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Winter limnology in a changing world

**Key Points:**
- Trends in lake ice phenology are faster than shown in previous studies when including most recent data
- Significant breakpoints in ice phenology are associated with changing weather and climate
- Warmer air temperature explains most of the variation in later ice-on and earlier ice-off dates, in addition to shorter ice duration

**Supporting Information:**
Supporting Information may be found in the online version of this article.

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# Climate Change is Contributing to Faster Rates of Lake Ice Loss in Lakes Around the Northern Hemisphere

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**Abstract** Lake ice phenology has been recorded for decades, providing us with long-term records to investigate the impact of climate change in lakes since the Industrial Revolution. Here, we examine the trends and drivers of 18 lakes across the Northern Hemisphere, with 156–204 years of data, starting in the 1810s. We show that: (a) trends in ice phenology are faster than found by previous studies. Ice-on is 11 days later per century, ice-off is 9 days earlier per century, and ice cover duration is 19 days shorter per century; (b) there are significant breakpoints in the 1850s, 1870s, mid-1890s, and mid-1990s, after which trends in ice phenology are even faster, and associated with changing weather and climate; and (c) local air temperatures explain the most variation in ice phenology, on average 36.5%, followed by progressive climate change explaining around 17.5% on average, with teleconnection patterns explaining the least variation. Our findings support the assertion that broad-scale climatic changes have led to more rapid lake ice loss in lakes distributed across the Northern Hemisphere, with potential widespread impacts on critical ecosystem services that lake ice provides.

**Plain Language Summary** Lake ice cover has been recorded for decades and has been shown to be sensitive to climatic change. Hence, we can use lake ice cover to investigate how climate change has affected lakes over the past ~200 years. In this study, we explore 18 lakes across the Northern Hemisphere, with ice cover data starting in the 1810s. We find that ice-on is increasingly later, ice-off is earlier, and ice duration is shorter, with all these changes occurring at faster rates than previous studies showed. We discovered breakpoints in lake ice cover, after which the trends in lake ice phenology become faster than the trends before the breakpoints, and these breakpoints are related to changing local air temperatures and teleconnection patterns. Finally, we show that local air temperature influences the timing of ice-on and ice-off the most, followed by long-term climate change and teleconnection patterns. Hence, we provide support for the statement that climate change has contributed to faster trends in ice phenology, with likely negative impacts on the important ecosystem services provided by lakes.

## 1. Introduction

Lake ice cover is an important environmental resource both ecologically and culturally. Ice cover on lakes affects under-ice ecological processes with ramifications extending throughout the year (Hampton et al., 2017). For example, ice breakup dates are associated with increased greenhouse gas emissions from accumulated carbon dioxide under the ice (Ducharme-Riel et al., 2015; Striegl et al., 2001), in addition to lake mixing, thermal stratification, primary production, and trophic interactions (Caldwell, Chandra, Feher, et al., 2020; Gerten & Adrian, 2000; Katz et al., 2015; Salonen et al., 2009; Woolway et al., 2020). Culturally, ice breakup signifies the start of the spring in many regions. Importantly, lake ice is also a sensitive indicator of climate as ice phenology (the timing of ice-on, ice-off, and ice duration) is closely associated with local air temperatures (Benson et al., 2012; Magnuson et al., 2000; Weyhenmeyer et al., 2011).

Lake ice has been studied extensively, in part because of the availability of open-access long-term ice records across the Northern Hemisphere (Benson et al., 2012; Magnuson et al., 2000; Sharma et al., 2019; Weyhenmeyer et al., 2011). These records were often started because of the importance of ice to the local culture. For example, the ice formation date in Lake Suwa, Japan, has been recorded for centuries by Shinto priests because ice formation signified the voyage of God in the winter (Arakawa, 1954; Sharma et al., 2016). From the hundreds of ice records collected around the Northern Hemisphere, we have learned that over the past century, ice-on has been delayed, ice-off has been occurring earlier, and ice duration has been shorter (Benson et al., 2012; Magnuson et al., 2000; Woolway et al., 2020). Further, each of these studies successively

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shows that trends in ice phenology are faster than the trends found in preceding studies. For example, with an additional 24 years of ice phenology data from the data set used in the publication by Magnuson et al. (2000) and Woolway et al. (2020) showed that the same lakes monitored by Magnuson et al. (2000) had lost an additional week in lake ice cover in the recent 24-year period (Woolway et al., 2020). These patterns are generally consistent across Canada, the United States, Finland, Sweden (Duguay et al., 2006; Hodgkins, 2013; Korhonen, 2006; Sharma et al., 2013; Weyhenmeyer et al., 2005), and the Northern Hemisphere (Benson et al., 2012; Magnuson et al., 2000; Sharma & Magnuson, 2014; Warne et al., 2020).

A framework to understand the influence of climate variability on ecosystem responses was proposed by Schmitz et al. (2003). Several questions were proposed to understand climatic variability including: (a) is there an increasing or decreasing linear trend? (b) is there a discontinuity or abrupt change in the mean? and (c) are there oscillations or periodicities within the time series? (Schmitz et al., 2003). Here, we evaluate these questions using ice phenology data visually collected by humans starting before the Second Industrial Revolution. Multiple drivers have been associated with ice phenology, including local weather conditions, teleconnection patterns, sunspot cycles, solar radiation, precipitation, volcanic eruptions, and climate change (Caldwell, Chandra, Feher, et al., 2020; Livingstone, 2000, 2003; Schmidt et al., 2019; Sharma & Magnuson, 2014). Warming air temperature has often been shown to be the strongest predictor of changes in lake ice phenology across the Northern Hemisphere (Filazzola et al., 2020; Korhonen, 2006; Sharma et al., 2019; Weyhenmeyer et al., 2004), although solar radiation, snow cover, and wind are also important drivers of lake ice phenology (Brown & Duguay, 2010; Caldwell, Chandra, Albright, et al., 2020; Filazzola et al., 2020; Kirillin et al., 2012). In fact, solar radiation is one of the primary drivers of lake ice thaw and is affected in part by the transparency of ice, albedo of the snow layer on the ice, and latitude (Caldwell, Chandra, Albright, et al., 2020; Kirillin et al., 2012). Along the shoreline at shallow depths, solar radiation inputs and strong wind events commence the process of ice melt (Kirillin et al., 2012). Teleconnection patterns, including the El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), are also often associated with lake ice phenology, although they explain less variation than local weather (Blenckner et al., 2004; Bonsal et al., 2006; Livingstone, 2000; Robertson et al., 2000; Sharma et al., 2013). However, very few studies test all these aforementioned categories in tandem with lake ice phenology records beginning before the second Industrial Revolution to quantify the relative importance of each driver on lake ice phenology.

Interestingly, the lake ice records we use in this study cover the timespan of the recent three Industrial Revolutions. For example, the 1760s signified the start of the first Industrial Revolution which continued until the 1840s (Nef, 1934). During this era, manufacturing processes shifted from handmade items to machines, with the use of water and steam-powered machines (Heaton, 1956). The world also experienced significant growth in population (Martinez, 2005) and significant warming trends (Abram et al., 2016). By 1850, the first commercial oil refinery plant was launched in Scotland (Nersesian, 2014) and the Siemens-Martins process was implemented, a regenerative furnace used to make steel and utilized throughout the 20th century (Barraclough, 1990). These events led to the Second Industrial Revolution which saw a massive increase in steel production and use, application of the Siemens-Martins furnace, the opening of the first Transcontinental railroad followed by extensive rail and telegraph lines expansion, and high economic growth rates (Ambrose, 2000; Birch, 2015; Fogel, 1963; Vatter et al., 1995). As a result, people could travel more easily and extensively, as well as transport energy fuels to locations where they could be processed for use in machines. Unsurprisingly, global carbon emissions in the atmosphere started increasing during that era (Friedlingstein et al., 2019). The next important period was the Digital revolution, also known as the Third Industrial Revolution, starting in the 1970s. Computers were developed and implemented extensively in every aspect of life, such as mobile phones, personal computers, to large-scale supercomputers, with the most important innovation being the birth of the Internet (Debjani, 2014; Hauben & Cerf, 2004; Schoenherr, 2004). Interestingly throughout the industrial revolutions, people living or working on the shoreline of our study lakes continued to measure ice phenology in a similar way year after year.

In this study, we used long-term records of ice phenology (timing of ice-on, ice-off, and ice-duration) for 18 lakes across North America and Europe to ask three questions: (a) Are there trends in ice phenology related to warming; (b) Are there abrupt changes in lake ice phenology trends; and (c) What are the relative roles of climate change, local air temperatures, teleconnection patterns, and volcanic activity on ice phenology?

Here, we expand on previous studies (Benson et al., 2012; Lopez et al., 2019; Magnuson et al., 2000; Sharma & Magnuson, 2014) by extending the time series to the present-day and by examining trends, shifts, and drivers of ice-on, ice-off, and ice duration for lakes across the Northern Hemisphere. More specifically, we first determined if there is a trend in ice phenology for these lakes associated with a warming climate. Next, we identified significant breakpoints in our time series and determined if they coincided with broader weather and climatic events. Finally, we quantified the relative role of climate change, local air temperatures, teleconnection patterns, and volcanic activity on ice phenology.

## 2. Methods

### 2.1. Data Acquisition

We obtained ice phenology records for 18 lakes (13 lakes in North America and 5 lakes in Europe) from the National Snow and Ice Data Center (Benson et al., 2012) and updated to 2019 for each lake when possible by data providers who are continually updating ice phenology records for their lake(s). Each of these time series begins before the 1860s and ranges from 156 to 204 years long (Table S1). The earliest data record begins in 1815 (Lake Champlain) and the latest begins in 1859 (Lake Runn). Although there are hundreds of lakes recording ice phenology in the Lake and River Ice Phenology data set, we chose only lakes with records beginning before the 1860s and with fewer than 15% missing years. These lakes ranged from 0 to 21 years of missing ice phenology data, with an average of 3 missing years. During a year when an ice phenology record was missing, we used the average date over the entire time series so that the imputed value would not have influence on subsequent analyses. We compared several methods to impute the missing values, such as the mean of the whole time series, the mean of a 10-year window surrounding the gap year, linear interpolations, spline interpolations, and quadratic interpolations. Comparing the root mean squared error, the mean of the whole time series proved the best fit in filling in the gap years.

We also obtained information on local weather and teleconnection patterns. For each lake, we acquired monthly mean air temperature from the University of East Anglia's Climatic Research Unit (CRU TS4.02) from 1901 to 2018 (Harris et al., 2020), which are measured at a 2-m level above ground. To calculate fall air temperatures, we averaged the monthly air temperature data for September, October, and November. Similarly, we averaged the monthly air temperatures from December, January, and February for winter air temperatures, and March, April, and May for spring air temperatures. Note that CRU air temperatures are on a 0.5° grid and at grid cells larger than the lakes studied here. Further, we obtained time series of teleconnection patterns from the National Oceanic and Atmospheric Administration (NOAA), such as the NAO from 1864 to 2018, Southern Oscillation Index (SOI) from 1874 to 2018, ENSO, reconstructed from paleo records derived from the North America Drought Atlas (NADA) (Li et al., 2011) from 1815 to 2002, Arctic Oscillation (AO) from 1950 to 2018, Atlantic Multidecadal Oscillation (AMO) from 1856 to 2018, Pacific Decadal Oscillation (PDO) from 1900 to 2017, and the solar sunspot cycle from 1818 to 2018. Finally, data on sulfate aerosols released from volcanic eruptions (NH: Northern Hemisphere and SH: Southern Hemisphere) were acquired from paleo data (ice cores) (Gao et al., 2008) from 1815 to 2018.

### 2.2. Data Analysis

#### 2.2.1. Are There Trends in Ice Phenology Related to Warming?

We used a simple linear regression on each lake using the Python package *statsmodels* (Seabold & Perktold, 2010) to investigate whether lake ice phenology is changing in response to warming over time. We calculated the slopes on the dates of ice-on, ice-off, and ice duration over the time series. Linear regression was used to model the linear relationship between response variables (ice-on, ice-off, or ice duration) and the independent variable, which was the year in our data. We compared the trends obtained from the linear regression models with the trend calculated using the non-parametric Thiel-Sen estimator from the trend package in R (Pohlbert, 2020). The Sen's slope estimates the median of slopes of all lines through all possible pairs of points and is an efficient non-parametric approach to fit linear trends, insensitive to outliers, and provides a more conservative slope estimate compared to traditional linear regressions (McNeil, 2002).

#### 2.2.2. Are There Abrupt Changes in Lake Ice Phenology Trends?

To identify significant breakpoint years and to determine if there is a step-change in slopes before and after a breakpoint, we used a piecewise regression for ice-on dates, ice-off dates, and duration of ice cover for each of our lakes. The package "segmented" itself needs the breakpoints to be given in advance. To eliminate bias, we first used the package "SiZer" (Sonderegger, 2020), which is able to determine the best possible breakpoint from the data, without a specified breakpoint. We then used the breakpoint given by "SiZer" to input into the package "segmented" to confirm that the breakpoint year indeed fits in a piecewise linear regression. We also used "segmented" (Muggeo, 2003) because it allows us to obtain the AIC of the model, whereas "SiZer" does not, so that we could compare the linear and piecewise regression models. We selected the most parsimonious model between piecewise regression models and simple linear regressions using the Akaike Information Criterion (AIC) (Anderson & Burnham, 2004). The model with the lowest AIC value was selected as the most parsimonious model. In cases where the difference in AIC values between models was less than 2, we chose the simpler linear regression model.

#### 2.2.3. What is the Relative Role of Climate Change, Air Temperatures, Teleconnection Patterns, and Volcanic Activity on Ice Phenology?

##### *2.2.3.1. Correlations*

To assess the relationships between our variables, we performed Spearman correlations between all variables, namely ice phenology (ice-on dates, ice-off dates, and duration of ice cover), air temperature (fall temperature, winter temperature, and spring temperature), teleconnection patterns (PDO, QBO, SOI, NINO3, ENSO, AO, AMO, NAO, and Daily Solar Sunspot), and volcanic activity (NH and SH). We chose the more conservative non-parametric Spearman correlation rather than the Pearson correlation as some of our variables could be spatially and temporally dependent.

We used variation partitioning to quantify the relative proportion of variation in ice phenology explained by a climate warming trend, local air temperatures, and teleconnection patterns. Briefly, variation partitioning is calculated as the ratio of the sums of squared deviations of our explanatory variable to the total sums of squared deviations from the linear regression model (Legendre, 2007). We excluded volcanic activity from the variation partitioning as it did not explain any variation with ice phenology. First, we ran simple linear regressions, using *statsmodels*, with year on ice phenology data to quantify the trend that could be represented by a climate warming trend. If the linear regression was significant, the response variable was detrended to remove the linear trend in the response data as the linear trend indicated temporal structure within our data that was acting at a longer interval than the extent of the observations (Sharma & Magnuson, 2014). We used the residuals from the linear regression models as response variables for subsequent analysis. Next, we ran multiple linear regression models on the detrended ice phenology data, with air temperatures (local summer temperatures, fall temperatures, winter temperatures, and spring temperatures) and teleconnection patterns (which included NAO, SOI, ENSO, AO, AMO, PDO, and solar sunspot cycles) as explanatory variables. Finally, we ran a variation partitioning analysis using the varpart function from the "vegan" package (Oksanen et al., 2019) to quantify the relative amount of variation explained by climate change, air temperatures, and teleconnection patterns.

## 3. Results

### 3.1. Trends in Ice Phenology Related to Warming

On average, ice-on was 11 days later per century, ice-off was 9 days earlier per century, and ice duration was 19 days shorter per century (Figure 1), with all linear regression models being significant ($p < 0.05$). Sen's slopes indicated similar warming trends and revealed that ice-on was 10 days later per century, ice-off was 9 days earlier per century, and ice duration was 18 days shorter per century ($p < 0.05$) (Figure S1). Moving forward, we will focus on linear warming trends derived from least-squares regression slopes to facilitate comparisons with earlier studies (i.e., Benson et al., 2012; Magnuson et al., 2000).

For lakes considered in our study, Lake Champlain, situated along the border of Canada and the United States, was losing lake ice at the fastest rate. Lake Champlain froze 21 days later per century, with 29% of

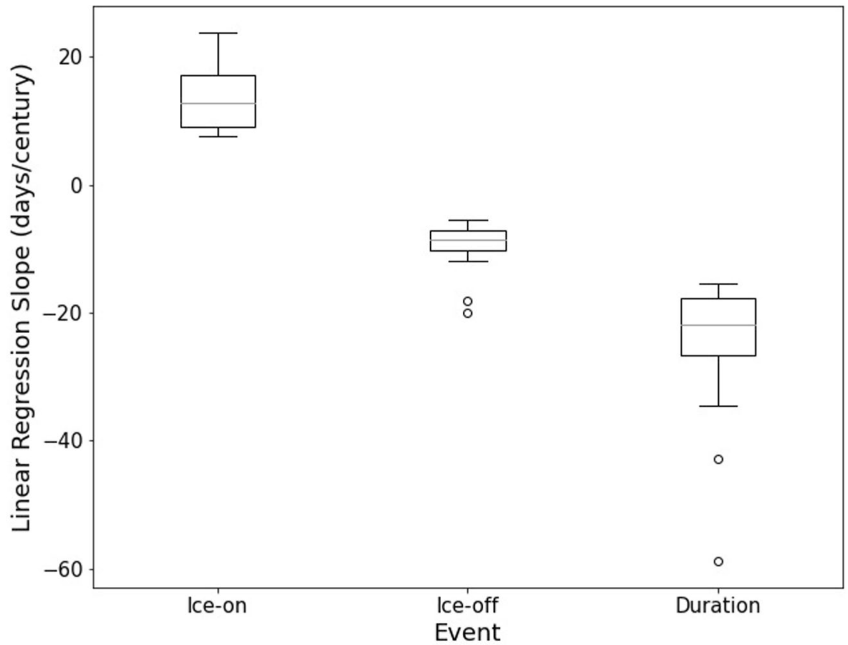


**Figure 1.** Trends in ice-on, ice-off, and ice duration for 18 lakes in the Northern Hemisphere over the last two centuries. On average, ice-on was delayed by 11 days, ice-off was earlier by 9 days, and these lakes experienced 19 fewer days of seasonal ice cover. The gray bars within the boxplots represent the median of the distributions.

the variation explained by the linear regression model ($p < 0.001$) and had the highest frequency of ice-free years (43 ice-free years over the past 204 years). Lake Superior, the largest freshwater lake by surface area and also situated in Canada and the United States, also showed rapid ice loss. Bayfield Bay in Lake Superior froze 19 days later per century ($R^2 = 26\%$; $p < 0.001$), thawed 18 days earlier per century ($R^2 = 33\%$; $p < 0.001$), and had 37 days per century fewer days with ice cover ($R^2 = 37\%$; $p < 0.001$). Bayfield Bay in Lake Superior lost an average of 61 days of ice cover over the last 164 years. This represents a drastic 2 months of ice cover loss. We observed similar results with Grand Traverse Bay, in Lake Michigan, United States. The trend in freeze dates was 17 later per century ($R^2 = 15\%$; $p < 0.001$), thaw was 17 days earlier per century ($R^2 = 14\%$; $p < 0.001$), and ice cover duration was 26 days shorter per century ($R^2 = 15\%$; $p < 0.001$). On average, 42 days of ice cover were lost in Grand Traverse Bay over the last 167 years. Lake Nasijarvi, in Finland, is one of the fastest-warming lakes in Europe. It froze 10 days later per century ($R^2 = 10\%$; $p < 0.001$), thawed 10 days earlier per century ($R^2 = 27\%$; $p < 0.001$) and had a shorter ice duration of 20 days per century ($R^2 = 22\%$; $p < 0.001$). Lake Nasijarvi lost 38 days of ice cover on average over the last 186 years (Table S1).

### 3.2. Abrupt Changes in Lake Ice Phenology Trends

We compared linear regression and piecewise regression models to identify the model which best describes the ice loss trend for ice-on, ice-off, and ice duration. In two-thirds of the cases, linear regression models (67%) were the most parsimonious model as they had lower AIC values compared to piecewise regression models. However, we generally observed that the fastest-warming lakes had significant piecewise regression models. Of the significant piecewise regression models, there were significant breakpoints in the 1850s for Lake Kallavesi (Finland) and Grand Traverse Bay (United States), 1870s for Lake Superior (United States/Canada), Grand Traverse Bay, and Lake Champlain (United States/Canada), and mid-1980s to mid-1990s for the Scandinavian lakes (Oulujarvi, Run, Nasijarvi, and Kallavesi) (Figure 2). For the 11 other lakes (two-thirds of the cases in which the linear trend was more parsimonious), the AIC values for piecewise regression and linear regressions were similar. Although we chose the simpler linear regression model when AIC values were similar, we note that the breakpoints for the other 11 lakes occurred within similar time periods. For example, there was a significant breakpoint in ice-on and ice cover duration in the 1970s, and late 1890s for ice-off in Lake Cazenovia. Lake Cobbosseecontee and Lake Damariscotta had break points in

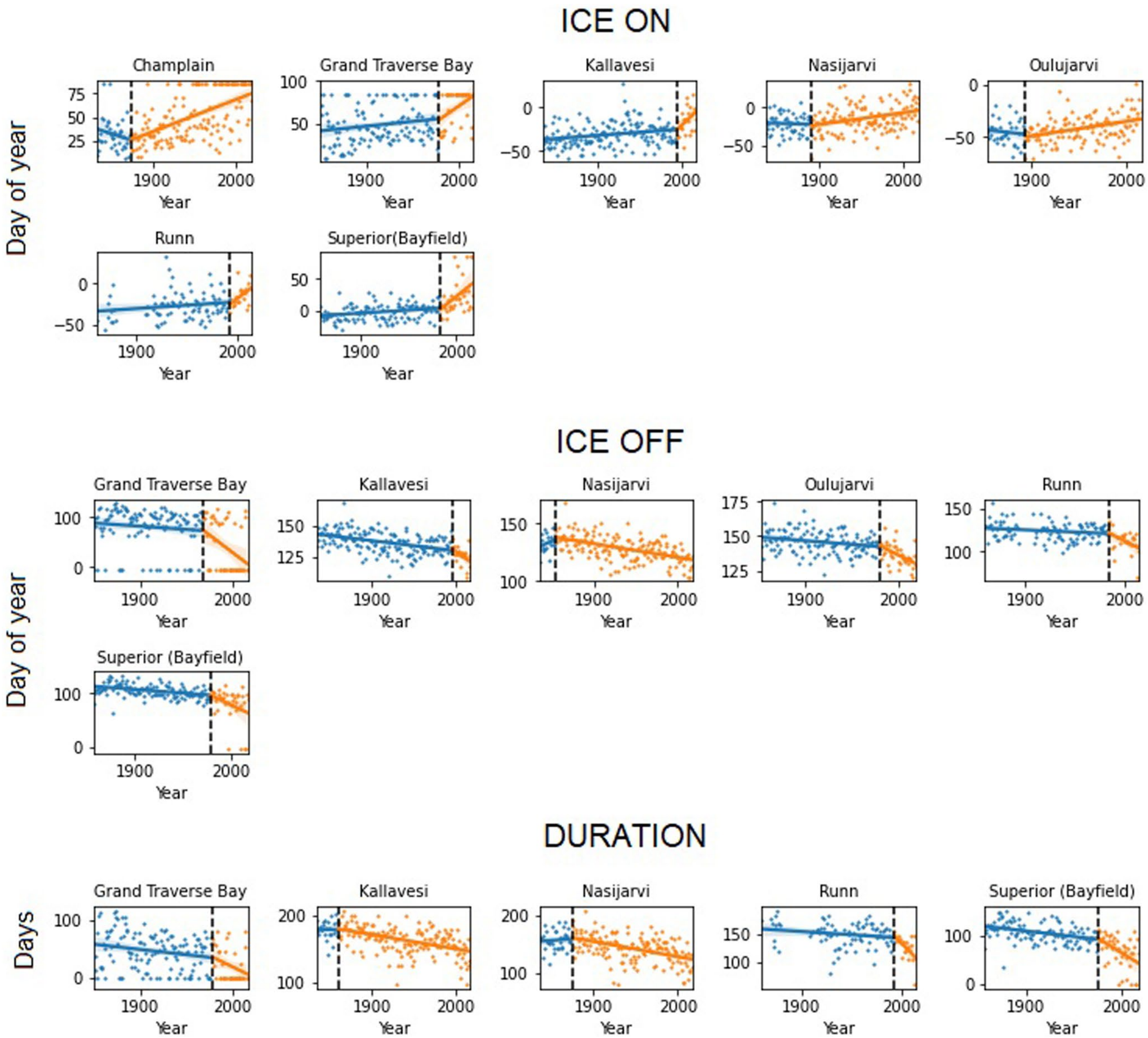


**Figure 2.** Abrupt changes in trends in lake ice phenology. Only lakes with significant breakpoints are shown. The dotted lines indicate the years at which a significant breakpoint was identified. Points in blue represent ice phenology values before the breakpoint with the blue line showing the linear trend in ice phenology in the years from the start of the time series to the year before the breakpoint. The orange points represent ice phenology values after the significant breakpoint. The orange line shows the warming trend over the years following the breakpoint to the end of the time series.

the late 1960s. Kempenfelt showed a breakpoint in the late 1970s for ice-on, late 1910s for ice-off, and 1900s for ice cover duration. Lakes Moosehead and Oneida had their breakpoints in the 1900s. For Lakes Mendota and Monona, we observed a breakpoint in the early 1980s for ice cover. For Lake Mendota, the breakpoint for ice-on was in the late 1880s and ice-off was 1970s, while for Lake Monona, ice-on breakpoint was in the late 1870s and 2000s for ice-off.

### 3.3. Relative Role of Climate Change, Local Air Temperatures, Teleconnection Patterns, and Volcanic Activity on Ice Phenology

Spearman correlations revealed that ice-on, ice-off, and ice duration were significantly correlated with SOI, NINO3, AO, winter temperature, spring temperature, and fall temperature (Figure 3). The strong-

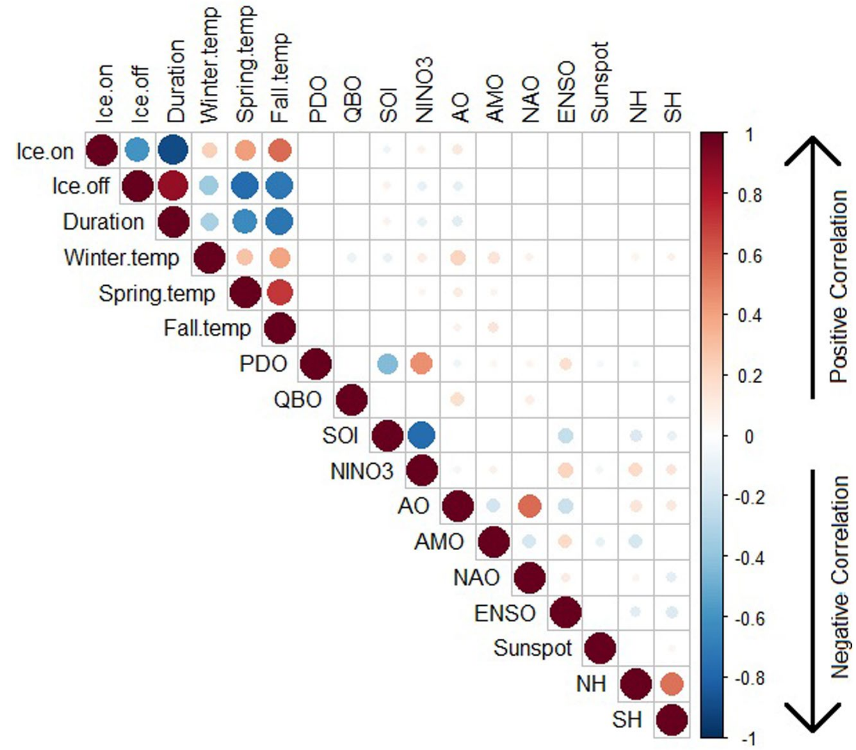


**Figure 3.** Spearman correlations between ice-on dates, ice-off dates, ice cover duration, teleconnection patterns, local weather, and sulfate aerosols injections from volcanic eruptions. The size (area) of the dots and the intensity of the colors are proportional to the correlation strength of the variables. Warm colors represent positive correlations, whereas negative correlations are associated with cooler colors. Empty slots represent non-significant correlations. PDO, Pacific Decadal Oscillation; QBO, Quasi-Biennial Oscillation; SOI, Southern Oscillation Index; NINO3, El Nino Southern Oscillation Region 3; AO, Arctic Oscillation; AMO, Atlantic Multidecadal Oscillation; NAO, North Atlantic Oscillation; Winter temp, Winter temperature; Spring temp, Spring Temperature; Fall temp, Fall temperature; ENSO, El Nino Southern Oscillation; Sunspot, Solar sunspot cycle; NH and SH (Sulfate aerosols injections from volcanic activity in the Northern Hemisphere [NH], and Southern Hemisphere [SH]).

est correlations were observed with temperature. Fall ($r$ = 0.56), spring ($r$ = 0.42), and winter ($r$ = 0.23) air temperatures were all positively correlated with ice-on date. Similar to correlations for ice-on dates, the strongest significant correlations for ice-off dates were with temperature. Ice-off dates were negatively correlated with spring temperature ($r$ = −0.77), fall temperature ($r$ = −0.71), and winter temperature ($r$ = −0.36). The length of ice-cover duration was negatively correlated with fall temperature ($r$ = −0.72), spring temperature ($r$ = −0.63), and winter temperature ($r$ = −0.32). Of the teleconnection patterns, SOI, NINO3, and AO were weakly correlated with ice phenology (Figure 3). All remaining variables were insignificant. However, air temperatures were significantly correlated with teleconnection patterns and volcanic activity. For example, winter temperature was significantly related to QBO ($r$ = 0.08), SOI ($r$ = 0.09), NINO3 ($r$ = 0.1), AO ($r$ = 0.21), AMO ($r$ = 0.14), and NAO ($r$ = 0.07), and volcanic activity (NH, $r$ = 0.06).

The multiple regression models for ice-on for our study lakes explained on average 52.7% of the variation and ranged from 24.7% to 71.3% variation (Figure 4). Local air temperatures were the most important variable and explained 32.7% of the variation in ice-on dates. The climate warming trend explained 14.5% of the variation, and teleconnection patterns explained 5.6% of the variation (Figure 4). For ice-off dates, the multiple regression models explained 60.0% of the variation on average but ranged from 41.6% to 79.7%. 36.9% of the variation was explained by air temperature, 17.8% by climate change, and 5.4% by teleconnection patterns (Figure 4). Finally, for ice duration, the average proportion of variation explained by our models was 67.4% on average and ranged from 50.7% to 82.6%. More specifically, 40.2% of the variation was explained by air temperatures, 20.5% explained by the climate warming trend, and 7.8% explained by teleconnection patterns (Figure 4). Emissions associated with volcanic eruptions were not significant in our models.

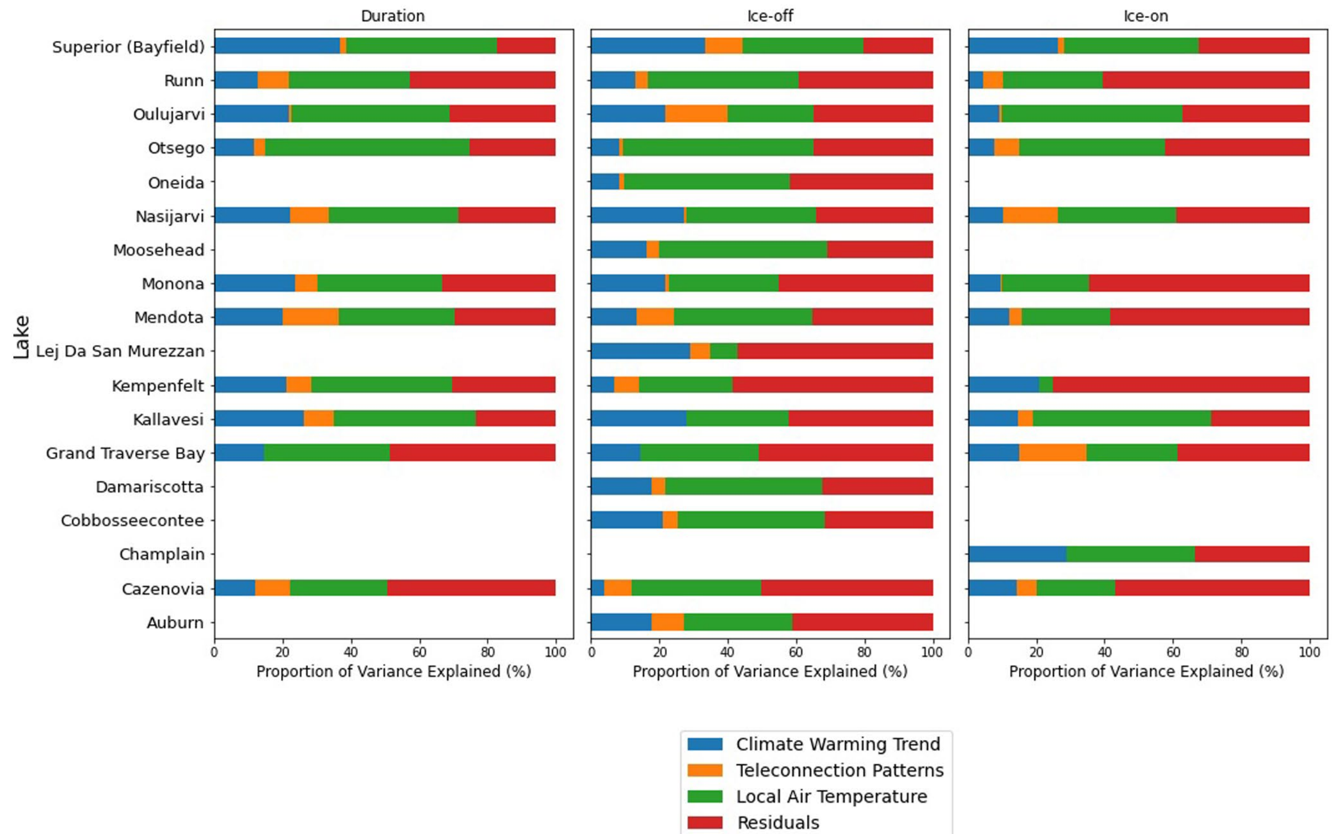


**Figure 4.** Proportion of variation explained by multiple linear regression models for ice-on, ice-off, and ice duration. The different colors represent the proportion of variation explained by the linear climate warming trend (blue), teleconnection patterns (orange), local air temperatures (green), or residuals (red) of the models. White spaces indicate models that could not be created because data were unavailable.

## 4. Discussion

The lake ice records from 18 lakes around North America and Europe revealed patterns consistent with climate change and climate variability over the past 156–204 years. First, we observed that our study lakes were freezing on average 11 days later per century, and thawing 9 days earlier per century, with 19 days of shorter seasonal ice cover per century. For example, Bayfield Bay in Lake Superior has experienced 2 months less ice cover since its ice record began in 1857. Second, we discerned abrupt changes in ice phenology after which the rates of lake ice loss (earlier thaw, later freeze, and shorter ice duration) were faster. We observed significant breakpoints for Lake Kallavesi and Grand Traverse Bay in the 1850s, 1870s for Lake Superior, Grand Traverse Bay, and Lake Champlain, and mid-1980s to mid-1990s for our Scandinavian lakes. Finally, a combination of a climate warming trend, local air temperatures, and teleconnection patterns explained variation in ice phenology. However, the most important driver of ice phenology for all lakes was warmer air temperatures.

### 4.1. Trends in Ice Phenology Related to Warming

All of our study lakes experienced significant trends in ice phenology over the past two centuries with ice-on delayed by 11 days, ice-off earlier by 9 days, and ice duration shorter by 19 days on average per century. Although previous studies have shown similar patterns (Benson et al., 2012; Magnuson et al., 2000; Woolway et al., 2020), the rates of ice loss that we observed are significantly faster with the inclusion of an additional 15–25 years of data. For example, Magnuson et al. (2000) observed ice-on was delayed by 5.8 days and ice-off was earlier by 6.5 days per century for a similar set of lakes, but with a final observation date of 1995. The rates of ice loss found in this study suggest that rates of ice loss are almost 1.5 times faster by adding an additional 24 years of data compared to previous studies. This faster rate of warming may be attributed to warmer air temperatures (Lopez et al., 2019) and a higher prevalence of extreme events in recent decades, such as ice-free years (Filazzola et al., 2020). In future studies, we recommend evaluating and estimating the drivers and mechanisms for the recent acceleration in warming.

### 4.2. Abrupt Changes in Lake Ice Phenology Trends

We found that the lakes with the fastest trends in lake ice loss were also the lakes experiencing abrupt changes in warming, often leading to even faster rates of warming after a significant breakpoint. Lake Kallavesi and Grand Traverse Bay showed the first significant breakpoints in the 1850s coinciding with an increase in warming during that decade (GISTEMP team, 2020). In the 1870s, three lakes (Lake Superior, Grand Traverse Bay, and Lake Champlain) experienced significant breakpoints once again coinciding with an increase in air temperature within the United States that decade (GISTEMP team, 2020).

We detected significant breakpoints in the mid-1980s to the mid-1990s in the Scandinavian lakes (Oulujarvi, Runn, Nasijarvi, and Kallavesi). Nordic regions showed a noticeable increase in air temperatures starting in the early 1980s (Tveito et al., 2000), which may have been associated with the breakpoints observed in these lakes. Further, in the late 1980s in Scandinavia, there was a shift to warmer air temperatures and lower precipitation levels (Lopez et al., 2019). At the same time, the North Atlantic Oscillation and Arctic Oscillation shifted to positive phases corresponding to warmer winters in the region (Lopez et al., 2019). These climatic shifts correlated with changes in the physical, chemical, and biological features of aquatic ecosystems, such as increasing water temperatures, water discharge, and phytoplankton biomass (Alheit et al., 2005; Lopez et al., 2019; North et al., 2013; Temnerud & Weyhenmeyer, 2008).

### 4.3. Relative Role of Climate Change, Local Air Temperatures, Teleconnection Patterns, and Volcanic Activity on Ice Phenology

Climate change, warmer local air temperatures, and teleconnection patterns, such as QBO, SOI, and NAO, explained on average 59.8% of the variation in ice phenology but ranged from 24.7% to 82.6%. We found that, on average, local air temperatures explained the most variation 36.5% (3.69%–59.6%), and the linear trend associated with climate warming explained 17.5% (3.9%–36.9%) of the variation. Teleconnection patterns explained 5.9% (0%–19.6%) of the variation. 40.2% of the variation on average remained unexplained and could be attributed to local weather conditions, such as solar radiation inputs, wind, snow cover; lake and landscape characteristics, such as lake depth, elevation, and fetch (Brown & Duguay, 2010; Sharma et al., 2020). Our findings are an improvement over Sharma and Magnuson's (2014) study, who were unable to include local air temperatures within their analysis and relied on statistical decomposition (i.e., Moran Eigenvector Maps) to explain variation that could be attributed to local weather or teleconnection patterns. Because of their use of spectral decomposition, they attributed 26% of the variation to teleconnection patterns, although they did not find a strong association with the indices representing teleconnection patterns (Sharma & Magnuson, 2014) similar to a study only focusing on Wisconsin lakes (Sharma et al., 2013). Interestingly, emissions associated with volcanic eruptions were not a significant variable in our models. Livingstone (1997) suggested that increasing volcanic eruptions might be correlated with a change in trends of ice phenology, with more volcanic eruptions being correlated with earlier ice-off dates in the subsequent years. However, we did not find any evidence that volcanic eruptions played a role in the changing trend of lake ice. We did not identify significant changes in ice phenology in lakes near major volcanic eruptions, such as Mount St. Helens in 1980. There were significant breakpoints in Scandinavian lakes but our data do not suggest any influence from volcanic eruptions in these regions, with no significant increase in sulfate aerosols following that period.

Our findings align with earlier studies suggesting that air temperatures generally explain the most variation in ice phenology (Adrian & Hintze, 2000; Arp et al., 2016; Assel & Robertson, 1995; Benson et al., 2012; Duguay et al., 2006; Korhonen, 2006; Lopez et al., 2019; Palecki & Barry, 1986; Sharma et al., 2013, 2016; Vavrus et al., 1996; Weyhenmeyer et al., 2011). We note that regardless of the lake and the event (freeze, thaw, or ice duration), local air temperatures explained most of the variation, explaining as high as 59.6% of the variation for lake ice duration in Lake Otsego. Warmer local air temperatures are associated with delayed ice formation or earlier ice breakup as the occurrence of ice is highly dependent upon the 0°C isotherm (Brown & Duguay, 2010; Sharma et al., 2020). In years when temperatures are anomalously warm, these lakes may not freeze at all (Filazzola et al., 2020). The linear trend representing climate warming, in this case, explained the second most variation, with an average of 17.5%. Relative to an earlier study (Sharma & Magnuson, 2014), the linear trend explained 2.7% additional variation, suggesting that the recent rapid rates of warming are having a greater impact on lakes. Similar to the case of air temperatures which always explained the most variation, the linear trend explained the second most variation in almost all of our lakes and events (except for ice-on events in Lake Nasijarvi), emphasizing the widespread impact of climate change (Magnuson et al., 2000). For example, the linear trend explained 36.9% of the variation in Bayfield Bay at Lake Superior, the highest of all our models. However, this was still dwarfed by weather, which explained 36.5% of the variation in this model. Hence, a combination of air temperature and climate warming affects lake ice phenology the most, with an average of 51% of the variation explained by both drivers.

On average, teleconnection patterns explained an average of 5.9% of the variation, but as high as 19.6% for Lake Nasijarvi ice-off dates. Previous studies which had suggested that teleconnection patterns explained more of the variation compared to this study (George, 2007; Livingstone, 2000; Robertson et al., 2000; Sharma & Magnuson, 2014; Sharma et al., 2013), may have not detrended the ice phenology time series before analysis, excluded local weather variables, or used spectral decomposition to estimate the influence of oscillatory dynamics which over-estimated the role of teleconnection patterns on lake ice phenology. Regardless, teleconnection patterns do explain some variation in ice phenology. For example, El Nino events have been associated with later ice breakup in North America (Bonsal et al., 2006; Livingstone, 2000; Robertson et al., 2000) and later ice formation in Japan (Sharma et al., 2016). In the Great Lakes region, positive NAO and El Nino events have been associated with less ice cover, whereas negative NAO and La Nina events have been associated with more ice cover (Bai et al., 2012). Solar sunspot cycles were not significant in our models and this may be owing to our lakes being at latitudes and elevations where solar sunspots have a decreased effects on these lakes (Baldwin & Dunkerton, 2005; Gleisner & Thejll, 2003; van Loon & Shea, 2000). We suggest that teleconnection patterns are affecting lake ice events through their impacts on local weather, such as air temperatures, snow cover, wind events, and solar radiation inputs (Brown & Duguay, 2010; Sharma et al., 2020).

### 4.4. Implications of Changes in Ice Phenology

Our study shows that ice-on is later, ice-off is earlier, and lakes are experiencing fewer days of ice cover than ever before. The loss of lake ice has major ecosystem, cultural, and socioeconomic ramifications. Later ice-on dates are associated with an increase in hypolimnetic oxygen concentrations because of changes in the lake mixing regime (Flaim et al., 2020). With shorter ice cover, $CO_2$ emissions by lakes during lake ice melting occurs earlier and may possibly emit more $CO_2$ into the atmosphere (Karlsson et al., 2013). Earlier ice breakup contributes to earlier thermal stratification, a longer open-water season for warming, and warmer water temperatures (Austin & Colman, 2007; Caldwell, Chandra, Feher, et al., 2020; Lathrop et al., 2019). Earlier ice-off also is associated with increased evaporation rates (Arp et al., 2016; Wang et al., 2018), and potentially decreasing water levels (Woolway et al., 2020). The most adverse effects would be the unpredictable change in lake mixing regimes and shifts in phytoplankton biomass, food web dynamics, greenhouse gas emissions, and community composition (Hampton et al., 2017; Saros et al., 2019; Woolway et al., 2020). For example, in Castle Lake, earlier ice breakup has contributed to warmer water temperatures, increased zoobenthic production in the littoral-benthic habitat, and ultimately decreased fitness in the brook trout population (Caldwell, Chandra, Feher, et al., 2020).

Lake ice loss is expected to directly influence millions of people within this century (Sharma et al., 2019). Winter sports, for example, outdoor ice skating, is expected to decline with warming winters (Brammer et al., 2015; Dickau et al., 2020; Knoll et al., 2019), which would result in detrimental ramifications on physical activity, social cohesion, social identity, and a sense of place (Knoll et al., 2019; Liu et al., 2017; Magnuson & Lathrop, 2014; Visser & Petersen, 2009). Ice fishing, prominent in North America, Europe, and Asia, is an activity that reels in many sports enthusiasts and commercial fishermen. These provide significant socioeconomic capital and food provisioning for the surrounding communities. For example, ice fishing accounts for more than 40% of the annual fish harvest from Lake Peipsi in Estonia (Orru et al., 2014), whereas a small community in Minnesota may earn $1 million in revenue with one ice fishing tournament (Knoll et al., 2019). We highlight the importance of preserving ice cover by mitigating greenhouse gas emissions before permanently losing this invaluable environmental resource (Sharma et al., 2021).

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

The time series of freeze-thaw cycles for the 18 lakes used in this study are available at Imrit, Mohammad; Sharma, Sapna (2020): Long term lake ice phenology records for 18 lakes across the Northern Hemisphere. Figshare. Data set. https://doi.org/10.6084/m9.figshare.13158209.v2. Climate data were obtained from the Climatic Research Unit part of the University of East Anglia (CRU TS4.04; http://www.cru.uea.ac.uk/).

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