI	FINLAND	1.8	0.048	2.0	0.018
OUNASJARVI	FINLAND	0.6	0.332	0.6	0.328
PAAJARVI - KARSTULA (1415)	FINLAND	2.6	0.023	2.6	0.008
PALOVESI	FINLAND	3.0	0.025	3.9	0.001
PIELAVESI - SAVIA (1427)	FINLAND	1.4	0.134	1.8	0.040
PIELINEN	FINLAND	1.8	0.050	2.2	0.013
REHJA	FINLAND	1.2	0.214	2.1	0.029
SAAKSJARVI - SAAKSKOSKI	FINLAND	1.2	0.117	1.9	0.064

SAANIJARVI (1403)	FINLAND	1.7	0.109	2.1	0.034
SIMPELEJARVI	FINLAND	-0.2	0.838	0.4	0.688
SUMMASJARVI (1419)	FINLAND	2.0	0.104	2.4	0.026
VISUVESI	FINLAND	2.5	0.072	3.5	0.003
YLA-KIVIJARVI - JURVALA (1488)	FINLAND	1.7	0.147	2.8	0.012
LAKE BAIKAL	RUSSIA	1.2	0.134	1.1	0.099
GOUTA	SWEDEN	-0.3	0.566	0.0	0.981
JUKKASJARVI	SWEDEN	1.8	0.063	1.8	0.014
KALLSJON	SWEDEN	1.8	0.090	1.7	0.186
NACKTEN	SWEDEN	3.3	0.018	3.1	0.001
ORSASJON	SWEDEN	1.7	0.125	1.7	0.072
RUNN	SWEDEN	3.2	0.002	3.0	0.002
BIG GREEN LAKE	UNITED STATES	2.4	0.070	2.7	0.025
BRANT	UNITED STATES	0.2	0.698	0.4	0.580
CAZENOVIA	UNITED STATES	0.5	0.481	1.2	0.169
DETROIT	UNITED STATES	1.0	0.119	1.2	0.046
DEVILS LAKE	UNITED STATES	3.5	0.002	4.2	0.000
EAST OKOBOJI LAKE	UNITED STATES	0.5	0.531	0.9	0.237
FAIR LAKE	UNITED STATES	2.6	0.000	2.8	0.001
GEORGE	UNITED STATES	1.0	0.404	1.0	0.310
GREEN	UNITED STATES	0.2	0.633	0.4	0.459
GULL LAKE	UNITED STATES	2.1	0.042	1.9	0.045
LAKE ESCANABA	UNITED STATES	1.9	0.010	2.0	0.006
LAKE GENEVA	UNITED STATES	3.7	0.010	3.6	0.001
LAKE KEGONSA	UNITED STATES	1.1	0.192	1.4	0.055
LAKE MENDOTA	UNITED STATES	1.7	0.053	1.8	0.017
LAKE MONONA	UNITED STATES	1.1	0.172	0.9	0.236
LAKE SUPERIOR AT BAYFIELD	UNITED STATES	3.7	0.000	5.1	0.000
MAPLE LAKE	UNITED STATES	-2.1	0.075	-0.7	0.432
MEDICINE	UNITED STATES	0.8	0.187	1.2	0.079
MIRROR	UNITED STATES	0.7	0.334	0.9	0.161
MOHONK	UNITED STATES	1.4	0.078	1.4	0.061
OTSEGO	UNITED STATES	0.7	0.614	1.2	0.268
PIERZ	UNITED STATES	1.0	0.117	1.4	0.016
PLACID	UNITED STATES	-0.8	0.336	-0.5	0.467
SHELL LAKE	UNITED STATES	1.3	0.012	1.5	0.004
SPIRIT LAKE	UNITED STATES	0.1	0.738	1.1	0.228
WACONIA	UNITED STATES	-0.3	0.639	-0.2	0.774
WASHINGTON	UNITED STATES	0.0	0.865	0.1	0.950
WEST OKOBOJI LAKE	UNITED STATES	1.1	0.252	1.3	0.073

Table S3: The timing of abrupt shifts in freeze up date detected by the continuous segmented regression analysis. The abrupt shift year is the first year in the segment following the shift.

Lake	Country	Abrupt Shift Years
AHTARINJARVI	FINLAND	1996
ALA-KIVIJARVI - YLA-MUNNI (1489)	FINLAND	1991, 1996, 2009
ALA-RIEVELI (1468)	FINLAND	1952, 1996
HAUKIVESI	FINLAND	1956, 1984, 1989
IISVESI (1433)	FINLAND	2003
KALMARINJARVI (1417)	FINLAND	2011
KITUSJARVI (3548)	FINLAND	1956, 1958, 1983, 1986
KIVIJARVI - SAARENKYLA (1407)	FINLAND	1955
KUIVAJARVI	FINLAND	1997
KUKKIA - PUUTIKKALA (3512)	FINLAND	1992
LAKE NASIJARVI (3568)	FINLAND	1964
LAKE PAIJANNE (1463)	FINLAND	1977
LAKE VESIJARVI (1462)	FINLAND	1994
LANGELMAVESI - KAIVANTO (3506)	FINLAND	1952
LAPPAJARVI - HALKOSAARI (4703)	FINLAND	1995
LESTIJARVI	FINLAND	1963, 1965
MUTUSJARVI	FINLAND	1986
OIJARVI	FINLAND	1973
OULUJARVI	FINLAND	1995
OUNASJARVI	FINLAND	1979
PALOVESI	FINLAND	1956, 2000
PIELINEN	FINLAND	1959, 1997
REHJA	FINLAND	1996
SAAKSJARVI - SAAKSKOSKI	FINLAND	1999
SIMPELEJARVI	FINLAND	1998
SUMMASJARVI (1419)	FINLAND	1996
YLA-KIVIJARVI - JURVALA (1488)	FINLAND	1998
GOUTA	SWEDEN	1963
JUKKASJARVI	SWEDEN	1956, 1965, 1973, 1975
KALLSJON	SWEDEN	1957, 1959
ORSASJON	SWEDEN	1974
BIG GREEN LAKE	UNITED STATES	1966, 1999
DEVILS LAKE	UNITED STATES	1996
GEORGE	UNITED STATES	1959, 1984, 1986, 1999
GREEN	UNITED STATES	1980, 1982, 1986, 2008
GULL LAKE	UNITED STATES	1999, 2006

LAKE ESCANABA	UNITED STATES	1964, 1969
LAKE GENEVA	UNITED STATES	1954, 1996
MEDICINE	UNITED STATES	1963, 1978, 1981, 1988
MOHONK	UNITED STATES	1965
PIERZ	UNITED STATES	1983
PLACID	UNITED STATES	1991, 2000
SPIRIT LAKE	UNITED STATES	1957, 1962, 1991
WACONIA	UNITED STATES	1953, 1964
WEST OKOBOJI LAKE	UNITED STATES	1968, 1978

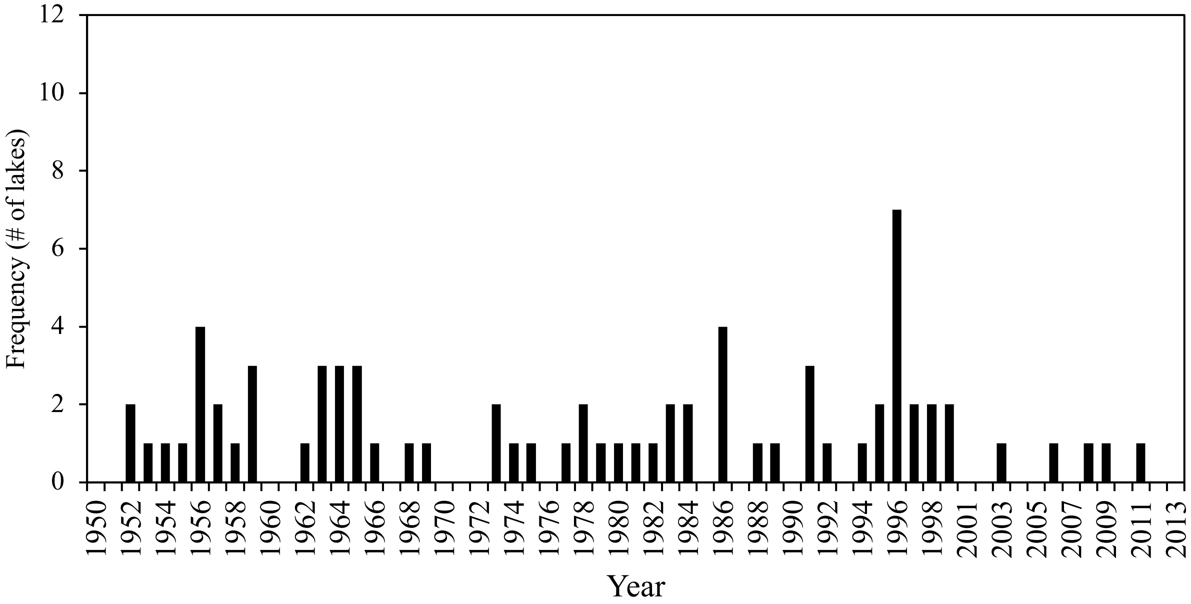

Figure S1: Number of lakes in which lake ice freeze up abrupt shifts were detected using the continuous segmented regression analysis on lakes across the Northern Hemisphere between 1950 and 2013.

GENERAL CONCLUSIONS

Seasonally ice-covered lakes have been experiencing shorter ice cover seasons over the last six decades. Our goal was to identify the impacts of climate change on lake ice freeze up on freshwater lakes across the Northern Hemisphere. In Chapter 1, we studied nine lakes in the Great Lakes region to determine the trends and drivers of lake ice freeze up and to project freeze up dates into the future. In Chapter 2, we identified the patterns and drivers of lake ice freeze up on 75 lakes around the Northern Hemisphere. Lake ice freeze up is later primarily as a result of increasing air temperatures in the months leading up to freeze up. The advancements in freeze dates are not always linear trends, but may also shift abruptly with later periods exhibiting later freeze up dates. Overall, lake ice freeze up is projected to advance even further as air temperatures continue to rise as a result of climate change.

Lake ice freeze up for lakes around the Northern Hemisphere is currently advancing at higher rates relative to those found over the past 150 years (Magnuson *et al.* 2000). Magnuson *et al.* (2000) found that freeze up became later at an average rate of 0.58 days per decade on 14 lakes around the Northern Hemisphere between 1846 and 1995. Whereas lake ice freeze up on small lakes in the Great Lakes region became later at an average rate of 2.2 days per decade between 1981 and 2014 (Chapter 1), while across the Northern Hemisphere lake ice freeze up became later at an average rate of 1.5 days per decade between 1950 and 2013 (Chapter 2). Freeze up on the lakes in the Great Lakes region was driven by air temperatures in November, except for one lake where fall air temperatures were more important. This is consistent when examining the patterns across the Northern Hemisphere where air temperature during the freeze up month was an important predictor of freeze up trends. In addition to meteorological influences, there were also relationships between freeze up and physical characteristics of lakes in both studies. The lakes in the Great Lakes region showed a significant relationship with lake depth such that deeper lakes froze later. In the Northern Hemisphere study, lakes that had larger surface areas and were situated at below-average elevations experienced the most significant delays in freeze up.

In our Northern Hemisphere study, we highlight the importance of potential abrupt shifts in the timing of lake ice freeze up. We found that 44% of the study lakes experienced an abrupt shift towards later lake ice freeze up dates over the 64-year period. These shifts often coincide with shifts in air temperature and climate oscillations. Few studies consider the possibility of both linear trends and abrupt shifts in the mean (e.g., Assel and Robertson 1995; Van Cleave *et al.* 2014).

It is well documented that lake ice freeze up has been advancing faster in recent decades (Benson *et al.* 2012), but far less is known about what we should expect in the future. In our study of lakes in the Great Lakes region, we used multiple linear regression models in conjunction with climate projections from the Intergovernmental Panel on Climate Change to project lake ice freeze up dates to 2050 and 2070. We found that lake ice freeze up will become an average of 9 days later by 2050 and 11 days later by 2070 which would contribute to an overall decrease in ice season length of 24 days (Hewitt *et al.* 2018). Developing our understanding of future changes to lake ice cover will give us an idea of the level to which the ecosystems in and around the lakes will be impacted as temperatures continue to rise.

Lake ice freeze up is both an indicator of climate change and an ecosystem response to increasing temperatures. We have seen advances in freeze up across the Northern Hemisphere and suggest that these shifts will continue under future scenarios of climate warming. Significant delays to lake ice freeze up have the potential to cause a number of ecological, cultural, and socioeconomic implications. As freeze up becomes later and the ice cover seasons become shorter, lake ecosystems may experience a variety of changes. Photosynthesis would continue for a longer period of time each year and the evaporation from a lake would increase (Benson *et al.* 2012). The changes to the ice season would also be a detriment to species that are winter specialists (Benson *et al.* 2012). Reductions in the length of the ice season would also impact a multibillion dollar recreation and tourism based industry which includes activities such as ice fishing, snowmobiling, and winter festivals (Scott *et al.* 2008; Yao *et al.* 2013; Magnuson and Lathrop 2014; Yao *et al.* 2014). We hope that these results provide a clear message: that mitigating climate change is of incredible importance as we move towards a time where increased temperatures will result in drastic changes to our lakes and their ecosystems.

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