Investigating Changes in Lake Ice Breakup Under Current and Future Climate Change

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ABSTRACT

Changes in climate profoundly influence the timing of lake ice breakup. We assessed: 1) potential future changes in lake ice breakup date in the Great Lakes Region and 2) historical linear changes and shifts in ice breakup across the Northern Hemisphere. We found that at the regional and global scales, warming air temperatures contributed to earlier ice breakup. In the Great Lakes region, ice breakup was forecasted to occur 13 days earlier on average by 2070. Across the Northern Hemisphere, we detected abrupt changes in ice breakup dates in the 1970s to the 2000s, coinciding with shifts in air temperature, precipitation, and phase switches of climate oscillations. The structure and function of many lakes in the mid- and high latitudes are influenced by seasonal ice cover, and these ecosystems will likely undergo a variety of changes with earlier ice breakup and a shorter ice season.

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GENERAL INTRODUCTION

Climate change has occurred rapidly especially in the last few decades (IPCC 2013), with far-reaching consequences for terrestrial and aquatic ecosystems. Many ecological events are inextricably linked to climate cues, for example the flowering of cherry blossoms in Japan (Primack et al. 2009), the arrival of spring-breeding amphibians (Chadwick et al. 2006), and the freeze up and breakup timing of lake ice (Magnuson et al. 2000; Benson et al. 2012). Interestingly, observations of lake ice phenology (freeze up, duration, and breakup) have been recorded for decades or even centuries in some regions where the ice-covered season held cultural or economic importance (Wang et al. 2012; Sharma et al. 2016). In general, these records suggest that lake ice freeze up has become later, breakup has become earlier, and ice duration has become shorter, indicating climate warming across the Northern Hemisphere (Magnuson et al. 2000; Benson et al. 2012; Sharma et al. 2016).

Projected climate change is expected to produce earlier lake ice breakup, with some lakes at risk of losing their seasonal ice cover altogether (Jensen et al. 2007). Future projections estimate a warming of 0.3°C to 4.8°C globally relative to the 1986-2005 period by the end of the 21st century. Predictions for precipitation vary across the Northern Hemisphere, with wet regions mostly becoming wetter, however, spring snow cover is estimated to generally decrease 7% to 25% by 2100 (IPCC 2013). Changes in future lake ice breakup dates will depend on the concentration of greenhouse gases released and associated changes in climate. Considerable variation in ice breakup projections have been estimated using different greenhouse gas scenarios (Tan et al. 2018). For example, under the mitigated greenhouse gas scenario, Tan et al. (2018) projected ice breakup for Harp Lake in Ontario, Canada to occur 20 $\pm$7 days earlier between

2015 and 2099. However, with continued increases in greenhouse gases (business-as-usual scenario), ice breakup was estimated to occur 44±16 days earlier during the same period (Tan et al. 2018). In addition, projections of ice breakup dates can vary depending on the climate model being used (Beaumont et al. 2008). Under the same concentration of greenhouse gases distinct climate models may predict different future climatic changes because components making up these models may vary such as calculations used to represent physical processes and their spatial and vertical resolutions (Beaumont et al. 2008; IPCC 2013). For the few studies that have estimated the timing of future lake ice breakup, many have not included more than one climate model in their prediction (e.g. Dibike et al. 2011; Shuter et al. 2013; Tan et al. 2018). In order to take into consideration the variation of future ice breakup date estimates, it is important to include a range of climate models and greenhouse gas scenarios to reduce uncertainty of projections.

Furthermore, while linear changes in climate have induced prominent changes in ice phenology, there have also been periods of intensified warming since the 1980s (IPCC 2013; Reid et al. 2016), which may be reflected non-linearly in lake ice records. During this period of amplified climatic changes, several studies have identified abrupt shifts in abiotic and biotic components of aquatic ecosystems. This includes abrupt increases in average lake temperatures, sudden changes in phytoplankton, and abrupt shifts in ice phenology (Temnerud and Weyhenmeyer 2008; Möllmann et al. 2009; North et al. 2013; Van Cleave et al. 2014). However, only a few studies have focused on shifts in lake ice breakup despite the strong association with climate dynamics (Temnerud and Weyhenmeyer 2008; Van Cleave et al. 2014). Therefore, we expect to detect abrupt shifts in ice breakup instead of solely linear changes for lakes across the Northern

Hemisphere during periods of enhanced climate change.

Current and future changes in ice phenology may have various consequences for seasonally ice-covered lake ecosystems that are adapted to these winter conditions. Ice minimizes the interaction with the atmosphere leading to several changes such as the reduction of turbulence, light, and oxygen compared to the ice-free period (Bengtsson 1996; Arst et al. 2006). These conditions allow for the preservation of several ecosystem components including overwintering survival success of autumn-spawning fish species (Taylor et al. 1987), coexistence of competitor fish species (Helland et al. 2011), and maintenance of spring phytoplankton dynamics (Weyhenmeyer 2001). Thus, ice cover is important in maintaining the structure and function of seasonally ice-covered lakes and under climate change earlier ice breakup may disrupt these ecosystems as it can reduce the duration of lake ice cover.

This thesis aims to reveal the effects of climate change on the timing of lake ice breakup at a regional and global scale. First, we focused on nine lakes in the Laurentian Great Lakes region to examine current ice breakup trends and potential drivers between 1982 - 2015. We then projected ice breakup dates for the years 2050 and 2070 under future climate change scenarios (Hewitt et al. 2018). Few studies have predicted future changes in ice breakup dates and fewer have based their predictions on empirical data. Here we empirically predicted ice breakup dates using all climate models and scenarios from the most recent Intergovernmental Panel on Climate Change (IPCC) report to decrease the uncertainty in projections and include variations that exist within and between the models (Beaumont et al. 2008; IPCC 2013). We hypothesized that spring temperature has been the main driver of recent ice breakup trends and that breakup will become earlier in the future as the climate continues to warm.

Secondly, we broadened our study region to include 152 lakes across the Northern Hemisphere from 1951 - 2014. With this broader geographic dataset, we aimed to (1) identify past lake ice breakup trends, (2) examine the potential climatic, morphometric, and geographic drivers that have influenced these trends at the global level, and (3) identify any abrupt shifts in lake ice breakup since the 1980s, a period in which climatic changes have intensified (Temnerud and Weyhenmeyer 2008; North et al. 2013; Shuter et al. 2013). Interestingly, sudden changes in lake ice breakup has received little attention in the literature, especially at a global spatial scale despite the close association between ice phenology and climate dynamics. We hypothesized that spring temperatures were the most important factor affecting global ice breakup trends, and that abrupt shifts in ice breakup would be detected during similar periods of abrupt climatic shifts.

Citations for MSc thesis:

Over the course of the MSc degree, I have published two papers and submitted one other related to the impacts of climate change on lakes. Please note that an * denotes joint first authorship.

1. Lopez, L.*, Hewitt, B.*, Gaibisels, K., Murdoch, A., Higgins, S., Magnuson, J., Paterson, A., Rusak, J., Yao, H. and Sharma, S. 2018. Historical trends, drivers, and future projections of ice phenology in small north temperate lakes in the Laurentian Great Lakes Region. Water **10:** 70. doi:10.3390/w1001007

2. Chen, M.M., Lopez, L., Bhasavar, S. and Sharma, S. 2018. What's hot about mercury? Examining the influence of climate on mercury levels in Ontario top predator fishes. Environ. Res. **162:** 63-73.

3. Lopez, L., Hewitt, B. and Sharma, S. Reaching a breaking point: How is climate change influencing the timing of ice breakup in lakes across the Northern Hemisphere? Submitted to Limnol. Oceanogr.

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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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MY CONTRIBUTION

The publication, "Historical trends, drivers, and future projections of ice phenology in small north temperate lakes in the Laurentian Great Lakes region," examined both lake freeze up and ice breakup. I focused on lake ice breakup and only included ice breakup sections in this thesis. The authors of this publication included Bailey Hewitt (also first joint author), Katrina Gaibisels, Alyssa Murdoch, Scott Higgins, John Magnuson, Andrew Paterson, James Rusak, Huaxia Yao, and Sapna Sharma. I analyzed all lake ice breakup data (historical trends, drivers, and future projections), contributed to the summary/ abstract and wrote the sections in the Introduction, Methods, Results, and Discussion pertaining to the results of lake ice breakup. I also created figure 2, 4, supplementary figure S1, and table 3 and provided data to all other figures and tables.

SUMMARY

Lake ice phenology (timing of ice breakup and freeze up) is a sensitive indicator of climate. We acquired time series of lake ice breakup, local weather conditions, and large-scale climate oscillations from 1981/2–2014/5 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 in 2050 and 2070. Lake ice melted 5 days earlier over the past 35 years and warmer spring and winter air temperatures contributed to earlier ice breakup. 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. 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^{O}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 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 [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 appeared 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 ^{o}C [36]. However, a small, shallow lake would continue to freeze with increases in daily mean air temperatures up to 10 ^{o}C, suggesting that ice cover in shallow lakes may be more resilient to climatic change [36].

Research Objectives

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 in nine small north temperate lakes in the Laurentian Great Lakes region of Wisconsin, USA and Ontario, Canada between 1981/2 and 2014/5? (2) What are the local weather and large-scale climate drivers of lake ice breakup over this time period based on multiple regression models? and (3) What is the projected timing of lake ice breakup 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 Dates

Lake ice breakup dates for nine north temperate lakes in Wisconsin, United States and Ontario, Canada, were acquired for the period between 1981/2 and 2014/5 (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.

We obtained lake ice breakup 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 International Institute for Sustainable Development Experimental Lakes Area. Lake ice breakup date in Grandview Lake was defined as the date it was less than ~15% ice cover and Lake 239 was considered thawed when 90% of the lake was ice-free. Importantly, each site defined ice breakup in the same manner every year, although each source of data defined it 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 (1981/2–2014/5) 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 breakup. 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 Theil-Sen's slopes to calculate trends in lake ice breakup between 1981/2 and 2014/5 using the "openair" package in R [42]. Theil-Sen's slopes are a nonparametric method of statistically testing trends. The Theil-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

We used multiple linear regression models on the time series of lake ice breakup, local weather, and large-scale climate oscillations, to identify significant local weather and large-scale climate oscillations explaining the timing of lake ice breakup. 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 $p = 0.05$ 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. We developed a linear regression model for all lakes in our dataset using year as a covariate in the model. In addition, we ran linear regressions to examine the relationships between ice breakup (trends and average day of breakup) 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 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 in 2050 (2041–2060) and 2070 (2061–2080). The change in the timing of lake ice breakup from forecasted to historical was calculated by subtracting the forecasted average DOY of 126 climate change scenarios from the historical average DOY (1981/2–2014/5).

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). 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.

Drivers of the Timing of Lake Ice Breakup

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).

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).

The variability in forecasted breakup 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 (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 (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 (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 have increased 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].

Drivers of the Timing of Lake Ice Breakup

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 breakup 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].

We did not find any significant relationships between lake ice breakup 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]. There are several reasons large-scale climate oscillations may not have a direct influence on ice breakup 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].

We found that no morphometric characteristics were significantly related to lake ice breakup trends. 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 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 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. 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 (°N)**	**Longitude (°W)**	**Elevation (m)**	**Surface Area (km^2)**	**Mean Depth (m)**	**Maximum Depth (m)**
Wisconsin	Allequash Lake	46.04	-89.62	494	1.64	2.9	8.0
	Big Muskellunge Lake	46.02	-89.61	500	3.63	7.5	21.3
	Crystal Bog	46.01	-89.61	503	0.01	1.7	2.5
	Crystal Lake	46.00	-89.61	502	0.38	10.4	20.4
	Sparkling Lake	46.01	-89.70	495	0.64	10.9	20.0
	Trout Bog	46.04	-89.69	499	0.01	5.6	7.9
	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
	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. The most parsimonious models with their respective R^2_{adj}, AIC, and *p*-values are displayed.

Response Variable	Lake	Model Equation[1]	R^2_{adj}	AIC	*p*-value
Breakup Day of Year	All lakes	DOY= 99.28−2.79 (MarAprTemp) − 1.13 (WinTemp) +0.06 (WinPrecip)	0.91	1643.22	<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.

FIGURES

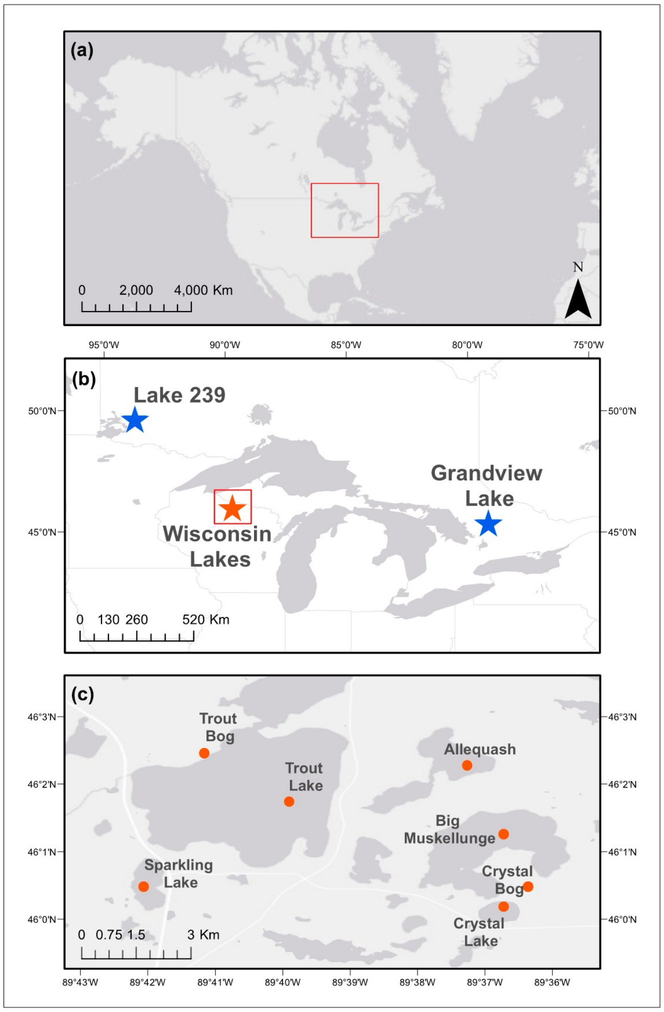

Figure 1. Maps of (**a**) North America (the red box indicates the location of the study regions); (**b**) the study regions in Ontario, Canada (blue stars) and Wisconsin, USA (orange star); and (**c**) a close up of the seven study lakes in northern Wisconsin.

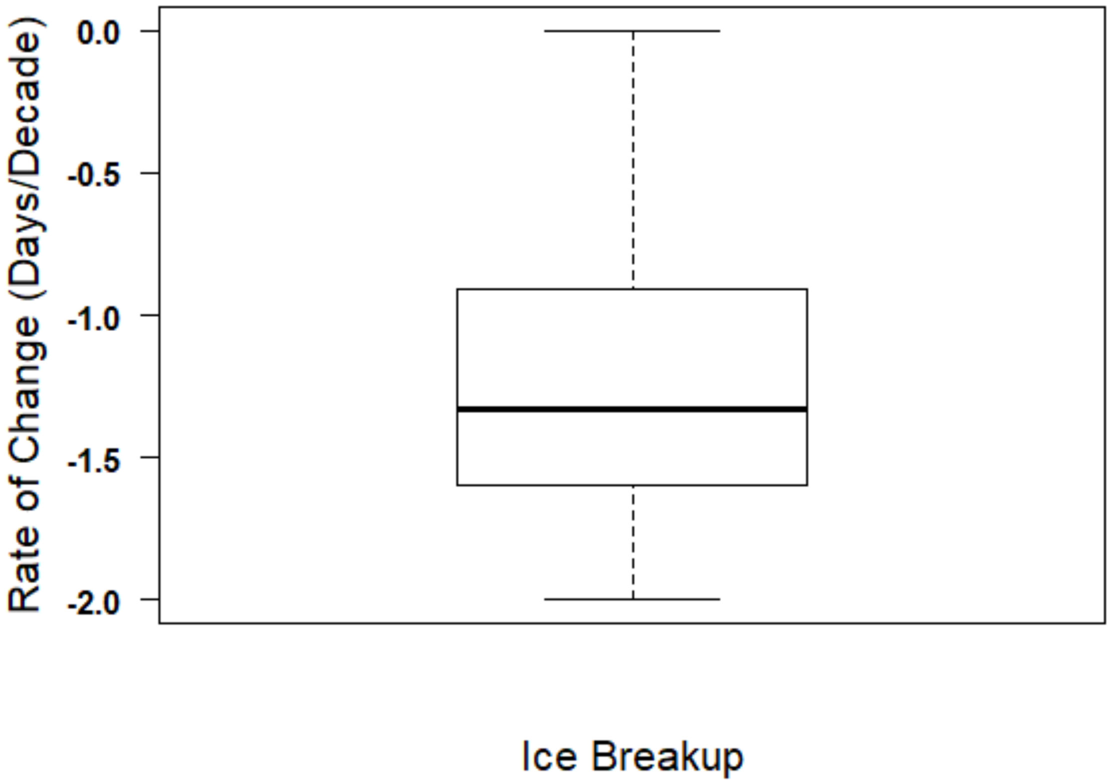

Figure 2. Rate of change of lake ice breakup (day of year) in nine north temperate lakes between 1981/2 and 2014/5.

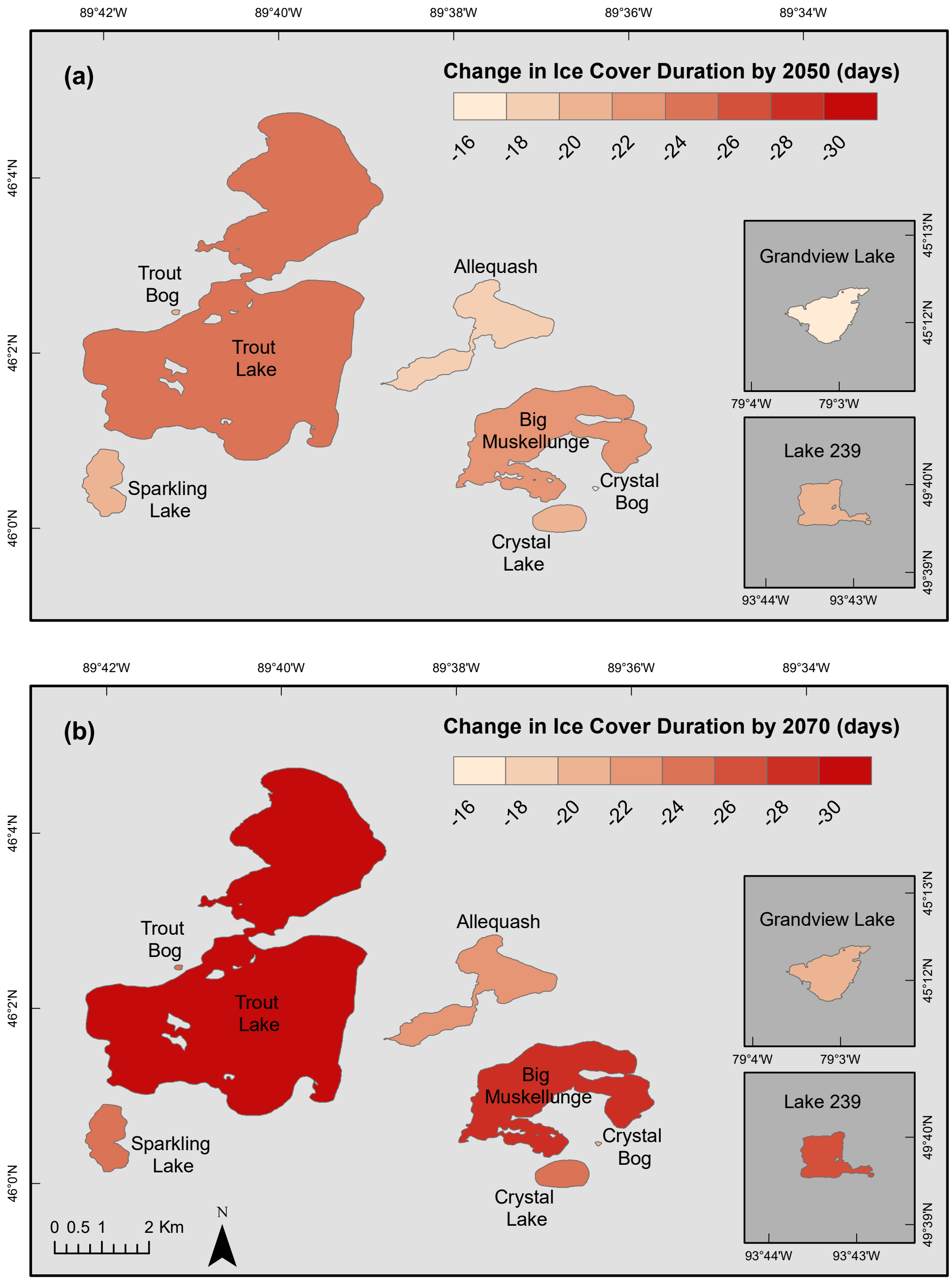

Figure 3. Projected mean loss of ice duration in nine north temperate study lakes by the year (**a**) 2050 and (**b**) 2070. The seven northern Wisconsin lakes are featured in the main map layout; Grandview Lake and Lake 239 in Ontario are featured in the darker insets.

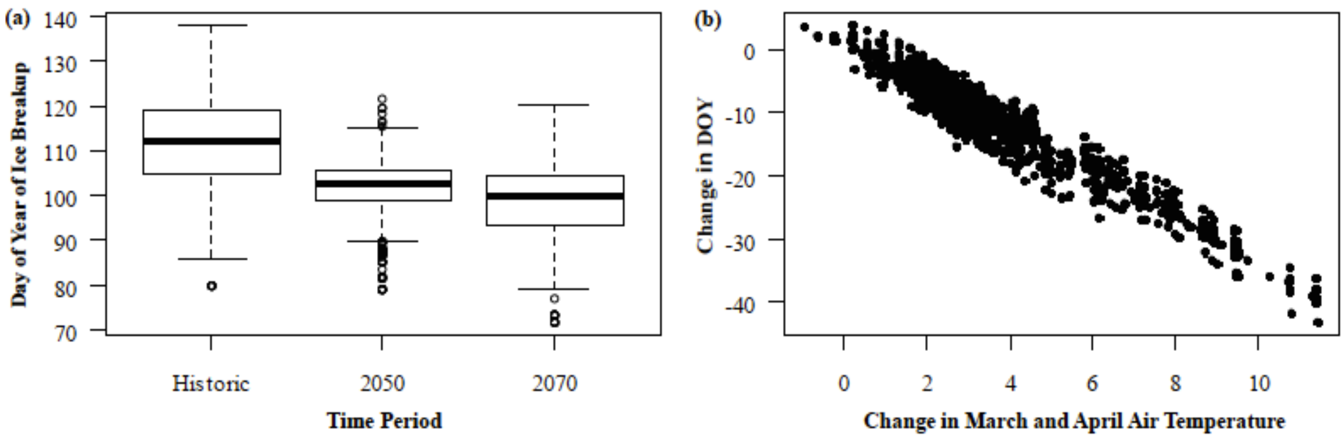

Figure 4. (**a**) The timing of lake ice breakup (day of year) for the historic period (1981/2–2014/5), and forecasted in 2050, and 2070; (**b**) Forecasted change in the day of ice breakup with the corresponding change in mean March–April air temperature (°C) under 126 projected climate scenarios.

SUPPLEMENTARY MATERIAL

Table S1. The change in climatic variables (mean annual temperature and mean annual precipitation), day of ice breakup 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, DOY_b = breakup day of year.

Region	Year	RCP	*n*	*Δ*MAT	*Δ*MPPT	*Δ*DOY (min *Δ*DOY,max *Δ*DOY)
Wisconsin	2050	2.6	15	2.63	4.01	−8.34 (−27.61, 2.20)
		4.5	19	3.23	4.56	−10.80 (−29.65, −2.15)
		6.0	12	2.76	4.50	−8.98 (−26.98, 3.79)
		8.5	17	3.91	4.93	−13.03 (−35.80, 1.21)
	2070	2.6	15	2.61	5.09	−8.01 (−24.95, 2.83)
		4.5	19	3.94	4.39	−13.15 (−35.31, 0.51)
		6.0	12	3.68	4.19	−13.05 (−35.79, −1.32)
		8.5	17	5.63	5.99	−19.09 (−43.16, −3.59)
Ontario	2050	2.6	15	0.51	−2.07	−6.56 (−23.72, 1.23)
		4.5	19	1.13	−1.85	−9.07 (−25.01, −2.32)
		6.0	12	0.68	−1.62	−7.19 (−22.61, 3.28)
		8.5	17	1.84	−0.96	−11.63 (−30.86, 1.25)
	2070	2.6	15	0.47	−0.96	−5.81 (−22.83, 1.98)
		4.5	19	1.82	−1.17	−11.52 (−31.00, −1.23)
		6.0	12	1.58	−1.18	−10.94 (−27.95, −3.19)
		8.5	17	3.50	0.93	−17.39 (−38.93, −4.49)
Regional	2050	2.6	15	1.57	0.97	−7.94 (−27.61, 2.20)
		4.5	19	2.18	1.36	−10.41 (−29.65, −2.15)
		6.0	12	1.72	1.44	−8.58 (−26.98, 3.79)
		8.5	17	2.87	1.98	−12.72 (−35.80, 1.25)
	2070	2.6	15	1.54	2.06	−7.52 (−24.95, 2.83)
		4.5	19	2.88	1.61	−12.78 (−35.31, −0.51)
		6.0	12	2.63	1.51	−12.58 (−35.79, −1.32)
		8.5	17	4.57	3.46	−18.71 (−43.16, −3.59)

Table S2. Slope, explained variation, and significance of linear regressions examining the relationship between lake ice breakup 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

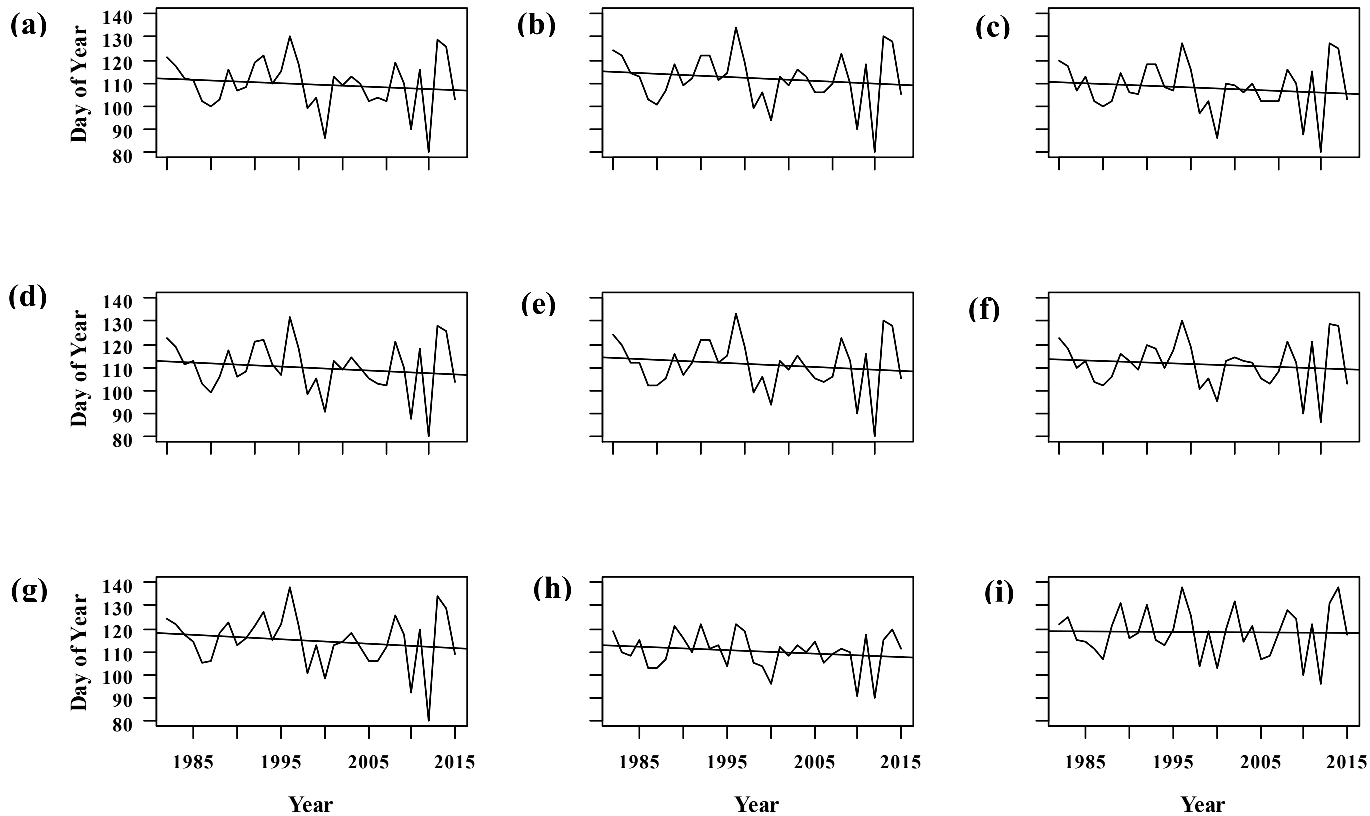

Figure S1. Lake ice breakup and for **(a)** Allequash Lake, **(b)** Big Muskellunge, **(c)** Crystal Bog, **(d)** Crystal Lake, **(e)** Sparkling Lake, **(f)** Trout Bog, **(g)** Trout Lake, **(h)** Grandview Lake, **(i)** Lake 239 during the study period.

Chapter 2: Reaching a breaking point: How is climate change influencing the timing of ice breakup in lakes across the Northern Hemisphere?

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MY CONTRIBUTION

The manuscript titled, “Reaching a breaking point: How is climate change influencing the timing of ice breakup in lakes across the Northern Hemisphere” submitted to the journal Limnology and Oceanography. The authors of this publication included Bailey Hewitt and Sapna Sharma. I analyzed all data and wrote the Abstract, Introduction, Methods, Results, and Discussion. I also created all figures and table 1, supplementary tables S1 to S4.

SUMMARY

The ice season has been diminishing in many mid- and high-latitude regions around the world as the climate continues to warm. We obtained lake ice breakup dates, air temperature, precipitation, and large-scale climate oscillation data for 152 lakes across the Northern Hemisphere from 1951 to 2014. Ninety-seven percent of study lakes exhibited earlier ice breakup trends which were driven by changes in spring air temperature and elevation. However, changes in ice breakup have not always been in a gradual or linear pattern. Using the Sequential T-test Analysis of Regime Shifts we found evidence of abrupt changes in mean ice breakup for 53% of lakes with shift years identified between 1970 and 2002. Along with several ice breakup shift years, we found abrupt changes in mean spring and winter temperature, winter precipitation, and climate oscillation index values that occurred the same year or one year prior. Earlier ice breakup and the shortening of the ice season will likely have several cascading consequences affecting cultures, economies, and ecosystems around the world.

INTRODUCTION

Lake ice phenology is highly sensitive to changes in climate, therefore, long-term ice phenology records (timing of breakup and freeze up) can serve as an indicator of climate over time (Magnuson et al. 2000; Adrian et al. 2009). Lake ice breakup has been a subject of interest for centuries due to its role in welcoming the spring season, ushering in important economic activities such as fishing (Adams 1981), and navigation for transportation and shipping (Howk 2009; Wang et al. 2012; Sharma et al. 2016). Earlier ice breakup over time can also affect ecosystem processes that are dependent on the timing of ice melt. For example, the timing of spring phytoplankton population growth and decline (Weyhenmeyer 2001), lake mixing (Croley et al. 1998), and water quality (Weyhenmeyer 2009) can be influenced by the timing of lake ice breakup.

Across the Northern Hemisphere, lake ice has broken up earlier over the last 150 years (Magnuson et al. 2000; Benson et al. 2012). For example, across the Northern Hemisphere, ice breakup has occurred 0.63 days per decade earlier over the past 150 years (Magnuson et al. 2000) and accelerated to 1.87 days per decade earlier in the past 30 years (Benson et al. 2012). Specifically, in the Great Lakes region, ice breakup date advanced by 2.1 days per decade between 1975 and 2004 (Jensen et al. 2007) and 1.5 days per decade between 1982 and 2015 in northern Wisconsin (Hewitt et al. 2018). Similar trends have been observed in several lakes across Canada (Duguay et al. 2006; Shuter et al. 2013), United States (Sharma et al. 2013; Hodgkins 2013), Finland (Korhonen 2006), Estonia (Nõges and Nõges 2014), and Sweden (Weyhenmeyer et al. 2005). The premature degradation of ice cover on lakes observed indicate considerable changes in the climate over the extent of these ice records.

The timing of ice breakup has been associated with air temperatures, precipitation, and cloud cover. However, studies have shown that air temperature is the most important predictor of ice breakup dates (Palecki et al. 1986; Vavrus et al. 1996; Korhonen 2006). Even a 1℃ increase in air temperature resulted in earlier ice breakup dates by 7.1 days in Grand Traverse Bay, Lake Michigan (Assel and Robertson 1995). Across the Northern Hemisphere, increases in air temperature of 1.2°C was associated with premature ice breakup by 6.3 days over a century (Magnuson et al. 2000). Furthermore, other climate variables such as precipitation and cloud cover may also contribute to changes in the timing of ice breakup, although to a lesser extent than air temperature (Brown and Duguay 2010; Sharma et al. 2013). Snow precipitation can either delay or accelerate ice breakup depending upon the amount of snowfall and the size of the snowpack settled on the ice (Vavrus et al. 1996). Increases in the snowpack can shield ice from incoming solar radiation, facilitate the formation of gray ice, and add extra frozen snow and ice mass resulting in thicker ice cover (Vavrus et al. 1996). However, increased rainfall can produce the opposite effect, rapidly melting the ice as heat is released from rain on contact (Jakkila et al. 2009; Nõges and Nõges 2014). Cloud cover can indirectly affect ice breakup by altering the amount of incoming solar radiation (Jakkila et al. 2009). Despite the prominent effect of air temperature on breakup, the combination of other climatic factors such as precipitation and cloud cover can also induce further changes in lake ice breakup dates.

Although the timing of lake ice breakup is highly dependent on climatic changes, variation have also been associated with lake morphometry and geography (Williams et al. 2004; Brown and Duguay 2010). Variables such as lake surface area, depth, and elevation may affect the timing of lake ice breakup. For example, ice on smaller lakes tend to break earlier than larger lakes, even with the same increases in temperature (Magee and Wu 2017). While top, bottom, and internal melting all occur at similar rates, warmer air temperatures enhance lateral melting, i.e. melting at the ice-shoreline interface (Jakkila et al. 2009; Arp et al. 2013). Therefore, smaller lakes have less ice at the edges to melt when temperatures increase and break earlier than larger lakes. Furthermore, Williams and Stefan (2006) found weak positive associations between lake ice breakup dates and mean depth and elevation. While climatic changes tend to have a prominent effect on lake ice breakup dates, some of the variation may be additionally explained by lake morphometry and geography especially for lakes within the same region.

The effect of climate on lake ice phenology may be observed as a gradual shift, or it may constitute several abrupt shifts over an otherwise steady period. Previous studies have observed both patterns across the Northern Hemisphere, with abrupt climate shifts starting in the 1980s that may be reflected in lake ice breakup records (Marty 2008; Temnerud and Weyhenmeyer 2008; Reid et al. 2016). For example, in Sweden, the late 1980s, 1990s, and the year 2000 exhibited sudden changes in mean annual air temperatures and precipitation. Concurrently, several lakes underwent sudden changes in the timing of ice breakup (Temnerud and Weyhenmeyer 2008). In addition, phase switches of several climate oscillations including the North Atlantic Oscillation, El Niño-Southern Oscillation, and Pacific Decadal Oscillation in the 1980s and 1990s, induced changes in climate across the Northern Hemisphere (Hurrell 1995; Assel et al. 2000; Rodionov and Assel 2003; Van Cleave et al. 2014). Therefore, ice breakup changes may be detected as a combination of gradual shifts and abrupt shifts owing to the combination of sudden changes in climate and phase switches of prominent climate oscillations in the past few decades.

Research Objectives

We aimed to identify the trends, drivers, and abrupt shifts in the timing of ice breakup for 152 lakes across the Northern Hemisphere from 1951 to 2014. Specifically, we: i) calculated trends in ice breakup dates; ii) identified the climatic, lake morphometric, and geographic drivers of these trends; and iii) identified abrupt changes in ice breakup dates, weather variables, and large-scale climate oscillations. We hypothesized that ice breakup has continued to occur earlier in the year over the study period with air temperature as the main driving force of these changes. Furthermore, we hypothesized that shifts in lake ice breakup have occurred since the 1980s onward and would be related to concurrent climatic shifts.

METHODS

Data Acquisition

Ice phenology data were obtained from the Lake and River Ice Phenology Analysis Group housed at the National Snow and Ice Data Center (http://nsidc.org/data/g01377.html). Ice records were updated to the most recent year of ice phenology observations with data obtained from collaborators in North America, Europe, and Asia and originally contributed data to the National Snow and Ice Data Center. Lakes were located in six different countries including Canada, United States, Switzerland, Sweden, Finland, and Russia. A total of 152 lake ice breakup records were analyzed in this study with no more than 15% of years missing during the 1951-2014 period. For lakes with years of missing data, the average date of breakup was used for that specific lake. Eight lakes did not freeze in certain years, and to account for this we used the earliest breakup date in their ice record. No-freeze years consisted of 2% to 12% of the ice breakup record for these eight lakes. Ninety-two percent of ice records began in 1951 and the remaining began between 1952-1955. Forty-three percent of records ended in 2014 and 57% ended between 2000-2013. The shortest ice breakup record was 51 years, however 51% of study lakes had the maximum length of 64 years. Ice breakup dates were not always measured comparably across lakes. For example, definitions of ice breakup date varied from the date that the lake was completely ice free, to when the lake was 90% ice-free, or when it was possible to travel from one point to another by boat. Although different lakes may have different definitions of ice breakup, importantly, the criteria was the same for an individual lake each year. Additionally, we obtained lake morphometric and geographical characteristics for each lake including mean and maximum depth, surface area, and elevation from the National Snow and Ice Data Center (Table S1). Historical climate data were acquired from the Climate Research Unit based in the University of East Anglia (Harris et al. 2014). Surface air temperature, precipitation, and cloud cover monthly means were downloaded as a gridded time-series dataset (Version 4.01) with a spatial resolution of 0.5° x 0.5°. Data was extracted using the "ncdf4" package in the R programming language environment (Pierce 2017; R Development Core Team 2017). Seasonal means of the weather variables were calculated by averaging monthly values. Winter seasonal means included December of the previous year, January and February. Spring temperature for each lake included only one month and depended on the average ice breakup date of each lake. If average breakup throughout the time series of a lake occurred during the first half of the month, the mean air temperature of the month before this date was used to represent spring temperature. For lakes where the average breakup date occurred in the second half of the month, we then used temperature from the same month to represent spring temperature. Studies have suggested that the air temperature closest to average breakup date has greater importance on ice disintegration compared to seasonal averages that include months further away from the time of the event (e.g. Palecki et al. 1986). Therefore, we chose to represent spring with the month closest to average ice breakup date. In addition, we also acquired annual and monthly index values for eight climate oscillations including the El Niño-Southern Oscillation index (ENSO), North Atlantic Oscillation, Pacific Decadal Oscillation, Sunspots Cycle, Quasi-biennial Oscillation, and Arctic Oscillation from several open sources available online (Table S2).

Data Analysis

<u>Trends</u>

To identify temporal trends in ice breakup dates; winter air temperature, precipitation and cloud cover; and spring air temperature, precipitation and cloud cover across the Northern Hemisphere, we used the nonparametric Theil-Sen's slopes (Theil 1950; Sen 1968). Theil-Sen's slopes calculate the median of the slopes between all pairs of points (Wilcox 2010). The estimate of the true slope is relatively unaffected by outliers thus producing a more conservative estimate. Theil-Sen's slopes were calculated using the "openair" package in R (Carslaw and Ropkins 2012).

Drivers

We used a regression tree model to identify important drivers of lake ice breakup trends (De'Ath and Fabricius 2000). Predictor variables included lake mean depth, maximum depth, surface area, elevation (Table S1), and trends in winter and spring air temperature, precipitation and cloud cover. Regression trees repeatedly split the response variable into groups based on a criteria imposed by one or more of the predictor variables (De'Ath and Fabricius 2000). The splitting criteria minimizes the sum of squares about the group mean making each group on either side of the split as homogenous as possible (De'Ath and Fabricius 2000). The regression tree was pruned to avoid overfitting of the data using the "rpart.plot" package in R (Milborrow 2018).

Abrupt shifts

We first used a Sequential T-test Analysis of Regime Shifts (STARS) to identify abrupt shifts in ice breakup, seasonal weather, and large-scale climate drivers for each lake (Rodionov 2004). We used a macro-enabled sheet that can be accessed via https://sites.google.com/site/climatelogic/documentation/installation. We set $p= 0.05$ as the target significance level, 20 as the cutoff length (ℓ), and a Huber weight of 2. We used the Inverse Proportionality with 4 corrections prewhitening technique on ice breakup, seasonal weather, and large scale climate drivers for lakes with autocorrelation at lag 1 and/or a significant trend according to the Theil-Sen's slope estimator (Rodionov 2006). The cut-off length is the minimum length of time for which the magnitude of the shift must continue in order to be classified as a significant shift (Rodionov 2004). The Huber weight parameter lessens the effect of outliers on detecting a significant shift in the data. The weights of the outliers are inversely proportional to the deviation from the mean value of the time segment the outliers are a part of (Rodionov 2006). A shift is identified when there is a significant difference in mean between two time segments using a two-tailed Student *t*-test (Rodionov 2004). Initially, the first segment is the time length of the cut-off length (in this case 20). If a significant shift is not detected (according to the t-test) between the first and second time segment, the start of the first time segment moves to the second observation and one more observation is added to the end first segment and the process is repeated. Once a significant shift is detected, the Regime Shift Index is calculated and defined as the cumulative sum of normalized anomalies from the mean of the new time segment (Rodionov 2004). If the Regime Shift Index is positive for the number of observations equivalent to the cutoff length, then a shift is formally established (Rodionov 2004). The final Regime Shift Index values identifies the magnitude of the shift between the time segments.

The second method we used, breakpoint analysis, measures the changes in coefficients from one linear regression to another (Zeileis et al. 2003). This analysis fits separate linear relationships on each time segment before and after the shift year (Bai and Perron 1998; Zeileis et al. 2003). It is an unconstrained method, therefore the time segments are not required to be connected or continuous. We used the "strucchange" package in R to run this analysis (Zeileis et al. 2002). Subsequently, we ran linear regressions for each time segment before and after each shift year.

Last, we ran continuous segmented regressions which also detect a significant shift in the linear relationship between the response and explanatory variable (Muggeo 2008). We used the R package "segmented" which constrains the time segments and therefore the linear relationships for each time segment were connected at a common point (Muggeo 2008). The shift years were unknown before running the analysis and were instead estimated by the algorithm. Overall, these three methods of abrupt shift detection were employed for data exploration purposes, to compare the suitability of each analysis method, and to examine common trends among analyses.

RESULTS

Trends

The median lake ice breakup trend was 1.2 days per decade earlier across the Northern Hemisphere ranging from 5.0 days per decade earlier to 0.3 days per decade later (Fig. 1, Table S3). In total, 97% of lakes exhibited earlier ice breakup trends and 43% of these trends were significant ($p < 0.05$; Table S3).

Drivers

The regression tree revealed that spring air temperature trends were the most important predictor of lake ice breakup trends, partitioning lakes which exhibited slow (e.g. -0.09 days/ yr) and fast trends (e.g. -0.29 days/ yr) (Fig. 2). Lakes with the fastest ice breakup trends during the study period were found in regions with warming springs and at lower elevations (< 265 m). Spring air temperature trends and elevation alone explained 46% variation in global ice breakup trends.

Abrupt shifts

<u>Shifts in Ice Breakup Date</u>

STARS

Eighty-two shifts in ice breakup dates were identified for 81 lakes from 1970 to 2002 and 76 of these shifts were significant at the $p = 0.05$ level (Fig. 3; Table 1). All shifts in the mean were in the direction of earlier ice breakup, except for one (Lake Nipissing). Between 1970 and 1979, 10% of shifts were detected and ice breakup occurred earlier by 4.9 to 8.1 days, except for Lake Nipissing. Lakes with shift years in the 1970s are located in northeastern U.S.A and Sweden. Furthermore, 35% of total shifts began in the 1980s for which lake ice breakup occurred earlier by 5.2 to 23.4 days in the period after the shift. For the 1980s, 1989 was the most prominent year (12% of total shifts) and these lakes were located in the Scandinavian countries (Sweden and Finland). Thirty-nine percent of total shifts began in the late 1990s for which lake ice breakup occurred earlier by 4.6 to 12.5 days in the period after the shift. The most frequent individual years detected among all the shifts were 1998 and 1999. Lakes with a shift in 1998 are mostly located in the U.S.A., whereas mostly Finnish lakes exhibited a significant switch in ice breakup dates in 1999. Lastly, in the 2000s, a total of 13% of shifts were identified with the year 2000 as the most common year of this decade. All lakes with shifts beginning in 2000 to 2002 are located in Sweden and Finland and ice breakup occurred 6.2 to 12.5 days earlier following the shift year.

Breakpoint Analysis

A total of 43 shift years were detected with the breakpoint analysis ranging from 1962 to 2000 in 30 lakes for ice breakup trends (Figure 3; Table 2). Two shifts were identified for eight lakes and three lakes had three shift years in ice breakup trends.

In the 1970s, 33% of shifts occurred with 1972 being the most prominent year in this decade accounting for 19% of total shifts. Most of the lakes with shift years in 1972 are located in northeastern U.S. and the trends after the shift year ranged from 0.2 day/ year earlier to 0.2 day/ year later. The most frequent years identified with the breakpoint analysis were 1988, accounting for 28%, and 1997, which amounted to 26% of total shifts identified. Trends for the period after 1988 ranged from 0.3 day/year to 3.85 days/ year later earlier and for the period after 1997 ranged from 1.28 days/ year earlier to 7.82 days/ year later. Most of the lakes with shift years in the 1980s and 1990s are located in the Scandinavian countries.

Segmented Regression

Segmented regression identified 153 shift years in ice breakup trends for 100 lakes ranging from 1953 to 2013 (Figure 3; Tables S4). The most shift years identified for a single lake was six. Given the total number of shifts identified and the number of lakes with multiple shift years we concluded that the segmented regression analysis was highly sensitive to variation in the ice breakup data. The automatic version of this analysis in the "segmented" package has also been suggested to overestimate the number of shifts (Muggeo 2017). Therefore, we excluded the results of the segmented regression as it did not properly represent the years of abrupt shifts well.

Shifts in Weather Variables and Climate Oscillations

A few shifts in the mean of seasonal temperature and precipitation were found that matched or were within one year of the ice breakup shifts previously identified with STARS (Table 1). Warmer spring and winter temperatures were evident following a shift year. Several lake sites with a shift in ice breakup date in 1989, 1998, 1999 or 2000 also underwent an abrupt increase in air temperatures in the same year or one year before. For example, a sudden increase in winter air temperatures was detected in 1988, 1989, 1997, and 1998 which matched with all study sites with ice breakup shifts in 1989 and 88% of lakes with the 1998 shift. Spring temperature suddenly increased in 1999 for 69% of study sites with a shift in ice breakup in 1999 and 43% with the 2000 shift. Furthermore, 42% of study sites with a shift in ice breakup date in 1980 or 1981 also underwent an abrupt decrease in winter precipitation in 1980. We also detected a few shifts with STARS for large-scale climate oscillations. The Arctic Oscillation index switched to mainly positive values after 1988 and El Nino Southern Oscillation index switched to negative values in 1977 (Table 2).

DISCUSSION

In order to identify abrupt shifts in ice breakup date we ran three shift detection tests: STARS, breakpoint analysis, and segmented regression. We mentioned previously the overestimation of shift years with segmented regression and concluded that it was not suitable for identifying sudden changes in ice breakup. In contrast, the breakpoint analysis appeared to detect a reasonable number of shifts (maximum of three) per lake and most shifts occurred in the 1970s to the 1990s, similar to STARS. Between the breakpoint analysis and STARS eleven lakes had similar shift years (up to two years difference). However, several of the linear trends after the 1970s and 1988 were indicating later breakup rather than earlier. We expected the later period to have earlier ice breakup because 97% of linear trends were negative over the whole study period, indicating warming between 1951 and 2014. Furthermore, in 1989 there was a switch to the positive phase NAO which is associated with warmer temperatures in northern Europe (Hurrell 1995) and all the lakes with a shift year in 1989 were located in Sweden or Finland. Both breakpoint analysis and segmented regression detect abrupt shifts in linear trends. With ice records spanning 51 to 64 years the time periods before and after the shift year were divided into relatively short segments and may not represent the shifts well. Therefore, we focused on the results obtained with STARS.

Our study is one of the first to identify the trends, drivers, and abrupt shifts in ice breakup dates for lakes across the Northern Hemisphere. We found that 97% of lakes exhibited earlier ice breakup dates across the Northern Hemisphere from 1951-2014. These trends are consistent with regional and global ice phenology studies indicating a period of climate warming over the last few decades (e.g. Anderson et al. 1996; Magnuson et al. 2000; Benson et al. 2012; Soja et al.

2014). Specifically, warming spring air temperature was the primary driver of earlier ice breakup dates, but differences in elevation also explained some of the variation in ice breakup at the global level. We detected abrupt shifts in average ice breakup dates from the 1970 to early 2000s for 53% of study lakes with more rapid warming following the shift year. Although shift years in the 1970s was a few years earlier than expected, abrupt shifts in ice breakup from the 1980s onwards encompassed a period of sudden changes in the climate (Marty 2008; Temnerud and Weyhenmeyer 2008; Reid et al. 2016) and phase switches of prominent climate oscillations (Hurrell 1995; Assel et al. 2000; Rodionov and Assel 2003; Van Cleave et al. 2014).

Trends

Overall, lake ice has broken up earlier across the Northern Hemisphere with 97% of study lakes exhibiting a warming trend. From 1951-2014 ice breakup trends have ranged from 5 days per decade earlier to 0.3 days per decade later with a median rate of -1.2 days per decade. Benson et al. (2012) also analyzed ice breakup trends using Theil-Sen's slopes at three temporal scales: 150-year, 100-year, and 30-year periods for lakes across the Northern Hemisphere. At the 150-year (-0.86 days/decade) and 100-year (-0.46 days/decade) time scales the median rate of change in ice breakup was slower than found in this study (Benson et al. 2012). However, the 30-year time series (from 1975 to 2005) was almost double the median rate we found since 1951, potentially implying intensified changes in climate since the mid-1970s compared to the 1950s.

Drivers

We found that the most important driver of earlier ice breakup trends globally was spring air temperature. Generally, lakes warming most rapidly were found in regions with higher spring temperatures and at lower elevations. The importance of warming spring temperatures on lake ice stems from the earlier arrival of the 0°C isotherm date during this season (Duguay et al. 2006). The 0°C isotherm date marks the time of year when mean daily temperatures are above 0°C (Duguay et al. 2006). Since the melting process begins prematurely with warmer spring temperatures, this can lead to earlier ice breakup dates. In several studies air temperature has been the most influential factor on the timing of ice breakup in lakes (Palecki et al. 1986; Vavrus et al. 1996; Korhonen 2006). Robertson et al. (1992) found that an increase of 1℃ in early spring temperatures and winter temperatures resulted in ice breakup occurring 6.4 days earlier in Lake Mendota in Wisconsin. Across Canada, 83% percent of variation in lake ice breakup dates was explained by the 0°C transition date in the spring, a date that marks the beginning of temperature increases above 0°C after a period of below freezing temperatures (Shuter et al. 2013). Our results demonstrate that even at the global level, warming spring air temperatures have a prominent effect on earlier ice breakup trends.

Our regression tree also showed that ice breakup trends were of greater magnitude for lakes at lower elevations. Jensen et al. (2007) found similar results where large lakes located at lower elevations were warming the fastest across the Laurentian Great Lakes region. In this case, seven percent of variation in breakup dates was explained by elevation. Focusing on spatial trends of weather variables, locations at higher elevation were significantly associated with colder temperatures, having more snow days and greater snow depth (Jensen et al. 2007). Although incoming solar radiation increases with altitude, greater amount of snow days and snow depth at higher elevation may increase the albedo of the area and reflect the energy that would melt the snow and ice (Blumthaler et al. 1997; Jensen et al. 2007). Similarly, Sharma et al. (in press) found that deeper lakes at lower elevations were most vulnerable to losing annual winter ice cover. Therefore, as temperatures continue to warm, shallow high elevation lakes are most likely to conserve their ice seasons in the winter.

Abrupt Shifts

We detected a few shifts in average ice breakup date in the 1970s with most of these lakes located in northeastern U.S. While abrupt shifts in seasonal temperature or precipitation were not detected during this decade for these sites, shifts in ice breakup may have still occurred with linear changes in the climate. This is especially important for lakes located at lower latitudes because average temperatures are closer to the freezing point of 0°C. Slight variations in temperature may therefore tip this threshold and be reflected as shifts in ice breakup instead of a gradual change. Further, a shift was identified in 1977 for ENSO where average index values switched from positive to negative. Negative values have been associated with milder-than-average winters (Assel 1998; Assel et al. 2000) and has been shown to induce changes in lake ice in the Great Lakes region. For example, Anderson et al. (1996) found that for lakes located in Wisconsin the year following the onset of a negative ENSO phase (El Niño event) usually had the earliest ice breakup dates. Therefore, along with linear changes in air temperature, the shift to negative ENSO index values in 1977 likely induced shifts to earlier ice breakup dates in the period from 1977-2014.

We also identified the 1980s as a significant period of abrupt shifts in ice breakup dates. Specifically, 1989 was the most common shift year in this decade and these lakes were located in Sweden and Finland. Several studies have indicated the prominence of the late 1980s climatic shift, especially across the European region, which coincided with sudden changes in physical, chemical, and biological aspects of aquatic ecosystems (Alheit et al. 2005; Marty 2008; Temnerud and Weyhenmeyer 2008; Möllmann et al. 2009; North et al. 2013). For example, in 1987-1988 annual regional air temperatures in northern Switzerland abruptly increased and coincided with an abrupt increase in river temperatures (North et al. 2013). Similarly, 1987-1988 also marked a time of sudden changes in fish populations, salinity, oxygen, and water temperature in the Baltic Sea (Möllmann et al. 2009). The shifts in ice breakup date in the 1980s, may have been driven by a combination of factors. For example, we found that 42% of lakes with ice breakup shifts in 1980 and 1981 also underwent an abrupt decline in winter precipitation in 1980. This abrupt decline in winter precipitation may have led to thinner ice formation in the winter and increased exposure to solar radiation in the spring inducing sudden changes in ice breakup (Vavrus et al. 1996). In addition, all lakes with a shift year in 1989 also experienced an abrupt increase in winter air temperatures that same year or one year before. Warmer winter temperatures can limit the thickness of ice formed throughout the winter (Leppäranta 2010). Thinner ice is more easily broken in the spring as less energy and temperature increases are required to melt the ice possibly inducing earlier ice breakup.

Furthermore, the North Atlantic Oscillation switched to the positive phase in the 1980s with the highest positive values in 1983, 1989, and 1990 (Hurrell 1995). The positive phase of the North Atlantic Oscillation is associated with strong westerlies across the North Atlantic and warmer winter temperatures over northern Europe (Hurrell 1995). In addition, we found that there was also a significant positive shift in mean Arctic Oscillation index values from 1951-87 period to 1988-14. The positive phase of the Arctic Oscillation is associated with notably low pressure over the polar region and higher pressure in the middle regions around 45°N (Thompson and Wallace 2000). These pressure anomalies are associated with warmer winter and spring temperatures over northern Europe (Buermann et al. 2003). Therefore, a combination of phase switches of the North Atlantic Oscillation and Arctic Oscillation as well as significant sudden changes in seasonal air temperatures and precipitation may have contributed to earlier ice breakup dates.

Overall, 1998 and 1999 were identified as the most common years of abrupt shifts in ice breakup dates. Warmer winters were associated with the 1998 shift for American lakes. Warmer spring air temperatures corresponded to shifts in lake ice breakup dates for Finnish lakes in 1999-2000. Ice breakup dates follow the changes in spring air temperatures closely (Duguay et al. 2006), therefore sudden increases in spring air temperature likely resulted in shifts in the average ice breakup dates for these lakes. Prominent climate oscillations also underwent a phase switch in the late 1990s. Specifically, ENSO and Pacific Decadal Oscillation switched to their negative phases in 1997-1998 (Van Cleave et al. 2014). The negative phases of these climate oscillations have been associated with warmer air temperatures over the Great Lakes region (Assel 1998; Assel et al. 2000) possibly inducing sudden changes in ice breakup in study lakes located within this region.

Abrupt changes in ice dynamics have the potential to greatly affect seasonally ice-covered lakes because the under-ice conditions of the winter season are essential in maintaining the structure and function of northern lakes (Shuter et al. 2012). Shifts in ice dynamics may induce sudden changes in the lake environment leading to a cascade of consequences including changes in fish

(Helland et al. 2011; Shuter et al. 2012) and phytoplankton (Weyhenmeyer 2001) population dynamics. Some organisms may not adapt to such drastic and rapid changes in ice while others may thrive in these conditions potentially restructuring lakes and altering ecosystem function.

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TABLES

Table 1: Shift year and magnitude of shift in ice breakup date (days), temperature (°C), and precipitation (mm) identified by STARS. Also, shift year and magnitude of shift in ice breakup (days per decade) identified by the breakpoint analysis. Significant shifts with $p < 0.05$ (*).

		STARS Shift Years					STARS Difference in Mean Between Period 1 and 2					Breakpoint Analysis	
Lake	**Country**	**Ice Breakup**	**Spring Temp**	**Winter Temp**	**Spring Pre**	**Winter Pre**	**Ice Breakup**	**Spring Temp**	**Winter Temp**	**Spring Pre**	**Winter Pre**	**Ice Breakup**	**Slope of Period After Shift**
Gouta	Sweden	2001*	2002*	1989*		1989*	-9.61	0.93	2.23		25.16	1964*	-0.34
Ponkapoag Pond	United States			1997*					1.4			1972*	-0.04
Sebec	United States	1998*		1997			-5.48		0.96			1972*	-0.12
Swan	United States	1979*					-7.23					1972*	0.07
Thompson	United States	1979*		1997*		1980*	-6.75		1.22		-15.2	1972*	-0.04
China	United States	1973*		1997*		1980*	-7.67		1.03		-17.44	1972*	0.12
Rangeley	United States	1998*		1997*		1980*	-6.31		1.21		-12.11	1972*	-0.18
Mooselookmeguntic	United States	1998*		1997*		1980*	-7.2		1.21		-12.11	1975*	-0.19
Portage	United States	1979*					-5.43					1975*	-0.08
Aziscohos	United States	1998*		1997*			-4.67		1.11			1975*	-0.03
Moosehead	United States	1998		1997*			-4.89		1.01			1975*	-0.05
Pennesseewassee	United States	1980*		1997*		1980*	-5.66		1.24		-15.46	1979*	0.22
Runn	Sweden	1989*		1988*			-12.01		2.08			1988*	-0.22
Palovesi	Finland	2000*	1999*	1988*			-8.36	1.7	1.9			1988*	-0.31
Monona	United States		1985*	1998*			1.61	1.61	1.41			1997*	1.85
Geneva	United States		1985*	1987*			1.55	1.55	1.69			1997*	7.82
Kallsjon	Sweden	2000*		1988*			-11.56		2.08			1999*	0.89
Squa Pan	United States		1979*				0.76	0.76				1961*, 1969*, 1988*	-0.9, -1.1, -0.2
Erken	Sweden	1989*	1989*	1988*	1978*		-23.37	2.08	2.15	5.67		1971*, 1985*, 1993*	1.6, -4.9, -0.1

Mutusjarvi	Finland		2002*	1989*	2003*	1989*	1.68	1.68	1.93	15.12	5.28	1972*, 1988*, 1997*	0.8, 3.5, -0.5
Orsasjon	Sweden	1989*	1999*	1988*			-11.77	1.91	2.18			1988*, 1997*	3.9, -1.3
Nackten	Sweden	2002*	1999*	1988*			-12.47	1.85	2.24			1988*, 1997*	3.2, -0.8
Oulujarvi	Finland	2000*	1975*	1989*	2003*	1997*	-10.2	1.27	2.09	20.15	5.05	1988*, 1997*	2.7, -0.5
Kallavesi	Finland	2000*	1999*	1989*			-7.51	1.71	1.92			1988*, 1997*	2.6, -0.6
Muurasjarvi	Finland	1999*	1999*	1989*			-8.37	1.66	2.01			1988*, 1997*	3.4, -0.4
Pielavesi - Savia	Finland	1999*	1999*	1989*			-9.28	1.68	1.99			1988*, 1997*	2.6, -0.3
Kivijarvi - Saarenkyla	Finland	1999*	1999*	1989*			-9.62	1.66	2.01			1988*, 1997*	2.4, -0.4
Lestijarvi	Finland	1989*	1999*	1989*			-8.21	1.66	2.12			1988*, 1997*	2.6, -0.4
St. Moritz	Switzerland			1988*					0.9				
Mendota	United States	1981*	1985*	1998*			-9.26	1.61	1.41				
Auburn	United States	1980*		1997*		1980*	-7.47		1.22		-15.2		
Kezar	United States	1981*		1997*		1980*	-5.28		1.23		-12.43		
Maranacook	United States	1980*		1997*		1980*	-7.19		1.1		-14.42		
Richardson	United States	1998*		1997*			-5.69		1.18				
Sebago	United States			1997*		1980*			1.37		-16.09		
Sunapee	United States	1981*		1997*			-5.95		1.22				
Umbagog	United States	1998*		1997*			-4.6		1.18				
West Grand	United States	1998					-6.92						
Winnipesaukee	United States			1995*		1980*			1.32		-9.79		
Cobbosseecontee	United States	1980*		1997*		1980*	-8.15		1.1		-14.42		
Damariscotta	United States	1998		1997		1980*	-7.89		0.95		-19.26		
Embden Pond	United States	1979*		1997*		1980*	-4.87		1.09		-13.02		
First Connecticut	United States	1998*		1997*			-5.09		1.11				
Houghtons Pond	United States		1973*	1997*			1.06	1.06	1.4				
Jukkasjarvi	Sweden	1974*	2002*	1989*			-5.36	1.56	2.11				
Kegonsa	United States	1981*					-11.92						
Spirit	United States	1985*		1998*			-8.8		1.98				

East Okoboji	United States	1985*		1998*			-7.95		1.98		
West Okoboji	United States			1998*					1.98		
Escanaba	United States			1998	2001*				1.45	23.52	
Rock	United States	1981*	1985*	1987*			-11.78	1.7	1.82		
Shell	United States	1998		1998*			-5.13		1.52		
Big Green	United States		1985*	1987*			1.67	1.67	1.9		
Superior At Bayfield	United States	1998*		1998			-12.46		1.44		
Nasijarvi	Finland	1989*	1999*	1988*			-8.78	1.7	1.9		
Vesijarvi	Finland			1988*					1.91		
Paijanne	Finland			1988*					1.91		
Kalmarinjarvi	Finland	1999*	1999*	1989*			-7.79	1.66	1.94		
Summasjarvi	Finland	1999*	1999*	1989*			-8.98	1.67	1.91		
Hankavesi - Rautalampi	Finland	1999*	1999*	1989*			-7.78	1.69	1.9		
Yla-Kivijarvi - Jurvala	Finland	1999*		1988*			-6.68		2.01		
Lappajarvi - Halkosaari	Finland	1989*	1999*	1989*			-8.96	1.65	2.03		
Kitusjarvi	Finland	1999*	1999*	1988*			-8.49	1.68	1.91		
Kukkia - Puutikkala	Finland			1988*					1.94		
Langelmavesi - Kaivanto	Finland	1989*		1988*			-7.37		1.93		
Ala-Kivijarvi - Yla-Munni	Finland	1999*		1988*			-6.9		1.93		
Ala-Rieveli	Finland	1999*	1999*	1988*			-7.17	1.76	1.89		
Vesijarvi - Lahti	Finland			1988*					1.91		
Jaasjarvi - Hartola	Finland	1989*	1999*	1989*			-7.38	1.7	1.81		
Paajarvi - Karstula	Finland	1999*	1999*	1989*			-9.35	1.66	1.94		
Saanijarvi	Finland	1999*	1999*	1989*			-9.14	1.66	2		
Haukivesi	Finland		1999*	1989*				1.73	1.93		
Inari - Nellim	Finland	2001*	2002*	1989*	2003*	1989*	-9.9	1.68	1.95	15.62	4.07
Kilpisjarvi	Finland	2001*		1989*		1989*	-6.17		1.94		12.85
Lentua	Finland	2000*	1975*	1989*	2003*	1997*	-8.81	1.33	2.02	18.91	5.51

Oijarvi	Finland	2000*		1989*	2003*	1997*	-7.77		2.46	16.78	7.47
Ounasjarvi	Finland	2001*	2002*	1989*		1989*	-6.94	1.66	2.12		5.24
Pielinen	Finland	2000*	1999*	1989*		1997*	-7.34	1.72	1.98		6.25
Rehja	Finland	1999*	1975*	1989*	2003*	1997*	-7.67	1.26	2.05	19.7	4.71
Visuvesi	Finland	1999*		1988*			-8.53		1.92		
Simpelejarvi	Finland		1999*	1989*				1.74	1.93		
Ahtarinjarvi	Finland	1999*	1999*	1989*			-9.89	1.64	1.94		
Kuivajarvi	Finland	1989*		1988*			-9.14		1.94		
Saaksjarvi - Saakskoski	Finland	1989*		1988*			-9.82		1.96		
Mirror	United States			1995					1.11		
Mohonk	United States	1985*					-5.94				
Otsego	United States	1985*					-7.87				
Placid	United States			1995					1.11		
Schroon	United States	1981*					-5.47				
Brant	United States	1980*					-6.11				
Sylvia	United States	1973*					-8.14				
Titus	United States			1995					1.11		
Chateaguay- Lower	United States			1995					1.11		
Genegantslet	United States	1983*					-7.77				
Loon	United States					1980*					-8.93
Oneida	United States	1973*		1997*			-7.73		1.19		
Cazenovia	United States			1997*					1.07		
Black Oak	United States					1996					6.31
Nipissing	Canada	1970*, 1998*		1998*			6.51		1.25		
Big Sandy	United States			1998*					1.82		
Fountain	United States	1985*					-5.77				
Minnetonka	United States			1998*					1.5		
Diamond	United States				1975					10.67	

Rainy	United States	1998		1998*			-5.23		1.65					
Osakis	United States	1998	1976*				-5.98	1.22						
Clear	United States					1987*					-5.69			
White Bear	United States		1985*	1987*				2	1.73					
Big Stone	United States				1975*					8.62				
Bemidji	United States			1998*					1.71					
Bone	United States		1985*	1987*			2.01	2.01	2.01					
Galpin	United States			1998*					1.5					
Waconia	United States	1987*		1998*			-5.18		1.5					
Leech	United States			1998*					1.79					
Gull	United States			1998*					1.81					
Itasca	United States			1998*					1.62					
Baikal	Russia		1994*	1988*			1.67	1.67	1.8					
Medicine	United States			1998*					1.52					
Christmas	United States	1998*		1998*			-6.76		1.5					
Jessie	United States			1998*					1.79					
Washington	United States	1981*					-7.1							
Silver	United States	1999*					-11.5							
Pierz	United States			1998*					1.67					
Shamineau	United States			1998*					1.67					
Owasso	United States			1998*					1.57					
Shields	United States			1998					1.48					
Burntside	United States			1998					1.55					
Koronis	United States				1975					10.76				
Hanska	United States			1998*		1987*			2.14		-5.02			
Cedar	United States			1987*	1975*				1.76	12.4				
Bonaparte	United States											1972		0.17

Table 2: Shift year for large-scale climate oscillations index values by STARS and breakpoint analysis and magnitude of shift. Significant shifts with *p*< 0.05 (*).

	STARS		Breakpoints	
Climate Oscillation	**Shift Years**	**Change in Mean**	**Shift Years**	**Slope of Period After Shift Year**
AO	1988	0.30*	-	-
ENSO	1977	-3.93*	-	-
NAO	-	-	-	-
PDO	-	-	1980*	-0.5*
Sunspot	-	-	-	-

FIGURES

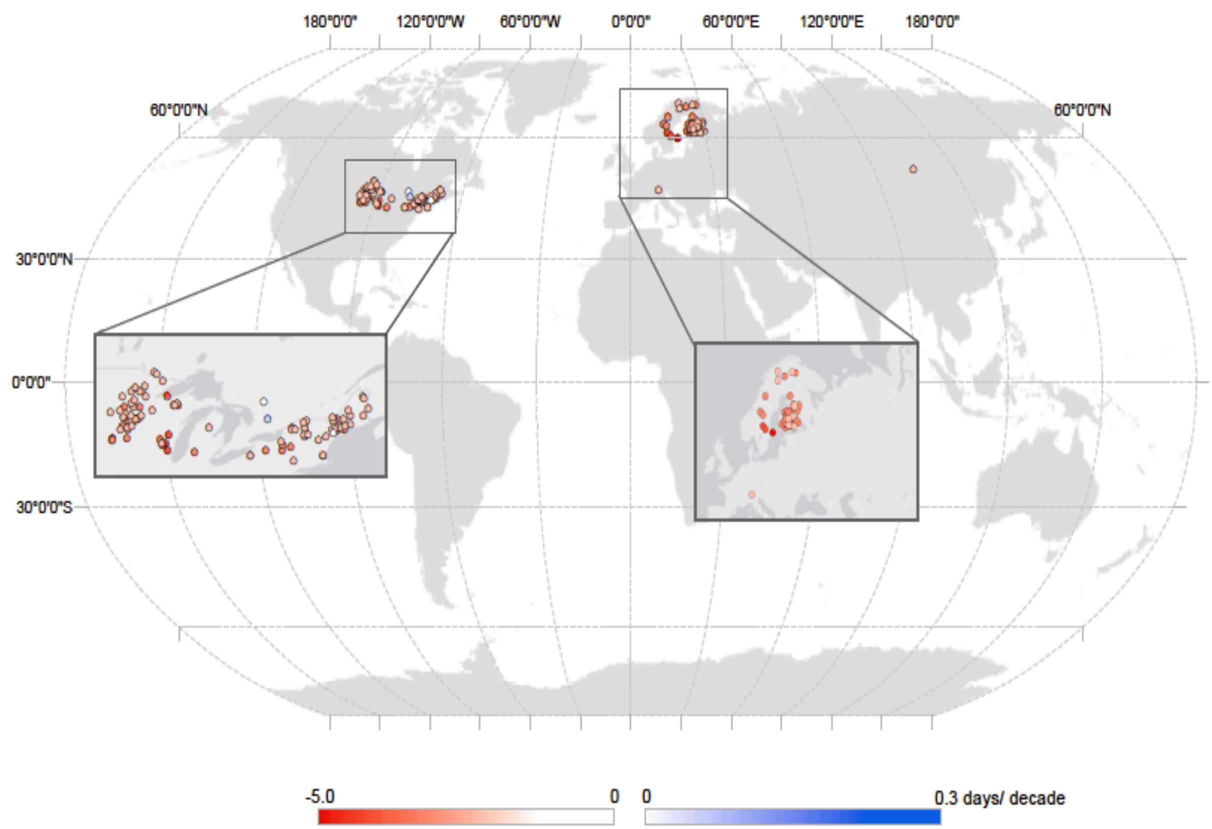

Figure 1: Trends in the timing of ice breakup dates for 152 lakes across the Northern Hemisphere calculated between 1951 and 2014 using Theil-Sen's slopes. Red shades represent warming trends while blue represents cooling trends.

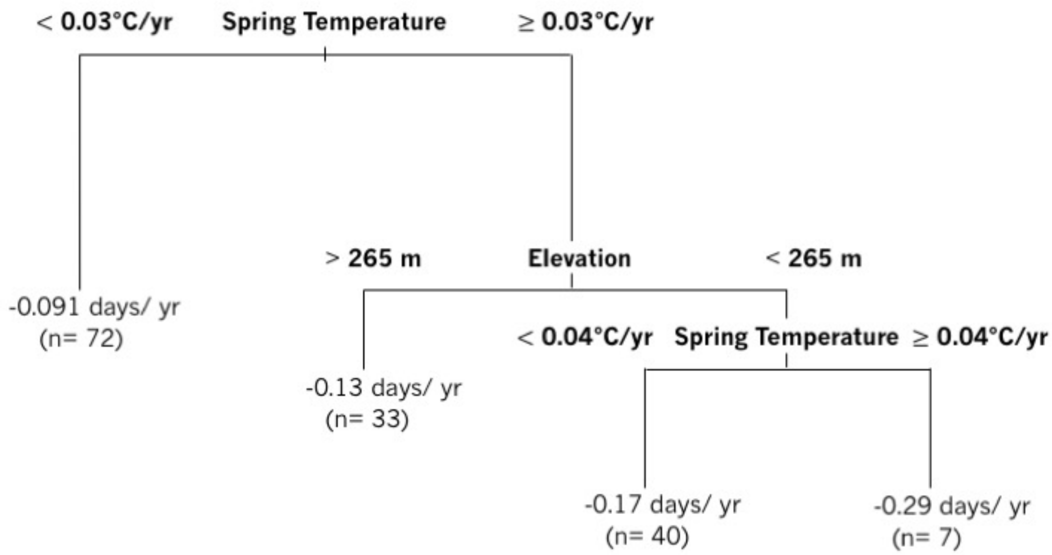

Figure 2: Drivers of global ice breakup trends from 1951-2014 identified using regression tree analysis. Trends in spring air temperatures and elevation explained 46% of the variation in ice breakup trends for 152 lakes across the Northern Hemisphere.

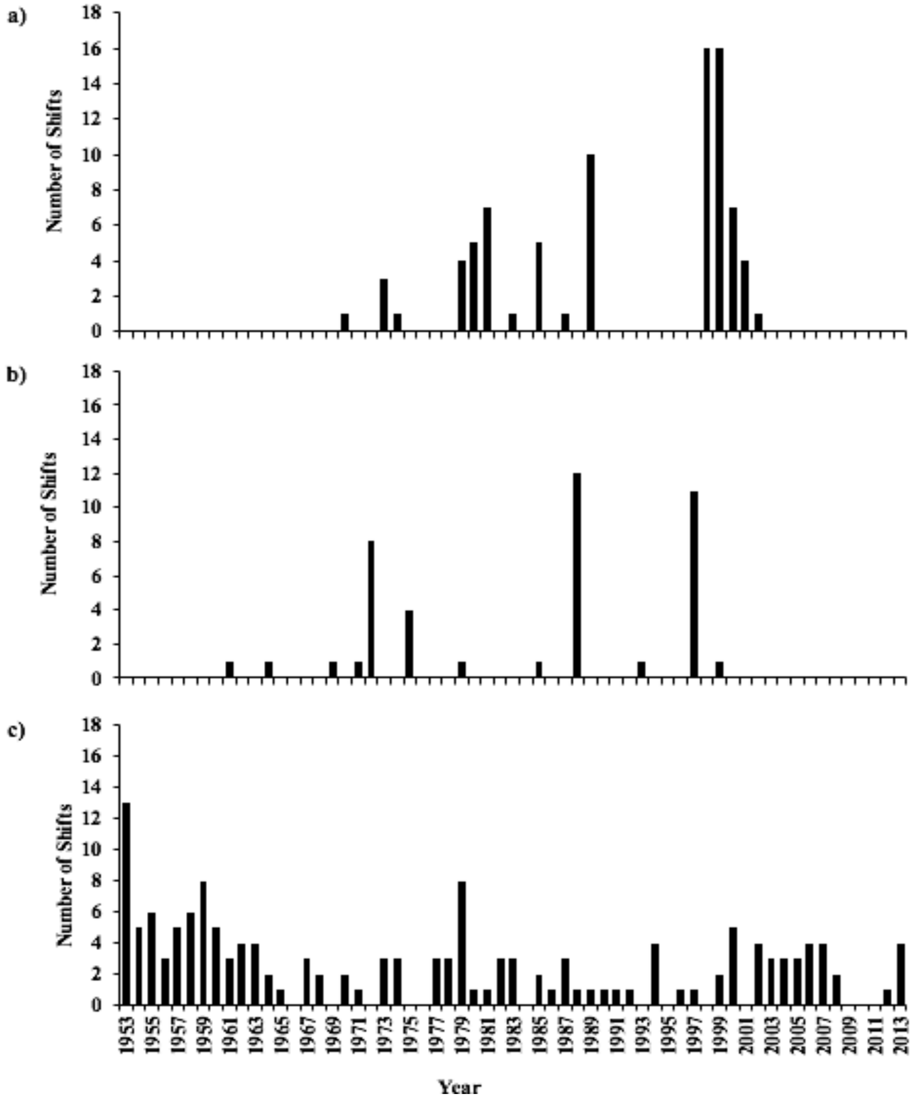

Figure 3: Number of abrupt shifts in lake ice breakup from 1951-2014 detected by a) STARS, b) breakpoint analysis, and c) segmented regression.

SUPPLEMENTARY MATERIAL

Table S1. Geographic and morphometric characteristics of 152 study lakes.

Lake	Latitude (°)	Longitude (°)	Country	Elevation (m)	Mean Depth (m)	Maximum Depth (m)	Surface Area (km^2)
Skiff	45.84	-67.50	Canada				
Head	45.05	-78.52	Canada	317			0.6
Oulujarvi	64.3	27.30	Finland	122.7	7	38	887
Kallavesi	62.83	27.77	Finland	81.8	9.7	75	316
Nasijarvi	61.53	23.75	Finland	95.4	13	61	256
Vesijarvi	61.18	25.54	Finland	81.4	6.6	40	107.6
Paijanne	61.18	25.54	Finland	78.3	15	94.5	1080
Muurasjarvi	63.47	25.34	Finland	112.2	9	35.7	21.1
Kalmarinjarvi	62.79	25.00	Finland	129.8	5.7	22	7.1
Summasjarvi	62.68	25.35	Finland	108.5	6.8	41	21.9
Pielavesi - Savia	63.2	26.67	Finland	102.3			110
Hankavesi - Rautalampi	62.62	26.83	Finland	96.1	7	49	18.2
Yla-Kivijarvi - Jurvala	60.95	27.76	Finland	75.2	5.3	27	76.4
Lappajarvi - Halkosaari	63.26	23.64	Finland	69.5	6.9	39	145.5
Kitusjarvi	62.28	24.06	Finland	116.2			0.5
Kukkia - Puutikkala	61.33	24.62	Finland	86.6			43.4
Langelmavesi - Kaivanto	61.42	24.15	Finland	84.2	6.8	59.3	133
Ala-Kivijarvi - Yla-Munni	60.94	27.51	Finland	75.1	4.8	19	91.9
Ala-Rieveli	61.34	26.20	Finland	77.8	11.3	46.9	13
Vesijarvi - Lahti	60.99	25.65	Finland	81.4	6.6	40	107.6
Jaasjarvi - Hartola	61.57	26.05	Finland	92.3	4.6	28.2	81.1
Ala-Kintaus	62.28	25.34	Finland	154.4	5.2	19	7.2
Iisvesi	62.67	27.04	Finland	97.9	17.2	34.5	164.5
Paajarvi - Karstula	62.86	24.81	Finland	144.4	3.8	14.9	29.5
Kivijarvi - Saarenkyla	63.27	25.13	Finland	130.8	8.4	43.8	154
Saanijarvi	63.4	25.58	Finland	114	2	6	12.6
Haukivesi	62.11	28.61	Finland	75.8	9.1	55	560
Inari - Nellim	68.85	28.30	Finland	118.7			1
Kilpisjarvi	69.05	20.79	Finland	472.8	19.5	57	37.3
Lentua	64.2	29.69	Finland	167.9	7.4	52	77.8
Lestijarvi	63.58	24.72	Finland	140.7	3.6	6.9	64.5
Mutusjarvi	68.94	26.81	Finland	146.2	8.5	74	50.5

Oijarvi	65.62	25.93	Finland	89.8	1.1	2.4	21.1
Ounasjarvi	68.4	23.72	Finland	286.9	6.6	31	6.9
Pielinen	63.54	29.13	Finland	93.7	10	61	894
Rehja	64.23	27.79	Finland	137.9	8.5	42	96.4
Visuvesi	62.12	23.93	Finland	96.1	7	62	46.2
Palovesi	61.86	23.91	Finland	96	9.6	61	25.5
Simpelejarvi	61.6	29.49	Finland	68.8	9.3	25.5	58.6
Ahtarinjarvi	62.76	24.05	Finland	153.5	5.2	27	39.9
Kuivajarvi	60.78	23.84	Finland	96.6	2.2	9.9	8.2
Saaksjarvi - Saakskoski	61.39	22.46	Finland	49	3.7	9.1	33.2
Baikal	51.85	104.87	Russia	450	730	1637	31924.6
Runn	60.47	15.59	Sweden	106.8	8.3	29.5	64.7
Orsasjon	61.02	14.58	Sweden	159.9	17.3	92.2	52.8
Nackten	62.91	14.57	Sweden	324	15.5	44	84.2
Kallsjon	63.39	13.39	Sweden	380.5	40.1	102.8	156.4
Gouta	65.6	15.52	Sweden	438.6	17.2	58	31.6
Jukkasjarvi	67.8	20.81	Sweden	322.4			13.5
Erken	59.85	18.58	Sweden	11.1	9	20.7	23.7
San Murezzan	46.49	9.84	Switzerland	1768	25	44	0.8
Mendota	43.1	-89.40	United States	259.1	12.8	25.3	39.4
Monona	43.05	-89.37	United States	257.5	8.2	22.5	13.2
Auburn	44.14	-70.25	United States	79.2	11	36	9.1
Kezar	44.18	-70.9	United States	114.9	10.4	47.2	10.2
Maranacook	44.33	-69.96	United States		9.1	36	6.8
Mooselookmeguntic	44.91	-70.81	United States	447.1	18.3	42.4	66
Pennesseewassee	44.23	-70.58	United States	121	5.5	14.6	3.7
Ponkapoag Pond	42.19	-71.09	United States				
Portage	46.77	-68.50	United States	185.3	3	7.6	10
Aziscohos	45.02	-71.01	United States	462.4	9.4	18.3	27.1
Richardson	44.86	-70.87	United States	441.4	13.4	32.9	20.6
Sebago	43.87	-70.57	United States	81.4	32.6	96.3	116.4
Sebec	45.29	-69.28	United States		12.8	47.2	27.5
Squa Pan	46.56	-68.31	United States	183.2	6.4	17.7	20.7
Sunapee	43.39	-72.05	United States				

Swan	44.54	-68.99	United States	61.3	10.4	26.5	5.5
Thompson	44.07	-70.48	United States	99.1	10.7	36.9	17.9
Umbagog	44.8	-71.03	United States	379.5	4.3	14.6	31.8
West Grand	45.22	-67.81	United States	90.8	11.3	39	58
Winnipesaukee	43.6	-71.33	United States				
China	44.43	-69.54	United States	59.7	8.5	25.9	15.6
Cobbosseecontee	44.28	-69.93	United States	50.6	11.3	30.5	22.4
Damariscotta	44.19	-69.48	United States	15	9.1	35	17.5
Embden Pond	44.94	-69.95	United States	126.5	18.9	54.9	6.3
First Connecticut	45.09	-71.25	United States				
Houghtons Pond	42.21	-71.09	United States				
Kegonsa	42.97	-89.25	United States	257	5.2	9.5	13
Spirit	43.46	-95.10	United States	427	5	3.2	4.3
East Okoboji	43.39	-95.10	United States	426	3	6.7	7.5
West Okoboji	43.39	-95.16	United States	426		41.5	15.7
North Twin	46.05	-89.13	United States	512.7	8.5	18.3	11.3
Escanaba	46.07	-89.58	United States	502.9	4.3	7.9	1.2
Rock	43.07	-88.92	United States	252.1	4.9	18.3	5.6
Shell	45.73	-91.90	United States	370.9	7	11	10.5
Big Green	43.8	-89.00	United States	242.9	31.7	71.9	29.7
Devils	43.42	-89.73	United States	293.5	9.1	14.3	1.5
Geneva	42.57	-88.50	United States	263.4	18.6	41.1	20.7
Maple	46.13	-89.72	United States	497.7		4.3	0.2
Superior At Bayfield	46.81	-90.81	United States	182.9	147	406	82100
Bonaparte	44.16	-75.40	United States	240	9.4	21.3	5.1
George	43.83	-73.43	United States	97		57	115.3
Mirror	44.29	-73.99	United States	565	4.3	18.3	0.5
Mohonk	41.76	-74.16	United States	380			
Otsego	42.75	-74.89	United States	363	24.9	50.6	17.1
Placid	44.3	-73.99	United States	566	15.8	42.7	8.8

Schroon	43.73	-73.81	United States	246			
Star	44.15	-75.04	United States	442	6.8	18.3	0.8
Brant	43.68	-73.74	United States	243	9.1	18.3	5.5
Sylvia	44.26	-75.41	United States	199	21.3	42.7	1.3
Titus	44.74	-74.29	United States	426			
Chateaguay (Lower)	44.84	-74.04	United States	399			
Genegantslet	42.51	-75.77	United States	454		18.3	0.4
Loon	42.48	-77.56	United States	518	5.7	13.7	0.6
Chautauqua North	42.11	-79.10	United States	399	7.8	23	28.6
Chautauqua South	42.11	-79.10	United States	399	3.5	6	24.7
Moosehead	45.65	-69.67	United States	314		75	303
Oneida	43.24	-76.14	United States	112	6.8	16.8	206.7
Cazenovia	42.93	-75.86	United States	363	7.2	14.5	4.8
Black Oak	46.16	-89.31	United States			25.9	2.4
Houghtons Pond	44.35	-84.73	United States	346.9	2.6	6.1	89.2
Gull	42.4	-85.41	United States	268.2	11.6	33.5	8.3
Big Sandy	46.75	-93.25	United States	370.8	4.9	25.6	38
Fountain	43.5	-93.50	United States	370.4		4.3	2
Minnetonka	44.87	-93.57	United States	283	6.9	34.4	58
Diamond	45.18	-94.87	United States	357.5	4.9	8.2	6.9
Rainy	48.6	-93.37	United States	337.7	9.8	49.1	893.6
Detroit	46.78	-95.93	United States	406.6	4.5	25	13
Minnewaska	45.6	-95.47	United States	346.9	5.2	9.8	31
Kabetogama	48.53	-93.08	United States	341.1	9.1	24.4	104.3
Vermillion	47.17	-93.87	United States	390.1		14.6	199
Osakis	45.87	-95.13	United States	403.3	6.1	20.4	27
Clear	44.45	-94.52	United States	310.6	1.9	2.4	1.9
White Bear	45.07	-92.98	United States	281.9	6.1	25	9.8
Big Stone	45.5	-96.50	United States	294.9	3.4	4.9	24
Bemidji	47.5	-94.83	United States	408.1	10.4	23.2	28

Bone	45.28	-92.87	United States	277.1	4.1	9.1	0.8
Galpin	44.9	-93.57	United States	287.1		4.1	0.2
Green	45.25	-94.90	United States	352.4	6.4	35.1	23.6
Waconia	44.87	-93.80	United States	293.6	4	13.4	13
Leech	47.12	-94.12	United States	395	5.6	45.7	443
Gull	46.47	-94.37	United States	363.9	9.7	24.4	30
Itasca	47.17	-95.13	United States	447.2	5.3	13.7	4
Rangeley	44.95	-70.65	United States	463		45	24.3
Madison	44.19	-93.80	United States	310	3.1	18	5.9
Hanska	44.14	-94.61	United States	309.1	1.4	4.9	7.3
Calhoun	44.94	-93.31	United States	260	9.1	27.4	1.7
Medicine	45.01	-93.42	United States	266.7	4.8	14.9	3.7
Christmas	44.90	-93.54	United States	284.1	11.3	26.5	1.1
Jessie	47.58	-93.82	United States	403.9	6.9	12.8	7
Ann	45.915	-93.41	United States	317.3	1.9	5.2	2.6
Washington	44.25	-93.87	United States	299	3.4	15.5	6.1
Silver	44.90	-94.20	United States	317	1.1	1.8	1.8
Pierz	45.96	-94.15	United States	335.9	6.1	10.4	0.8
Shamineau	46.25	-94.60	United States	387.1	5.2	15.8	5.8
Owasso	45.03	-93.12	United States	268.5	3.4	12.2	1.5
Shields	44.37	-93.44	United States	326.1	3.1	12.8	3.8
Burntside	47.93	-91.98	United States	417.9	13.7	38.4	29.6
Koronis	45.34	-94.70	United States	342	8.8	40.2	12
Howard	45.072	-94.07	United States	303.9	4.9	11.9	3
Cedar	45.27	-94.06	United States	304.5	9	32.9	3.2
Nipissing	46.27	-79.54	United States				

Table S2: Sources of large-scale climate oscillation index data.

Climate Oscillation	Source	Length of Record	Scale
Arctic Oscillation (AO)	National Oceanic and Atmospheric Administration (NOAA) http://www.esrl.noaa.gov/psd/data/climateindices/list/	1950-2018	Monthly
El Niño-Southern Oscillation index (ENSO)	National Climate Center, Australia (Bureau of Meteorology) http://www.bom.gov.au/climate/enso/#tabs=SOI	1876-2018	Monthly
North Atlantic Oscillation (NAO)	National Center for Atmospheric Research (NCAR) https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based	1865-2017	Annual
Pacific Decadal Oscillation (PDO)	Joint Institute for the Study of the Atmosphere and Ocean (JISAO) http://research.jisao.washington.edu/pdo/	1900-2018	Monthly
Total Sunspot Number (SS)	Sunspot Index and Long-term Solar Observations (SILSO) http://www.sidc.be/silso/	1700-2017	Annual

Table S3: Lake ice breakup trends analyzed for 152 study lakes using Theil-Sen's slopes.

Lake	Country	Slope (days/ decade)	*p*-value
Nipissing	Canada	0	0.9
Skiff	Canada	-0.08	0.25
Head	Canada	0.03	0.72
Saaksjarvi - Saakskoski	Finland	-0.21	0
Oijarvi	Finland	-0.21	0
Oulujarvi	Finland	-0.19	0
Pielavesi - Savia	Finland	-0.19	0
Lentua	Finland	-0.19	0
Kivijarvi - Saarenkyla	Finland	-0.18	0
Saanijarvi	Finland	-0.17	0
Simpelejarvi	Finland	-0.17	0
Lappajarvi - Halkosaari	Finland	-0.22	0
Kuivajarvi	Finland	-0.2	0
Ahtarinjarvi	Finland	-0.18	0
Lestijarvi	Finland	-0.18	0
Vesijarvi - Lahti	Finland	-0.17	0
Summasjarvi	Finland	-0.17	0
Jaasjarvi - Hartola	Finland	-0.19	0
Kukkia - Puutikkala	Finland	-0.18	0
Langelmavesi - Kaivanto	Finland	-0.18	0
Hankavesi - Rautalampi	Finland	-0.15	0
Kitusjarvi	Finland	-0.14	0
Paajarvi - Karstula	Finland	-0.17	0.01
Ala-Rieveli	Finland	-0.15	0.01
Palovesi	Finland	-0.14	0.01
Nasijarvi	Finland	-0.17	0.01
Visuvesi	Finland	-0.17	0.01
Muurasjarvi	Finland	-0.14	0.01
Ala-Kivijarvi - Yla-Munni	Finland	-0.14	0.01
Haukivesi	Finland	-0.15	0.01
Kalmarinjarvi	Finland	-0.14	0.01
Pielinen	Finland	-0.13	0.01
Ounasjarvi	Finland	-0.17	0.01
Rehja	Finland	-0.11	0.02
Yla-Kivijarvi - Jurvala	Finland	-0.12	0.02
Kallavesi	Finland	-0.11	0.03
Paijanne	Finland	-0.13	0.04

Vesijarvi	Finland	-0.12	0.04
Inari - Nellim	Finland	-0.15	0.04
Kilpisjarvi	Finland	-0.12	0.06
Iisvesi	Finland	-0.1	0.06
Mutusjarvi	Finland	-0.11	0.1
Ala-Kintaus	Finland	-0.07	0.19
Baikal	Russia	-0.05	0.46
Erken	Sweden	-0.5	0
Orsasjon	Sweden	-0.26	0
Nackten	Sweden	-0.21	0
Runn	Sweden	-0.25	0
Kallsjon	Sweden	-0.21	0
Gouta	Sweden	-0.19	0
Jukkasjarvi	Sweden	-0.12	0.06
San Murezzan	Switzerland	-0.1	0.16
Rock	United States	-0.31	0
Kegonsa	United States	-0.29	0
Superior At Bayfield	United States	-0.27	0
Spirit	United States	-0.23	0.01
Big Green	United States	-0.27	0.01
West Okoboji	United States	-0.22	0.01
Geneva	United States	-0.26	0.01
Silver	United States	-0.2	0.01
Genegantslet	United States	-0.22	0.01
Cobbosseecontee	United States	-0.17	0.02
Calhoun	United States	-0.17	0.02
Mendota	United States	-0.17	0.02
East Okoboji	United States	-0.21	0.03
White Bear	United States	-0.18	0.03
Ann	United States	-0.14	0.04
Loon	United States	-0.21	0.04
Christmas	United States	-0.14	0.04
Devils	United States	-0.18	0.05
Clear	United States	-0.18	0.05
Galpin	United States	-0.12	0.05
Auburn	United States	-0.13	0.05
Owasso	United States	-0.14	0.05
Mooselookmeguntic	United States	-0.1	0.06
Otsego	United States	-0.2	0.06
Kezar	United States	-0.1	0.06
Cazenovia	United States	-0.15	0.06

Brant	United States	-0.13	0.06
Rainy	United States	-0.12	0.07
Oneida	United States	-0.12	0.07
Portage	United States	-0.1	0.07
Fountain	United States	-0.14	0.08
Bone	United States	-0.11	0.08
Gull	United States	-0.22	0.09
Osakis	United States	-0.13	0.09
Thompson	United States	-0.11	0.1
Sylvia	United States	-0.15	0.1
North Twin	United States	-0.14	0.1
Minnetonka	United States	-0.11	0.1
Detroit	United States	-0.12	0.11
China	United States	-0.11	0.11
Sunapee	United States	-0.11	0.11
Schroon	United States	-0.11	0.11
Rangeley	United States	-0.09	0.11
Howard	United States	-0.14	0.11
Maranacook	United States	-0.12	0.12
Kabetogama	United States	-0.1	0.12
West Grand	United States	-0.1	0.13
Damariscotta	United States	-0.14	0.14
Pierz	United States	-0.1	0.14
Waconia	United States	-0.1	0.15
Swan	United States	-0.11	0.16
Washington	United States	-0.09	0.16
Black Oak	United States	-0.08	0.16
Winnipesaukee	United States	-0.1	0.17
Green	United States	-0.11	0.2
Koronis	United States	-0.09	0.21
Aziscohos	United States	-0.07	0.21
Chateaguay (Lower)	United States	-0.09	0.21
Medicine	United States	-0.1	0.21
Minnewaska	United States	-0.1	0.23
Shell	United States	-0.08	0.24
Madison	United States	-0.1	0.24
Vermilion	United States	-0.07	0.24
Sebec	United States	-0.07	0.25
Leech	United States	-0.07	0.26
Itasca	United States	-0.05	0.28
Umbagog	United States	-0.05	0.29

Pennesseewassee	United States	-0.06	0.3
Mohonk	United States	-0.11	0.31
Shields	United States	-0.08	0.32
Diamond	United States	-0.07	0.33
Burntside	United States	-0.04	0.33
Shamineau	United States	-0.08	0.34
George	United States	-0.07	0.34
Mirror	United States	-0.05	0.35
Gull	United States	-0.08	0.36
Richardson	United States	-0.05	0.37
Placid	United States	-0.06	0.37
Houghton	United States	-0.07	0.39
Monona	United States	-0.08	0.41
Embden Pond	United States	-0.04	0.42
Maple	United States	-0.06	0.42
Bonaparte	United States	-0.06	0.43
Big Stone	United States	-0.06	0.46
Star	United States	-0.05	0.46
Escanaba	United States	-0.05	0.46
Titus	United States	-0.05	0.5
Moosehead	United States	-0.05	0.5
Squa Pan	United States	-0.03	0.51
Hanska	United States	-0.04	0.53
Cedar	United States	-0.07	0.53
Bemidji	United States	-0.04	0.53
Houghtons Pond	United States	-0.08	0.55
Jessie	United States	-0.03	0.55
Ponkapoag Pond	United States	-0.08	0.56
Big Sandy	United States	-0.04	0.58
First Connecticut	United States	-0.03	0.6
Chautauqua South	United States	-0.06	0.62
Chautauqua North	United States	-0.05	0.78
Sebago	United States	0	0.92

Table S4: Shift years for lake ice breakup identified using continuous segmented regression.

Lake	Country	Shift Year
Skiff	Canada	1956, 2005
Nipissing	Canada	2013
Oulujarvi	Finland	1974
Kallavesi	Finland	1953, 1999
Nasijarvi	Finland	1956, 1958, 2004
Vesijarvi	Finland	1979
Paijanne	Finland	2000
Muurasjarvi	Finland	1978
Kalmarinjarvi	Finland	1979
Summasjarvi	Finland	1979
Pielavesi - Savia	Finland	1973
Yla-Kivijarvi - Jurvala	Finland	1955
Kitusjarvi	Finland	1988
Kukkia - Puutikkala	Finland	1955, 1994, 1997, 1999
Ala-Rieveli	Finland	1979
Jaasjarvi - Hartola	Finland	1987
Iisvesi	Finland	1955
Paajarvi - Karstula	Finland	1981
Saanijarvi	Finland	1978
Haukivesi	Finland	1958
Inari - Nellim	Finland	1955, 1978
Kilpisjarvi	Finland	1977, 1980, 2000, 2002
Lentua	Finland	2012
Mutusjarvi	Finland	1967, 2000, 2002, 2005, 1994, 1996, 2002
Palovesi	Finland	1979
Simpelejarvi	Finland	1955
Ahtarinjarvi	Finland	1979
Kuivajarvi	Finland	1957, 1961, 1979
Saaksjarvi - Saakskoski	Finland	1979
Runn	Sweden	1982
Nackten	Sweden	1985
Kallsjon	Sweden	1958, 1965, 1967, 1970
San Murezzan	Switzerland	1982
Monona	United States	1954, 1959
Kezar	United States	1974, 1977

Maranacook	United States	1961
Mooselookmeguntic	United States	1968, 2013
Pennesseewassee	United States	1974, 1983
Aziscohos	United States	1970
Richardson	United States	1994
Sebec	United States	1964
Squa Pan	United States	1963, 1967, 1973, 1985, 2002, 2007
Sunapee	United States	1962, 1990
Thompson	United States	1960
Umbagog	United States	1968
West Grand	United States	1959
Winnipesaukee	United States	1963
China	United States	1963, 1977
Cobbosseecontee	United States	1960, 2013
Damariscotta	United States	1960
Embden Pond	United States	1971, 1987, 1992
First Connecticut	United States	1962
Houghtons Pond	United States	1964, 1989, 2007
Kegonsa	United States	1973, 1986
Spirit	United States	1954
East Okoboji	United States	1953, 2006
West Okoboji	United States	1954
North Twin	United States	1953
Shell	United States	1953, 1991, 1994, 2000
Geneva	United States	1987, 2000
Maple	United States	1982
Superior At Bayfield	United States	2013
Bonaparte	United States	1960
George	United States	1962
Otsego	United States	1959
Schroon	United States	1959
Star	United States	1958
Sylvia	United States	1959
Titus	United States	1956
Chateaguay (Lower)	United States	1958
Genegantslet	United States	1959
Loon	United States	1957, 1983, 2004
Chautauqua South	United States	2003

Moosehead	United States	1963
Cazenovia	United States	1957
Black Oak	United States	1954
Houghton	United States	1983
Gull	United States	1959
Fountain	United States	1955, 2005
Minnetonka	United States	1954
Diamond	United States	1953
Vermilion	United States	2003
Osakis	United States	2007
Clear	United States	1953
White Bear	United States	1953, 2004
Big Stone	United States	2008
Galpin	United States	1957, 2003
Green	United States	2006
Waconia	United States	1953
Gull	United States	2008
Rangeley	United States	1962
Medicine	United States	2007
Silver	United States	1953
Pierz	United States	1953, 2006
Owasso	United States	1953
Shields	United States	1958, 1960
Madison	United States	1957, 1961
Hanska	United States	1953, 1959, 2006
Howard	United States	1953

GENERAL CONCLUSION

Changes in the timing of phenological events has been an indicator of climate dynamics for decades as the initiation of these events are induced by seasonal changes in climate (Magnuson et al. 2000; Walther et al. 2002; Primack et al. 2009; Benson et al. 2012). Specifically, changes in lake ice phenology is of particular interest because of its ecological, economic, and cultural significance to mid- and high latitude regions (Wang et al. 2012; Sharma et al. 2016). Ice phenology trends have indicated climate warming over the last few decades across the Northern Hemisphere with later freeze up, earlier breakup, and shorter ice duration (Magnuson et al. 2000). For this thesis we focused on the timing of lake ice breakup as it represents changes in the climate during the winter and spring season. We empirically quantified trends in ice breakup further into the 2010s compared to previous studies and identified the key drivers of these changes. We first analyzed trends for small north temperate lakes in the Great Lakes Region, and predicted the timing of ice breakup under future climate change scenarios in 2050 and 2070. For the second chapter, we expanded the spatial scale and assessed trends across the Northern Hemisphere. However, because there are known periods of enhanced climatic changes (IPCC 2013; Reid et al. 2016) and phase switches of prominent climate oscillations since the 1980s (Hurrell 1995), we also tested for abrupt shifts in the timing of ice breakup.

Climate warming in the Great Lakes region has been evident with ice breakup occurring earlier in these lakes over the last few decades (Jensen et al. 2007). We assessed seven lakes in Northern Wisconsin and two lakes in Southern Ontario and found that ice breakup occurred earlier by five days between 1982 and 2015 (Hewitt et al. 2018). All of these trends were nonsignificant, however, this may be a product of the short time period assessed and the high interannual variation of the times series. The primary drivers of ice breakup changes were combined mean of March and April temperatures, winter air temperature, and precipitation. Furthermore, under future climate scenarios we projected that lake ice breakup will occur earlier by 10 days in 2050 and 13 days by 2070 likely inducing a shorter ice season in the Great Lakes region (Hewitt et al. 2018).

Negative ice breakup trends are not only found regionally, but are also consistently found at the global scale (Magnuson et al. 2000; Benson et al. 2012). We examined 152 lakes across the Northern Hemisphere and found negative trends for 97% of these lakes between 1951 and 2014; 43% of these trends were significant. The rate of change in lake ice breakup ranged from 5 days per decade earlier to 0.3 days per decade later with an average of 1.19 days per decade earlier. Globally, both climatic and geographical variables have driven these changes in ice breakup. Lakes at lower elevations undergoing increases in spring air temperature exhibited the fastest rate of change in the direction of earlier ice breakup. Furthermore, we found abrupt shifts in ice breakup dates for 59% of the study lakes starting in the 1970s to the early 2000s with mean ice breakup date occurring earlier in the period after the shift year. Interestingly, several of these shifts in ice breakup occurred alongside abrupt shifts in spring and winter air temperature, winter precipitation, and climate oscillation index values such as the Arctic Oscillation and El Niño-Southern Oscillation.

The shortening of the lake ice season partially induced by earlier ice breakup is expected to affect seasonally ice-covered lake ecosystems as well as the economies and cultures dependent on ice cover. Future climate warming and changes in precipitation will likely exacerbate these effects as ice breakup becomes even earlier by the end of the 21st century. While rapid linear changes in ice breakup will likely prevent proper adaptation of lake biota, abrupt changes will present even more challenges as it will allow even less time to adapt to the new environment. Ice cover is important for maintaining the components of mid- and high latitude lake ecosystems, therefore current and future changes in climate will continue to threaten the existence of these ecosystems as they are today.

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