Climatic Change (2023) 176:119
https://doi.org/10.1007/s10584-023-03596-z

Projecting climate change impacts on ice phenology across Midwestern and Northeastern United States lakes

Kevin Blagrave[1] · Sapna Sharma[1]

Received: 20 September 2022 / Accepted: 6 August 2023 / Published online: 19 August 2023

Abstract
Lakes are sensitive indicators of climate change as freshwater requires temperatures below 0 °C to freeze. Here, we used 34-year records for 74 lakes distributed across the Midwestern and Northeastern United States to ask the following: (i) Which physical factors affect lake ice phenology in the Northern United States?; (ii) Can an empirical statistical modelling approach be used to effectively predict ice phenology across the morphologically diverse lakes of the Northern United States?; and (iii) How much ice is forecasted to be lost in response to climate change? We find that our study lakes require 19 days with air temperatures below 0 °C to freeze, ranging from 4 days for small lakes to 53 days for larger lakes. To thaw, lakes require 22 days with air temperatures above 0 °C, ranging from 8 to 33 days. We find that 64% of the variation in ice-on dates is explained by air temperatures, and the remaining 36% of variation is explained by lake morphology, primarily mean depth. For ice-off dates, 80–90% of the variation is explained by air temperatures. By the end of the century in response to climate change, these lakes may lose 43 days of ice cover, although ranging from 12 days of less ice cover to no ice cover at all. Understanding the drivers of variability in ice phenology for lakes within regions found to be highly sensitive to climate change will promote our understanding of ice cover and ice loss, and also the widespread ecological ramifications associated with ice loss.

Keywords Climate change · Climate change projections · Ice cover · Ice phenology · Lake morphometry · USA

1 Introduction

Perhaps one of the most striking effects of climate change on lakes is the loss of ice cover in recent decades (Benson et al. 2012; Sharma et al. 2021b). Lake ice cover is a sensitive indicator of climate, such that ice phenology (timing of ice-on and ice-off) is closely related to air temperatures (Palecki and Barry 1986; Brown and Duguay 2010; Nõges and

✉ Kevin Blagrave
kevin.blagrave@gmail.com

Sapna Sharma
sharma11@yorku.ca

[1] Department of Biology, York University, 4700 Keele Street, Toronto, ON, Canada

Nõges 2014; Sharma et al. 2020). Recorded observations of ice cover date back centuries before the start of the Industrial Revolution (Magnuson et al. 2000; Sharma et al. 2016) because of the cultural and socioeconomic importance of lake ice to refrigeration, transportation, recreation, religious traditions, and ice fishing (Magnuson and Lathrop 2014; Knoll et al. 2019). These ice records indicate that in response to warming climates, ice-on is later, ice-off is earlier, and ice duration is increasingly shorter (Magnuson et al. 2000; Duguay et al. 2006; Benson et al. 2012; Grant et al. 2021; Sharma et al. 2021b). Moreover, in recent decades, some lakes have reported an increased frequency of extreme events and may not reliably freeze every winter (Sharma et al. 2019, 2021a; Filazzola et al. 2020). Although we have a good understanding of how local weather and global climate interact to influence lake ice phenology trends (e.g., Robertson et al. 2000; Livingstone and Dokulil 2001; Ghanbari et al. 2009; Sharma et al. 2013; Imrit and Sharma 2021), we do not yet fully understand the interaction of climate and physical lake characteristics across a geographic landscape.

Air temperature is widely recognized as one of the most important climatic drivers of ice phenology, particularly in the weeks to months preceding ice-on and ice-off dates (Palecki and Barry 1986; Weyhenmeyer et al. 2004, 2011; Ghanbari et al. 2009; Sharma et al. 2013; Surdu et al. 2015; Lopez et al. 2019; Imrit and Sharma 2021). Ice-on and ice-off dates generally correlate with the 0 °C isotherm, as lakes tend to freeze when winter air temperatures are consistently below freezing and lakes tend to thaw when spring air temperatures rise above 0 °C (Duguay et al. 2006; Arp et al. 2013; Shuter et al. 2013). For example, in 55 Alaskan lakes, the timing of the 0 °C isotherm and lake area explained 80% of the variation in ice-off dates (Arp et al. 2013). Lakes in more southern regions of North America, Finland, and Sweden tend to experience the greatest rates of warming (Korhonen 2006; Jensen et al. 2007; Weyhenmeyer et al. 2011), in part because they are located in a region where air temperatures hover around 0 °C (Weyhenmeyer et al. 2004). Accumulated freezing degree days and accumulated positive degree days have been shown to reliably predict ice thickness and ice-off date, although the association with ice-on date is less clear (Karetnikov et al. 2017).

Lake characteristics further influence the timing of ice-on and ice-off and may even have an influence on whether the lake freezes or not. For example, even in regions with relatively colder climates, deep and circular lakes found at lower elevations are vulnerable to intermittent winter ice cover (Sharma et al. 2019) and forecasted to be most sensitive to permanent ice loss under future scenarios of climate warming (Sharma et al. 2021a). Deeper lakes take longer to cool in the fall and require persistently cool temperatures below 0 °C prior to freezing (Brown and Duguay 2010; Jeffries et al. 2012; Kirillin et al. 2012; Nõges and Nõges 2014; Magee and Wu 2017). More circular lakes tend to have longer stretches of open water which increase their sensitivity to wind action that breaks the initial skim of ice that forms on a lake (Williams et al. 2004; Jeffries et al. 2012; Magee and Wu 2017). By contrast, shallow lakes with more complex shorelines are more likely to freeze earlier, such as in Madison, WI, where the shallow Lake Wingra not only froze earlier but was forecasted to remain ice-covered even under an extreme warming scenario of 10 °C (Magee and Wu 2017). However, it is still unclear how sensitive ice phenology is for lakes of different sizes and depths across a broader landscape.

A combination of surface energy balance, air temperatures, precipitation, cloud cover, solar radiation, lake morphology, wind, and hydrology influences the timing of lake ice formation (Brown and Duguay 2010). For example, warmer air temperatures can delay ice formation, early snowfall can advance ice formation, and clouds can both trap longwave radiation and reflect solar energy away from the ice (Brown and Duguay

2010). Typically, the initial skim of ice will form at night under cold and calm conditions, and heat is lost from the lake surface through outgoing longwave radiation and latent heat flux (Vavrus et al. 1996). Shallow lakes will typically form this thin layer of ice before deeper lakes, as is especially evident across a geographic landscape in warmer winters (Marszelewski and Pius 2019). As lakes require substantially cool, dry, and low wind conditions to promote evaporative heat loss, this process takes longer in larger and deeper lakes (Woolway et al. 2020).

Climate typically governs the timing of ice-off dates, including air temperature, precipitation, elevation, solar angle, and large-scale climatic oscillations (Sharma et al. 2013; Shuter et al. 2013; Hewitt et al. 2018; Imrit and Sharma 2021), with lake characteristics contributing to a lesser extent (Shuter et al. 2013). Across a multitude of studies, air temperatures are often found to explain the most variation in ice-off dates (e.g., Palecki and Barry 1986; Assel and Robertson 1995; Vavrus et al. 1996; Livingstone 2000; Korhonen 2006; Weyhenmeyer et al. 2011; Benson et al. 2012; Imrit and Sharma 2021). When assessing the variation in ice-off dates explained by air temperatures, Sharma et al. (2013) found that summarizing air temperatures on a seasonal scale sufficiently encapsulated the variation explained by daily air temperatures. However, cooler air temperatures even in the month or week prior to ice-off can delay the ice breakup date. For example, in southern Finnish lakes, Palecki and Barry (1986) found a strong correlation between air temperatures 5 to 10 days prior to ice breakup and ice-off date. Furthermore, process-based models have illustrated the importance of precipitation and solar radiation to ice-off dates (Leppäranta 2010; Brown and Duguay 2010; Kirillin et al. 2012; Leppäranta and Wen 2022). Snow can affect lake ice formation and thickness in complex ways depending on when and how it falls (Jeffries et al. 2005; Brown and Duguay 2010; Sharma et al. 2020). For example, ice-off dates can be later because snow can act as an insulating layer on the ice and the high albedo of thick snowpack can lead to a longer snowmelt process, a process which is influenced by both air temperatures and solar radiation absorption (Jeffries et al. 2005; Kouraev et al. 2007; Bernhardt et al. 2012; Nõges and Nõges 2014; Preston et al. 2016; Sadro et al. 2018). Even in warm winters, lakes with high snowfall and a thick snowpack can have delayed ice-off dates because of the high albedo of snow cover (Nõges and Nõges 2014). However, for some lakes, a low, dense snowpack in a cold winter can produce thicker black ice which takes longer to melt and delay ice-off dates (Kouraev et al. 2007). Snowfall in the form of wet snow or "rain-on-snow" events can alter the quality and strength of ice formed under the lake (Block et al. 2019; Weyhenmeyer et al. 2022) and also affect the timing of ice-off dates.

Although previous studies have examined the mechanistic response of ice cover in a single lake or a few lakes of varying sizes within a region (e.g., Austin and Colman 2007; Bernhardt et al. 2012; Nõges and Nõges 2014; Magee and Wu 2017), we aim to fill a knowledge gap by forecasting the sensitivity of lakes with varying lake morphologies across a large landscape across Midwestern and Northeastern United States using the most recent climate change scenarios. Specifically, we ask the following: (i) Which physical factors affect lake ice phenology in the Northern United States?; (ii) Can an empirical statistical modelling approach be used to effectively predict ice phenology across the morphologically diverse lakes of the Northern United States?; and (iii) What are the forecasted changes in ice-on and ice-off dates by the end of the century based on a suite of climate change scenarios? We fill a knowledge gap in the lake ice phenology literature by providing predictive models to estimate ice-on and ice-off dates for lakes of varying sizes across the Midwestern and Northeastern United States.

2 Methods

2.1 Data acquisition

Lake ice phenology records were accessed from the National Snow and Ice Data Center (NSIDC) Lake and River Ice Phenology Analysis Group (LIAG) and the Minnesota Department of Natural Resources. Data were updated to 2018–2019 by contacting data contributors. For this study, we selected 100 lakes distributed in the USA that had both ice-on and ice-off dates recorded and at least 30 years of continuous or near-continuous time series without extensive multi-year gaps in observations. The exact definitions of ice-on and ice-off were not available for all 100 lakes in this study, but ice monitors generally maintain a consistent definition throughout a given time series (Sharma et al. 2022). However, these definitions may differ between lakes (Sharma et al. 2022). For example, ice-on for Lakes Mendota and Monona in Wisconsin is defined as the date when the lake is 50% ice-covered and ice-off is defined as the date when the lake is 50% ice-free. On the other hand, for Lake Geneva, also in Wisconsin, ice-on is defined as the date when the lake has been frozen for 2 days and ice-off as the date when the lake is free of ice, aside from small ice plates (Sharma et al. 2022). Next, we extracted lake morphology characteristics for each lake from HydroLAKES, such as lake surface area, mean depth, volume, elevation, shoreline length, and shoreline development (a measure of shoreline complexity calculated as the ratio of the shoreline length to the length of the circumference of a circle equal to the lake area, such that a circular lake has a value of 1, and lakes with more complex shorelines have larger values of shoreline development; Messager et al. 2016). Twenty-six of the 100 lakes did not have a geographic match with HydroLAKES either because they were smaller than the 10 ha threshold imposed by the database or did not cover the area of the entire lake (i.e., was only a bay or basin or a larger lake or a merger of 2 lakes). Thus, 74 lakes were retained for subsequent analysis (Fig. 1).

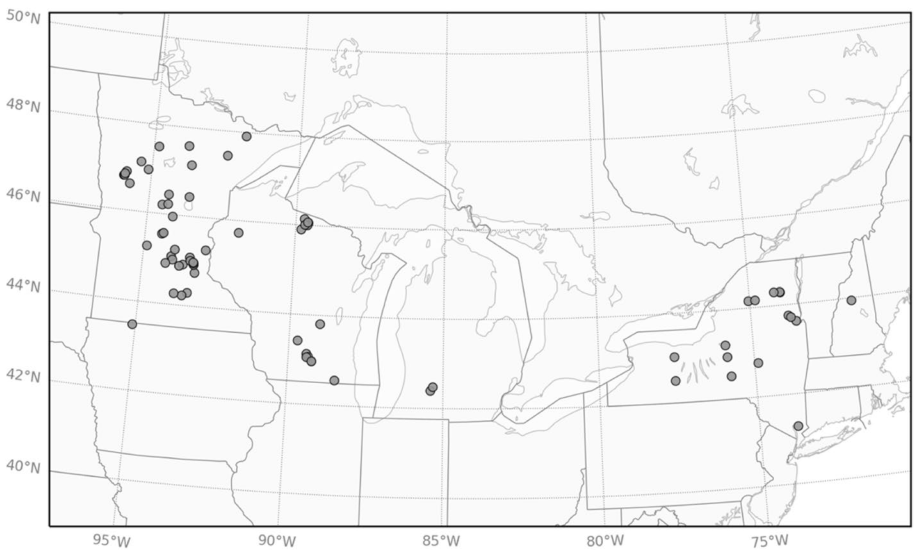

Fig. 1 Map of the Midwestern and Northeastern United States showing locations of the 74 lakes whose ice phenology records are analyzed in this study

We acquired daily meteorological data from the Global Historical Climatology Network through National Oceanic and Atmospheric Administration (NOAA, Menne et al. 2012) to build a multi-year daily meteorological record for each lake, inclusive of all years within the lake's ice phenology record. We obtained precipitation, snowfall, snow depth, maximum air temperature, and minimum air temperature, averaging the minimum and maximum air temperatures to obtain a daily mean temperature. Data quality flags were also acquired. A lake's multi-year daily meteorological record was assembled from nearby (within 50-km distance and 100-m elevation) weather stations, starting with data from the station with the longest and most complete air temperature time series (Fig. S1, Online Resource 1; Table S1, Online Resource 1; Blagrave 2023). Where meteorological data were missing or were of low quality, the data from another nearby station with a similarly long and complete time series were used to complete the lake's meteorological record. Remaining gaps in the temperature and snow depth time series were linearly interpolated (pandas; Reback et al. 2020) using the temperature and snow depth on either side of the gap, for a maximum of three consecutive missing days. For a given winter season, daily meteorological data were extracted from June 1st prior to the ice-on event to the following May 31st. Seasonal average temperature and total precipitation were used within the analysis, i.e., summer (June, July, August), fall (September, October, November), winter (December, January, February), and spring (March, April, May). Winter total snowfall and average snow depth data were also calculated from the daily meteorological time series. Additionally, downscaled monthly daily mean solar radiation data were obtained for each lake from ClimateNA v.7.21 (Wang et al. 2016), using the lake's latitude, longitude, and elevation as inputs (Table S2, Online Resource 1). Again, seasonal averages were used for this analysis.

We extracted seasonal mean air temperature projections for each lake's coordinate and elevation from January 2015 to December 2100 using ClimateNA v.7.21 (Wang et al. 2016) which locally downscales models from the Coupled Model Intercomparison Project (CMIP6). We used three combinations of Shared Socioeconomic Pathways and Representative Concentration Pathways, SSP1-RCP2.6 (i.e., SSP126), SSP3-RCP7.0 (SSP370), and SSP5-RCP8.5 (SSP585), and four general circulation models: Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM4), UK ESM (UKESM1-0-LL), Max Planck Institute for Meteorology ESM (MPI-ESM1-2-HR), and Meteorological Research Institute ESM (MRI-ESM2-0). The selection of different models allowed us to explore the variability across climate change projections. These four specific models were selected based on models available in both ClimateNA (Wang et al. 2016) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; Lange 2019), the latter of which can be used for global ice phenology analyses.

2.2 Data analysis

We used a lake's daily air temperature record (Figs. S2a, S3a) to determine the dates of two important transitions: one was the transition from primarily positive to primarily negative air temperatures, and the other was the transition from primarily negative to primarily positive air temperatures. These dates were determined for every year and every lake by first constructing a cumulative degree days record from the air temperature time series starting on September 8 and ending on June 8 (Figs. S2b, S3b). September 8 is 2 weeks prior to the earliest negative temperature on record, across the meteorological records of all 74 lakes. Similarly, June 8 is 2 weeks after the latest ice-off on record, again across all 74 lakes. This cumulative degree day record was modelled as a high-order (13th-degree) polynomial (Figs. S2b, S3b). A local maximum indicated the date of transition from primarily positive to primarily negative air temperatures, and a local minimum indicated the converse, from primarily negative to primarily positive air temperatures (Figs. S2b, S3b). Pairing these transition dates with their respective ice-on and ice-off dates, we calculated what we have termed a "delay" between the temperature transition and the ice-on or ice-off event. The number of days between the transition and the ice event is hereafter referred to as "ice-on delay" and "ice-off delay."

We calculated freezing degree days (FDD) for the days preceding ice-on directly from the lake's daily air temperature time series (Figs. S2a, S3a). FDD was calculated as a summation of the absolute values of all below zero air temperatures starting on the date that the air temperature transitioned from being primarily positive to primarily negative and ending on the date of ice-on (Figs. S2c, S3c). Similarly, we calculated positive degree days (PDD) for the days preceding ice-off by summing the values of all above zero air temperatures starting on the date that the air temperature transitioned from being primarily negative to primarily positive and ending on the date of ice-off (Figs. S2c, S3c). Note that different values of FDD and PDD were calculated for every lake in every year that ice-on and ice-off dates were recorded. From these values, we calculated a mean FDD and PDD for each lake and measured the correlation between these mean values and lake morphology characteristics using Pearson's correlation coefficients. We chose to present our results as freezing and positive degree days, since FDD and PDD are a simple, transferable, and yet effective metric for quantifying the cumulative effect of air temperatures on a lake's ice-on and ice-off events. The ice-on and ice-off delays complement these data, but do not contain any significant information on the cumulative effect of air temperatures.

Next, we developed a series of random forest models to identify which of our climatological data and lake morphological characteristics were significant drivers of ice-on and ice-off dates. We reduced the ice phenology dataset to the most recent 31 ice-on events and 34 ice-off events so that each lake had the same weight in the model training. We also chose to exclude the ice-on record for Gull Lake, MN, since there was no ice-on record between 1979 and 1997. We subsequently reduced the number of lake morphological characteristics by removing any highly correlated characteristics. In cases where Pearson r correlations were greater than 0.8 at $p < 0.05$, we removed one of the lake morphology variables. The remaining lake characteristics included lake area, lake depth, and shoreline development. The additional drivers used in our random forest models included lake elevation, seasonal mean air temperatures (summer, fall, winter, spring), seasonal total precipitation (fall, winter, spring), snowfall (winter), snow depth (winter), and seasonal mean solar radiation (winter, spring). The importance of these 15 drivers on ice-on and ice-off dates was thoroughly investigated using all 32,767 possible combinations of these 15 drivers as inputs into a series of random forest models, for a total of 65,534 models. Each of the random forest models (sklearn.ensemble.RandomForestRegressor, Pedregosa et al. 2011) used 100 regression trees to identify the hierarchical Gini impurity-based importance of the selected drivers in predicting ice-on or ice-off dates (Breiman 2001). Data are withheld from each of the 100 regression trees to calculate out-of-bag accuracy scores for each tree. The random forest model accuracy is the mean of these 100 scores. From a comparison of the observed ice-on or ice-off dates and the model predictions, we calculated the absolute mean error (AME) and root mean squared error (RMSE) for the models, in days. For each of the ice-on and ice-off sets of models, we selected the most parsimonious model using a combination of highest accuracy (R2) and lowest AME.

Finally, the selected random forest models were used to predict future ice-on and ice-off dates using the projected air temperatures from three Shared Socioeconomic Pathways (SSP126, SSP370, SSP585) across four different general circulation models (GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, MRI-ESM2-0). Predictions for ice-on and ice-off dates were generated for each lake for each winter season between 2015–2016 and 2099–2100 for all 12 pairings of climate models and scenarios to obtain a better understanding of the uncertainty around climate change projections. We calculated the ice-on and ice-off anomalies for each lake and each year relative to each lake's 1980–1999 historical mean. From the collection of lake anomalies, we calculated a mean anomaly for each year for both the historical and the future time periods. To better visualize the trend, the anomalies were smoothed temporally with a 30-year moving window. All analyses were conducted in Python version 3.8.

3 Results

3.1 Which physical factors affect lake ice phenology in the Northern United States?

Our study lakes froze on average after the cumulative number of freezing degree days (FDD) reached 78 °C·days, with a range between 17 and 286 °C·days (Table S2, Online Resource 1). This corresponds to lakes requiring an average 19 days of below 0 °C air temperatures to freeze, with a range from 4 days for small lakes to 53 days for larger lakes. Lakes thawed on average after positive degree days (PDD) reached 97 °C·days, with a range between 38 and 183 °C·days (Table S2, Online Resource 1). This translates to an average 22 days of above 0 °C air temperatures for a lake to thaw, with a range of 8–33 days.

Larger and deeper lakes with more complex shorelines required higher FDD to freeze (Fig. 2; Fig. S4, Online Resource 1; Table S3, Online Resource 1). For example, lake morphology characteristics associated with size, such as lake area (Pearson's $r=0.34$, $p=0.003$), mean depth ($r=0.48$, $p<0.001$), volume ($r=0.42$, $p<0.001$), and shoreline length ($r=0.55$, $p<0.001$), were all positively correlated to FDD prior to ice-on. Similarly, shoreline development ($r=0.33$, $p=0.005$) was positively correlated to FDD, suggesting that lakes with more complex shorelines were freezing later.

Conversely, there were no significant correlations between lake morphology characteristics and PDD required for ice-off, suggesting that ice-off date is not significantly modified by lake characteristics (Fig. 2; Fig. S4, Online Resource 1; Table S3, Online Resource 1). A closer examination of three lakes, Lakes Mendota, Monona, and Wingra, found within the same climatic region and city (Madison, WI) clearly revealed the influence of lake morphology on ice-on date, but not for ice-off date (Fig. 2; Fig. S4, Online Resource 1). For example, ice-on dates varied widely among the three lakes, such that the largest lake, Mendota, generally froze later. However, the ice from the lakes generally thawed around the same time, despite the differences in size between the lakes (Fig. 2; Fig. S4, Online Resource 1).

3.2 How effective are empirical statistical models at predicting ice phenology?

The most parsimonious random forest model explained 75.9% of the variation in ice-on dates for lakes across the Northern United States, using a combination of seasonal air temperatures (summer, fall, winter), lake morphology (mean depth, area), and lake elevation.

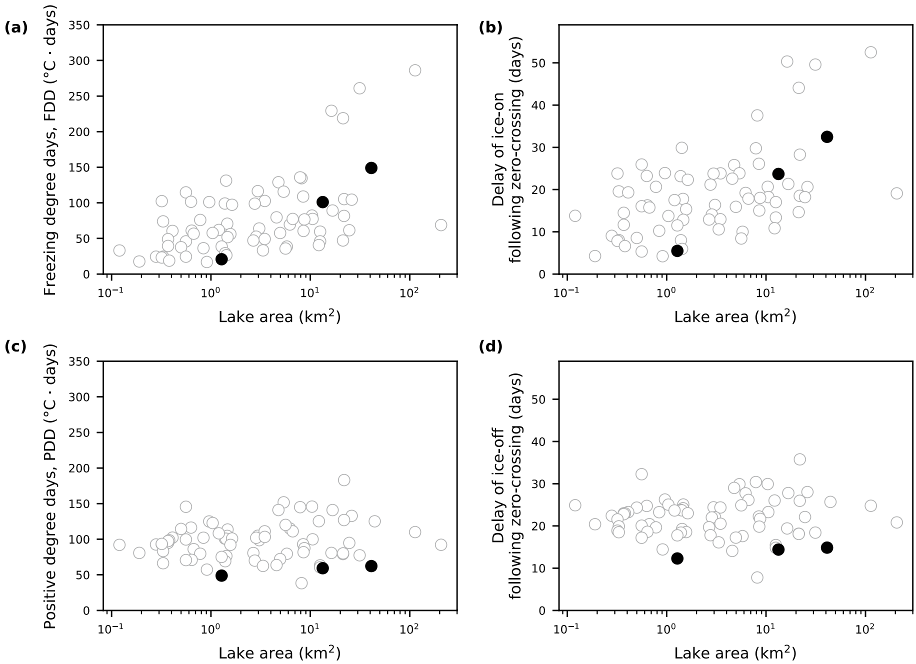

Fig. 2 (**a**) Mean freezing degree days (<0 °C) prior to ice-on, (**b**) mean number of days with $T_{air} < 0$ °C prior to ice-on, (**c**) mean positive degree days (>0 °C) before ice-off, and (**d**) mean number of days with $T_{air} > 0$ °C prior to ice-off, each presented as a function of lake area, on a log scale for visual clarity. Three spatially adjacent lakes, Wingra, Monona, and Mendota, highlight the difference in dependence on lake area for ice-on compared to ice-off dates

This corresponded to an absolute mean error of 6.6 days across all lakes, with a range from 3.3 to 15.8 days (Table S4, Online Resource 1). Seasonal air temperatures accounted for 64% of the explained variation, with fall air temperatures explaining the most variation (Fig. 3a). Lake morphology accounted for 30% of the explained variation in ice-on dates with mean depth explaining the most variation in ice-on date (Fig. 3a). Larger and deeper lakes found in warmer regions had the latest ice-on dates (Fig. 3c). Across all 32,767 models, the mean explained variation was 66.8% (range from −20.8 to 76.9%) with an absolute mean error of 7.6 days (range from 6.2 to 14.9 days).

For ice-off, the optimal random forest model explained 75.7% of the variation in dates using a combination of seasonal air temperatures (summer, fall, winter, spring), winter snowfall, spring precipitation, spring solar radiation, lake morphology (shoreline development), and lake elevation. The absolute mean error was 4.9 days. Air temperatures accounted for 80% of the explained variation, with spring air temperatures explaining most of the variation in ice-off dates. Snowfall and spring precipitation accounted for 8% of the variation, while spring solar radiation, elevation, and lake morphology (shoreline development) explained 5%, 4%, and 3% of the variation in ice-off date, respectively. A simpler model using a reduced list of drivers (seasonal air temperatures, lake morphology (shoreline development), and lake elevation) explained 75.2% of the variation and had an absolute mean error of 5.2 days, with a range from 1.5 to 11 days (Table S4, Online Resource 1). In this simpler model, air temperatures

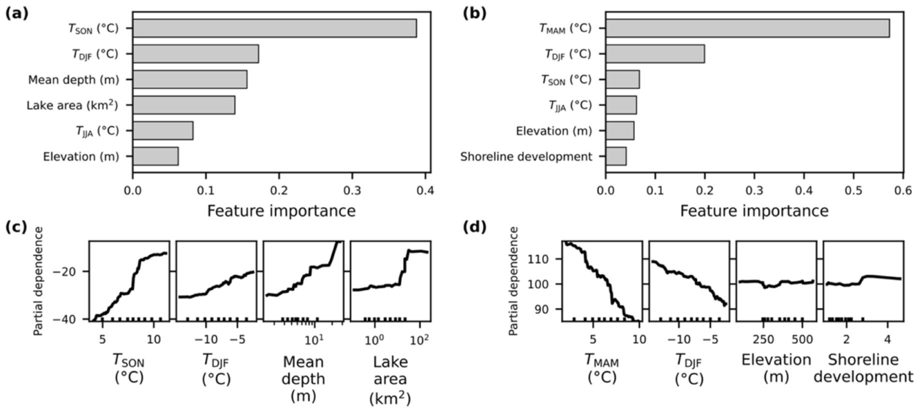

Fig. 3 Variable importance for the most parsimonious (**a**) ice-on and (**b**) ice-off random forest models. Variables with larger values of variable importance explain more variation in ice phenology. Partial dependence plots for (**c**) the ice-on and (**d**) the ice-off model illustrate the marginal effect that each of the variables has on the predicted ice-on and ice-off dates. Smaller values of the partial dependence indicate dates are earlier in the season, and larger values indicate dates are later in the season. Mean depth and lake area are presented here on a log scale for visual clarity

accounted for 90% of the variation, with spring air temperatures again explaining most of the variation (Fig. 3b). Lakes experiencing warmer springs had the earliest ice-off dates (Fig. 3d). Across all 32,767 models, the mean explained variation was 67.9% (range from − 13.4 to 77.1%) with an absolute mean error of 5.8 days (range from 4.8 to 11.5 days).

A limitation of many models lies in their ability to extrapolate. Random forest models are no exception. However, since the random forest models were trained with a range of winter and spring temperatures (− 18 to + 2 °C, − 1 to + 13 °C, respectively), and temperature was the primary driver for both ice-on and ice-off models; these models perform well given seasonal temperatures fall within these ranges.

3.3 What are the forecasted changes in ice-on and ice-off dates?

By the end of the century, on average, ice-on dates are forecasted to be 16 days later, and ice-off dates are forecasted to be 27 days earlier based on the Shared Socioeconomic Pathway (SSP) 585 scenario, which describes the rapid unconstrained growth in economic output and energy use (Fig. 4; Fig. S5, Online Resource 1). Within this climate scenario, across models and lakes, ice-on dates are forecasted to range between 2 and 60 days later, and ice-off dates are projected to be 2 days later to 58 days earlier by 2070–2099. Projections using this SSP scenario often reach the random forest model's mean upper-limit of 23 days later for ice-on anomaly and lower-limit of 42 days earlier for ice-off anomaly in a given year, which suggests that many lakes may not even be freezing (Fig. 4; Fig. S5, Online Resource 1; Table 1). In the slightly more conservative SSP370 scenario, where attempts at mitigation and adaptation are hampered by regional concerns and conflicts, ice-on dates are projected to be later by 14 days and ranging from 2 to 54 days, and ice-off dates are projected to be 24 days earlier and ranging from 0 to 56 days (Fig. 4; Fig. S5, Online Resource 1; Table 1). Finally, based on the most optimistic sustainability focused growth scenario, SSP126, ice-on dates are projected to be 8 days later on average by the

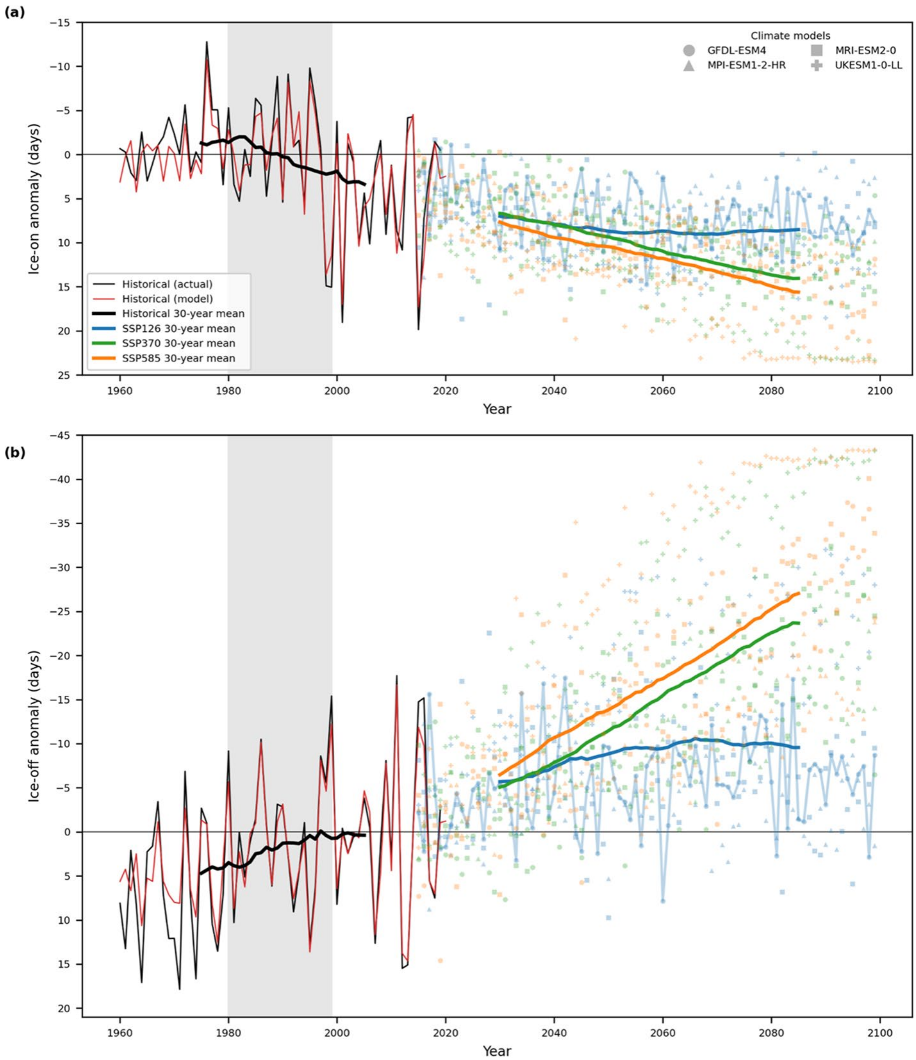

Fig. 4 (**a**) Mean ice-on and (**b**) mean ice-off anomalies both historically and for a suite of climate change models and scenarios. Anomalies are calculated relative to 1980–1999 (shaded zone) mean ice-on and ice-off date for each lake. The solid black line indicates the mean historical anomaly for all 74 lakes while the red line indicates the random forest model prediction. The faded blue, green, and orange markers (most connecting lines omitted for clarity) indicate our random forest model mean anomaly predictions for SSP126, SSP370, and SSP585, respectively, using seasonal air temperatures from ClimateNA locally downscaled GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, and UK-ESM1-0-LL models. The weighted black, blue, green, and orange lines represent the mean anomalies smoothed with a centered 30-year averaging window

end of the century (2070–2099) and range from 2 days earlier to 33 days later; whereas, ice-off dates are forecasted to be 10 days earlier and ranging from 7 days later to 41 days earlier (Fig. 4; Fig. S5, Online Resource 1; Table 1).

Table 1 Projected 30-year mean of all lakes' mean ice-on and ice-off anomalies under three SSP scenarios. The mean and range of predicted anomalies across all lakes and all four climate models (GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) are shown. Anomalies are relative to the 1980–1999 mean

	Years	SSP126	SSP370	SSP585
Mean ice-on anomaly (days)	2040–2069	+8.9 (−2.0 to +33.4)	+10.3 (−1.1 to +34.4)	+11.2 (−0.8 to +38.2)
	2070–2099	+8.5 (−1.9 to +33.4)	+14.0 (+1.5 to +53.8)	+15.6 (+1.9 to +59.5)
Mean ice-off anomaly (days)	2040–2069	−9.6 (−39.7 to +5.8)	−13.4 (−41.7 to +4.5)	−15.8 (−47.0 to +5.2)
	2070–2099	−9.6 (−41.4 to +7.0)	−23.7 (−55.8 to +0.1)	−27.0 (−58.4 to +1.8)

4 Discussion

With the proliferation of winter limnological studies, a key limitation in experimental or synthesis studies may be the lack of data on the timing of ice-on and ice-off, both of which are fundamental to understanding how shorter winters may be affecting under-ice processes. Thus, we provide highly predictive tools to estimate the timing of ice-on and ice-off by lake size. We found that ice-on dates are constrained by temperatures and lake morphological characteristics, whereas ice-off dates are primarily determined by temperatures. Larger and deeper lakes required air temperatures to be below 0 °C over a longer period of time than smaller and shallower lakes. In contrast, despite differences in lake characteristics, such as size, lakes experiencing similar climates will thaw at generally similar times. More specifically, lakes require 19 days (range: 4–53 days) with air temperatures below 0 °C to freeze and 22 days (range: 8–33 days) with air temperatures above 0 °C to thaw on average in the USA. By the end of the century, without constraints on energy use and rapid economic growth (i.e., SSP585), lakes across the Midwestern and Northeastern United States will experience 43 days less ice cover, if they freeze at all. However, the most optimistic climate change scenarios, which incorporate sustainable growth and aggressive mitigation of greenhouse gas emissions, forecast the loss of only 18 days of ice cover by the end of the century.

4.1 Timing of ice-on is moderated by climate and lake morphology

Air temperatures and lake morphology characteristics explained almost 76% of the variation in ice-on dates. Sixty-four percent of the variation is explained by air temperature and the remaining 36% by lake morphology. We found that the timing of ice-on is highly dependent upon lake morphological characteristics, most clearly seen for lakes found in the same geographical region which generally experience similar climatic conditions. For example, there was a positive and non-linear relationship between the freezing degree days required for lakes to freeze and lake size. We found that the smallest lakes in our study required as few as 4 days with below zero temperatures (FDD: 17 °C days) while the larger lakes required as many as 53 consistently cold days for complete ice coverage (286 °C days). Similar to lakes across a smaller geographic distance in the Experimental

Lakes Area (Higgins et al. 2021), we found that larger lakes freeze later because they require a higher number of days below freezing for ice to form. For example, we observed that although two neighboring lakes in Wisconsin, Lakes Wingra and Mendota, experience the same local weather conditions, there was a marked difference in the magnitude of FDD required for freezing, and widely anomalous ice-on dates between the two lakes, on the order of 8–49 days in the past 40 years. For example, Lake Wingra typically freezes after 7 days of air temperatures below 0 °C, whereas Lake Mendota requires 32 days.

Notably, large and deep lakes took longer to freeze. Large, deep lakes with deeper thermoclines have larger amounts of heat storage capacity which requires longer periods of cooler air temperatures in order for water temperatures to fall below 4 °C and prime the lake to freeze (Brown and Duguay 2010; Kirillin et al. 2012; Nõges and Nõges 2014; Yang et al. 2021), although this is a non-linear relationship with lake size (Hanna 1990) and also dependent on water clarity, particularly for small lakes (Fee et al. 1996). Interestingly, Yang et al. (2021) observed that at the time of ice-on, water temperatures are colder (0~2 °C) in larger and windier lakes than in smaller and calmer lakes (2 ~ 4 °C; Yang et al. 2021) aligning with our findings that smaller and shallower lakes were freezing earlier in the season, when air temperatures and thereby water temperatures were warmer. Unexpectedly, we observed a moderately positive relationship for lakes with more complex shorelines. In contrast, earlier studies suggested that lakes with less complex shorelines and thus longer fetches are more sensitive to wind action breaking up the initial skim of ice formed at the beginning of the ice season because of higher local wind speed, mixing, and turbulence leading to later ice-on dates (Williams et al. 2004; Jeffries et al. 2012; Magee and Wu 2017; Sharma et al. 2019; Higgins et al. 2021).

4.2 Timing of ice-off is predominantly governed by climate

In our analyses of lakes across the Midwestern and Northeastern United States, we found significant relationships between the timing of ice-off and climate, but no significant relationships with lake morphology. Our study lakes thawed on average after 22 days with air temperatures above 0 °C (corresponding to 97 °C days positive degree days (PDD)), and varied from 8 days (PDD: 38 °C days) to 33 days (PDD: 183 °C days). Ice-off requires temperatures close to or above 0 °C, in addition to strong wind action, for the lake ice to break up, and there is a strong relationship between air temperatures and the PDD required for lakes to thaw. We found a weak positive relationship between shoreline complexity and ice-off dates. Lakes with higher shoreline complexity are expected to have more protected bays, islands, a lower mean fetch, and thereby lower winds and later ice-off dates. However, we did not find a significant difference in ice-off dates for lakes of varying sizes. For example, Lakes Mendota, Monona, and Wingra, all found in Madison, WI, and generally experiencing similar climatic conditions, thaw at similar times despite the differences in lake size. Interestingly, Higgins et al. (2021) documented an influence of lake size on ice-off dates in lakes within a relatively small geographic area in the Experimental Lakes Area through the interaction of lake size and fetch with snow and ice thickness. They found that larger lakes with longer fetches had later ice-off dates as these lakes had decreased snow thickness and increased ice thickness (Higgins et al. 2021), similar to the observations from Efremova and Pal'shin (2011) in Northwestern Russian waterbodies (Efremova and Pal'shin 2011).

Climatic conditions explained the most variation in ice-off dates. We found that a combination of air temperatures, winter snowfall, spring solar radiation, spring precipitation, and lake morphology explained 75.7% of the variation in ice-off dates. The timing of ice-off dates was not significantly related to lake morphological characteristics. Our results support earlier empirical studies which have shown that the timing of ice-off is associated with air temperatures, precipitation, elevation, solar angle, and large-scale climatic oscillations (Sharma et al. 2013; Shuter et al. 2013; Hewitt et al. 2018; Imrit and Sharma 2021), with lake characteristics contributing to a lesser extent (Shuter et al. 2013). Air temperatures are the most important driver of ice-off dates accounting for 80–90% of the variation in this study. Simply put, lakes thaw earlier in regions with warmer spring air temperatures. Across a multitude of studies, air temperatures are often found to explain the most variation in ice-off dates (e.g., Palecki and Barry 1986; Assel and Robertson 1995; Vavrus et al. 1996; Livingstone 2000; Korhonen 2006; Weyhenmeyer et al. 2011; Benson et al. 2012; Imrit and Sharma 2021).

Winter snowfall and spring precipitation explained 8% of the variation in ice-off dates, whereas spring solar radiation only explained 5% of the variation in our study. In contrast, air temperatures explained 80% of the variation in ice-off dates. The coarse spatial and temporal resolution of solar radiation and precipitation variables available for use in our empirical models may explain the relatively low contributions of these variables relative to process-based models. Process-based models have illustrated the importance of precipitation and solar radiation to ice-off dates (Leppäranta 2010; Brown and Duguay 2010; Kirillin et al. 2012; Leppäranta and Wen 2022). Winter snowfall was positively correlated ($r = 0.54$, $p < 0.0001$) to ice-off date, such that in our study, more winter snowfall delayed ice-off date. Thick snowpack can act as an insulating layer on the ice, and the higher albedo can lead to a longer snowmelt process, a process which is influenced by both air temperatures and solar radiation absorption (Jeffries et al. 2005; Kouraev et al. 2007; Bernhardt et al. 2012; Nõges and Nõges 2014; Preston et al. 2016; Sadro et al. 2018). Unexpectedly, we did not observe a relationship between solar radiation and ice-off dates in our empirical model. Multiple mechanistic process-based models highlight the importance of solar radiation as a predominant driver of ice decay (Jakkila et al. 2009; Leppäranta 2010; Kirillin et al. 2012, 2017). As the rate of absorption of solar radiation in a lake is dependent on local factors and within days or weeks of ice breakup (Brown and Duguay 2010; Bernhardt et al. 2012; Jeffries et al. 2012), the solar radiation variables that we were able to access across a broad geographic landscape may be insufficient to capture the importance of solar radiation within our empirical models.

Our models were relatively simplistic, but effective at predicting ice-on and ice-off dates. Using lake morphology characteristics and seasonal air temperatures, we were able to predict ice-on dates and ice-off dates with an absolute mean error of 6.6 days and 5.2 days, respectively, for lakes across the USA. The difference in error between these two models can be partly attributed to the greater complexity of the processes involved in the initial ice formation versus the end-of-season thaw, a complexity that was not captured in our empirical statistical models. However, there was also a contribution to the error from the uncertainty in the definitions of ice-on and ice-off observations. Ice-on and ice-off definitions vary from lake to lake, but ice-off generally occurs overnight and as such is more consistently defined (Sharma et al. 2022). This would be reflected in a smaller ice-off observation uncertainty, in line with the smaller absolute mean error we found for ice-off models.

There have been many other ice phenology predictive models — both mechanistic and empirical — developed for single lakes (Magee and Wu 2017; Karetnikov et al. 2017; Hewitt et al. 2018) and subsets of lakes (e.g., Dibike et al. 2012; Shuter et al. 2013), all similarly finding a strong dependence on air temperature for ice-off, and air temperature and lake morphology for ice-on dates with absolute mean errors ranging from 3 days for single lake mechanistic models (Magee and Wu 2017) to 9 days for empirical models for a subset of lakes (Shuter et al. 2013). Although these earlier models provide a good understanding of the processes affecting lake ice phenology, they are generally more complex because of the inclusion of additional parameters, such as the solar angle on the day that the smoothed version of the daily temperature record crossed 0 °C (Shuter et al. 2013) or detailed lake hydrology and climatic conditions in the case of mechanistic one-dimensional lake models (e.g., Magee and Wu 2017).

There are a number of excellent studies using physical lake models that quantify the physical processes driving lake ice growth and decay (i.e., MacKay et al. 2009, 2017; Leppäranta 2010; Brown and Duguay 2010; Kirillin et al. 2012; Stepanenko et al. 2016; and many others); however, there remains a knowledge gap in integrating mechanistic relationships into empirical models, particularly when scaling from a few lakes up to regional, national, and global spatial scales. Although we were able to incorporate seasonal measures of air temperature, precipitation, and solar radiation, we were unable to incorporate wind speed, cloud cover, snow density, ice thickness, ice quality, under-ice stratification, or heat fluxes, within our empirical models, owing to a lack of coordinated data across a broad geographic landscape. We echo the call for integrating lake ice research across disciplines, including empirical and process-based modelling approaches, to further improve our understanding of lake ice dynamics across broad spatial and temporal scales in a warming world (Sharma et al. 2020).

4.3 Projecting later ice-on and earlier ice-off dates by the end of the century

We forecast that ice-on dates will be later by 13 days and ice-off dates will be earlier by 20 days on average for lakes in the Midwestern and Northeastern United States by 2070–2099. In every climate scenario by the end of the century, lakes may be losing up to 68 days (SSP 126), 103 days (SSP 370), and 113 days (SSP 585) of ice cover, implying that there will be lakes across the USA no longer freezing at all. In the extreme scenario of rapid unconstrained growth of economic output and energy use (SSP585), lakes are predicted to lose upwards of 43 days of ice cover on average. With a limited implementation of global policy scenario (SSP370), lakes are forecasted to lose 38 days of ice cover, and finally the sustainability focused growth scenario (SSP126) predicts a loss of 18 days of ice cover by the end of the century. Lakes in Northeastern United States are more sensitive to higher rates of ice loss. These findings are supported by earlier explorations projecting changes in ice-on and ice-off dates (Dibike et al. 2012; Shuter et al. 2013; Magee and Wu 2017; Leppäranta and Wen 2022) and also ice duration (e.g., Hewitt et al. 2018) under scenarios of climate change, although the forecasted rates of ice loss are much higher using the most recent climate projections. For example, in the period between 1961–1990 and 2041–2070, mean ice-on dates had been forecasted to be later by 5–15 days for Canadian lakes, and mean ice-off dates had been forecasted to be 5–20 days earlier for Canadian lakes (Dibike et al. 2012; Shuter et al. 2013). Similarly, a mean change in ice cover duration of 24 days was predicted between 1981–2015 and 2061–2080 for nine small lakes in the Great Lakes region (Hewitt et al. 2018). In northeastern Europe, lakes are forecasted to lose 12 days of ice cover in a winter season for every 1 °C of warming (Leppäranta and Wen 2022). A recent global analysis using a suite of one-dimensional lake models, spatially summarized onto half degree grid cells, predicted a global average decline of 46 days of ice cover by the end of the century relative to pre-industrial conditions under an extreme Representative Concentration Pathways (RCP) 8.5 scenario (Grant et al. 2021), more in line with our forecasts.

In the past 25 years, lakes lost ice cover at rates six times faster than the past century (Sharma et al. 2021b). Ice cover in large, deep lakes is especially sensitive to climate change, exhibiting a rapid loss of ice cover compared to small, shallow lakes, primarily due to later ice-on dates. For example, we found drastic differences in projected changes in ice-on dates between two lakes in northern Minnesota: the larger, deeper Lake Siseebakwet; and smaller, shallower Lake Shagawa. Ice-on dates are forecasted to be over 36 days later for Lake Siseebakwet, the larger and deeper lake, relative to the smaller, shallower Lake Shagawa, whose ice-on dates are forecasted to be 10 days later by the end of the century. Similarly, Magee and Wu (2017) found that ice-on for deep Lake Mendota could change by 30 days with a temperature change of + 8 to + 9 °C, while shallow Lake Wingra would experience a shift in ice-on of only a few days under that same temperature change (Magee and Wu 2017).

Forecasted changes in ice-off dates are less mediated by lake morphology. For example, we found that ice-off dates in Lakes Shagawa and Siseebakwet are forecasted to be earlier by 27–30 days, similar to the other lakes in their vicinity, regardless of their size. Likewise, in Madison, WI, Magee and Wu (2017) found that ice-off dates for Lakes Mendota and Wingra are forecasted to both shift to early- to mid-March (i.e., > 30 days earlier) with a temperature change of + 8 to + 10 °C (Magee and Wu 2017). However, there is a noticeable latitudinal gradient in the anomalies of ice-off dates, with ice-off dates in more northerly regions forecasted to change more than those at southern latitudes, which was unexpected compared to earlier historical studies. For example, in Finland, ice-on and ice-off dates changed most rapidly in Southern Finland, followed by Northern Finland. Lakes in Central Finland did not lose ice cover as rapidly as the north and south (Korhonen 2006), whereas in an earlier study in North America, Jensen et al. (2007) found that lakes in the southwest lost ice at the fastest rates (Jensen et al. 2007). Much work remains to be done on understanding the spatial heterogeneity of ice loss in lakes.

5 Conclusions

This paper is one of the first to forecast ice-on and ice-off dates across a vast landscape of lakes in the USA using long-term in situ observations and local weather stations. In this analysis, we were able to include lakes with a gradient of morphologies which could not all otherwise be simultaneously studied either by remote sensing, owing to some of their small sizes, or process-based modelling approaches because of the large geographical area studied. We showed that lake size is an important determinant of ice-on dates and models that do not include an on-the-ground measure of mean depth will be prone to large errors in predicting ice-on dates. As global temperatures rise, lakes will continue to lose seasonal ice cover. Simple predictive models for ice-on and ice-off dates will be an important tool for freshwater management. Similarly, with increased interest in winter limnology (Powers and Hampton 2016), many researchers are studying the impacts of shorter winters on under-ice limnological processes, including dissolved oxygen, nutrient concentrations, and biological activity across the food web, including phytoplankton, zooplankton, and fishes (i.e., Powers et al. 2017; McMeans et al. 2020; Hebert et al. 2021), and will continue to do so, as there continue to be many unanswered questions in the field (i.e., Woolway et al. 2020, 2022; Ozersky et al. 2021; Sutton et al. 2021). However, a key limitation in experimental or synthesis studies may be the lack of data on the timing of ice-on and ice-off (Hampton et al., in press), which is fundamental to understanding how shorter winters may be affecting under-ice processes. Thus, we provide simple, but highly predictive tools using freezing degree days, positive degree days, and random forest models to estimate the timing of ice-on and ice-off by lake size. Winter limnological activity is especially important to study before ice is lost altogether with future climate change, as lakes found in the midwestern and northeastern regions of the USA are among the most vulnerable to losing ice intermittently (Sharma et al. 2019) or even permanently (Sharma et al. 2021a).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-023-03596-z.

Acknowledgements We thank the Minnesota Department of Natural Resources, Wisconsin State Climatology Office, North Temperate Lakes Long-Term Ecological Research, Dale Robertson, John Magnuson, Greg Sass, Lolita Olson, Kevin Rose, Brendan Wiltse, Kiyoko Yokota, Holly Waterfield, Lars Rudstam, Steve Hamilton, Ken Blumenfeld, and Pete Boulay for providing updates to ice phenology records for the lakes included in the study. We thank Alessandro Filazzola for helpful comments and revisions on an earlier draft of the manuscript.

Author contribution Conception: Kevin Blagrave and Sapna Sharma; data acquisition: Kevin Blagrave; data analysis: Kevin Blagrave; drafting, editing, and approving manuscript: Kevin Blagrave and Sapna Sharma.

Funding This research was funded by the Natural Sciences and Engineering Research Council Discovery Grant, Ontario Ministry of Innovation and Science Early Researcher Award, and the York Research Chair program awarded to SS.

Data availability The 74-lake ice phenology datasets assembled and analyzed during the current study are available in the figshare repository, https://doi.org/10.6084/m9.figshare.21171619. The Python code used in this study is available in the GitHub repository, https://github.com/kblagrave/IcePhenologyModels/ (https://doi.org/10.5281/zenodo.8066213).

Declarations

Competing interests The authors declare no competing interests.

References

Arp CD, Jones BM, Grosse G (2013) Recent lake ice-out phenology within and among lake districts of Alaska, USA. Limnol Oceanogr 58:2013–2028. https://doi.org/10.4319/lo.2013.58.6.2013

Assel R, Robertson D (1995) Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. Limnol Oceanogr 40:165–176. https://doi.org/10.4319/lo.1995.40.1.0165

Austin JA, Colman SM (2007) Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback. Geophys Res Lett 34. https://doi.org/10.1029/2006GL029021

Benson BJ, Magnuson JJ, Jensen OP et al (2012) Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). Clim Change 112:299–323. https://doi.org/10.1007/s10584-011-0212-8

Bernhardt J, Engelhardt C, Kirillin G, Matschullat J (2012) Lake ice phenology in Berlin-Brandenburg from 1947–2007: observations and model hindcasts. Clim Change 112:791–817. https://doi.org/10.1007/s10584-011-0248-9

Blagrave K (2023) kblagrave/IcePhenologyModels: initial release. Zenodo. https://doi.org/10.5281/zenodo.8066213

Block BD, Denfeld BA, Stockwell JD et al (2019) The unique methodological challenges of winter limnology. Limnol Oceanogr: Methods 17:42–57. https://doi.org/10.1002/lom3.10295

Breiman L (2001) Random forests. Mach Learn 45:5–32. https://doi.org/10.1023/A:1010933404324

Brown LC, Duguay CR (2010) The response and role of ice cover in lake-climate interactions. Prog Phys Geogr: Earth Environ 34:671–704. https://doi.org/10.1177/0309133310375653
Dibike Y, Prowse T, Bonsal B et al (2012) Simulation of North American lake-ice cover characteristics under contemporary and future climate conditions. Int J Climatol 32:695–709. https://doi.org/10.1002/joc.2300
Duguay C, Prowse T, Bonsal B et al (2006) Recent trends in Canadian lake ice cover. Hydrol Processes 20:781–801. https://doi.org/10.1002/hyp.6131
Efremova T, Pal'shin N (2011) Ice phenomena terms on the water bodies of Northwestern Russia. Russ Meteorol Hydrol 36:559–565. https://doi.org/10.3103/S1068373911080085
Fee E, Hecky R, Kasian S, Cruikshank D (1996) Effects of lake size, water clarity, and climatic variability on mixing depths in Canadian Shield lakes. Limnol Oceanogr 41:912–920. https://doi.org/10.4319/lo.1996.41.5.0912
Filazzola A, Blagrave K, Imrit MA, Sharma S (2020) Climate change drives increases in extreme events for lake ice in the Northern Hemisphere. Geophys Res Lett 47. https://doi.org/10.1029/2020GL089608
Ghanbari RN, Bravo HR, Magnuson JJ et al (2009) Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin). J Hydrol 374:282–293. https://doi.org/10.1016/j.jhydrol.2009.06.024
Grant L, Vanderkelen I, Gudmundsson L et al (2021) Attribution of global lake systems change to anthropogenic forcing. Nat Geosci 14:849–854. https://doi.org/10.1038/s41561-021-00833-x
Hanna M (1990) Evaluation of models predicting mixing depth. Can J Fish Aquat Sci 47:940–947. https://doi.org/10.1139/f90-108
Hebert M-P, Beisner BE, Rautio M, Fussmann GF (2021) Warming winters in lakes: later ice onset promotes consumer overwintering and shapes springtime planktonic food webs. Proc Natl Acad Sci U S A 118. https://doi.org/10.1073/pnas.2114840118
Hewitt BA, Lopez LS, Gaibisels KM et al (2018) Historical trends, drivers, and future projections of ice phenology in small north temperate lakes in the Laurentian Great Lakes region. Water 10:70. https://doi.org/10.3390/w10010070
Higgins SN, Desjardins CM, Drouin H, et al (2021) The role of climate and lake size in regulating the ice phenology of boreal lakes. J Geophys Res: Biogeosci 126. https://doi.org/10.1029/2020JG005898
Imrit MA, Sharma S (2021) Climate change is contributing to faster rates of lake ice loss in lakes around the Northern Hemisphere. J Geophys Res: Biogeosci 126:e2020JG006134. https://doi.org/10.1029/2020JG006134
Jakkila J, Leppäranta M, Kawamura T et al (2009) Radiation transfer and heat budget during the ice season in Lake Pääjärvi, Finland. Aquat Ecol 43:681–692. https://doi.org/10.1007/s10452-009-9275-2
Jeffries M, Morris K, Duguay C (2005) Lake ice growth and decay in central Alaska, USA: observations and computer simulations compared. In: MacAyeal, DR (ed) Annals of Glaciology. INT GLACIOLOGICAL SOC, LENSFIELD RD, CAMBRIDGE CB2 1ER, ENGLAND, pp 195–199
Jeffries MO, Morris K, Duguay CR (2012) Floating ice: lake ice and river ice. In: R.S Williams Jr, Ferrigno JG (eds) Satellite image atlas of glaciers of the world – state of the Earth's cryosphere at the beginning of the 21st century: glaciers, global snow cover, floating ice, and permafrost and periglacial environments: U.S. Geological Survey Professional Paper 1386-A. United States Government Printing Office, Washington, pp A381–A424
Jensen OP, Benson BJ, Magnuson JJ et al (2007) Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. Limnol Oceanogr 52:2013–2026. https://doi.org/10.4319/lo.2007.52.5.2013
Karetnikov S, Leppäranta M, Montonen A (2017) A time series of over 100 years of ice seasons on Lake Ladoga. J Great Lakes Res 43:979–988. https://doi.org/10.1016/j.jglr.2017.08.010
Kirillin G, Leppäranta M, Terzhevik A et al (2012) Physics of seasonally ice-covered lakes: a review. Aquat Sci 74:659–682. https://doi.org/10.1007/s00027-012-0279-y
Kirillin G, Wen L, Shatwell T (2017) Seasonal thermal regime and climatic trends in lakes of the Tibetan highlands. Hydrol Earth Syst Sci 21:1895–1909. https://doi.org/10.5194/hess-21-1895-2017
Knoll LB, Sharma S, Denfeld BA et al (2019) Consequences of lake and river ice loss on cultural ecosystem services. Limnol Oceanogr Lett 4:119–131. https://doi.org/10.1002/lol2.10116
Korhonen J (2006) Long-term changes in lake ice cover in Finland. Nord Hydrol 37:347–363. https://doi.org/10.2166/nh.2006.019
Kouraev AV, Semovski SV, Shimaraev MN et al (2007) The ice regime of Lake Baikal from historical and satellite data: relationship to air temperature, dynamical, and other factors. Limnol Oceanogr 52:1268–1286. https://doi.org/10.4319/lo.2007.52.3.1268
Lange S (2019) Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). Geosci Model Dev 12:3055–3070. https://doi.org/10.5194/gmd-12-3055-2019
Leppäranta M, Wen L (2022) Ice phenology in Eurasian lakes over spatial location and altitude. Water 14:1037. https://doi.org/10.3390/w14071037

Leppäranta M (2010) Modelling the formation and decay of lake ice. In: George G (ed) Impact of climate change on European lakes. Springer, Dordrecht, pp 63–83
Livingstone DM (2000) Large-scale climatic forcing detected in historical observations of lake ice breakup. SIL Proceedings, 1922–2010 27(5):2775–2783. https://doi.org/10.1080/03680770.1998.11898171
Livingstone D, Dokulil M (2001) Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperature and the North Atlantic Oscillation. Limnol Oceanogr 46:1220–1227. https://doi.org/10.4319/lo.2001.46.5.1220
Lopez LS, Hewitt BA, Sharma S (2019) Reaching a breaking point: how is climate change influencing the timing of ice breakup in lakes across the Northern Hemisphere? Limnol Oceanogr 64:2621–2631. https://doi.org/10.1002/lno.11239
MacKay M, Neale P, Arp C et al (2009) Modeling lakes and reservoirs in the climate system. Limnol Oceanogr 54:2315–2329. https://doi.org/10.4319/lo.2009.54.6_part_2.2315
MacKay M, Verseghy DL, Fortin V, Rennie MD (2017) Wintertime simulations of a boreal lake with the Canadian Small Lake Model. J Hydrometeorol 18:2143–2160
Magee MR, Wu CH (2017) Effects of changing climate on ice cover in three morphometrically different lakes. Hydrol Processes 31:308–323. https://doi.org/10.1002/hyp.10996
Magnuson JJ, Lathrop RC (2014) Lake ice: winter, beauty, value, changes, and a threatened future. LakeLine 43:18–27
Magnuson J, Robertson D, Benson B et al (2000) Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289:1743–1746. https://doi.org/10.1126/science.289.5485.1743
Marszelewski W, Pius B (2019) Effect of climate change on thermal-ice regime of shallow lakes compared to deep lakes: case study of lakes in the temperate zone (Northern Poland). J Limnol 78:27–39. https://doi.org/10.4081/jlimnol.2018.1763
McMeans BC, McCann KS, Guzzo MM et al (2020) Winter in water: differential responses and the maintenance of biodiversity. Ecol Lett 23:922–938. https://doi.org/10.1111/ele.13504
Menne MJ, Durre I, Vose RS et al (2012) An overview of the global historical climatology network-daily database. J Atmos Oceanic Technol 29:897–910. https://doi.org/10.1175/JTECH-D-11-00103.1
Messager ML, Lehner B, Grill G et al (2016) Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat Commun 7. https://doi.org/10.1038/ncomms13603
Nõges P, Nõges T (2014) Weak trends in ice phenology of Estonian large lakes despite significant warming trends. Hydrobiologia 731:5–18. https://doi.org/10.1007/s10750-013-1572-z
Ozersky T, Bramburger AJ, Elgin AK et al (2021) The changing face of winter: lessons and questions from the Laurentian Great Lakes. J Geophys Res: Biogeosci 126. https://doi.org/10.1029/2021JG006247
Palecki MA, Barry RG (1986) Freeze-up and break-up of lakes as an index of temperature-changes during the transition seasons - a case-study for Finland. J Clim Appl Meteorol 25:893–902. https://doi.org/10.1175/1520-0450(1986)025%3c0893:FUABUO%3e2.0.CO;2
Pedregosa F, Varoquaux G, Gramfort A et al (2011) Scikit-learn: machine learning in Python. J Mach Learn Res 12:2825–2830
Powers SM, Hampton SE (2016) Winter limnology as a new frontier. Limnol Oceanogr Bull 25:103–108. https://doi.org/10.1002/lob.10152
Powers SM, Labou SG, Baulch HM et al (2017) Ice duration drives winter nitrate accumulation in north temperate lakes. Limnol Oceanogr Lett 2:177–186. https://doi.org/10.1002/lol2.10048
Preston DL, Caine N, McKnight DM et al (2016) Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure. Geophys Res Lett 43:5553–5560. https://doi.org/10.1002/2016GL069036
Reback J, McKinney W, jbrockmendel et al (2020) pandas-dev/pandas: Pandas 1.3.4. Zenodo, https://doi.org/10.5281/zenodo.3715232
Robertson DM, Wynne RH, Chang WYB (2000) Influence of El Niño on lake and river ice cover in the Northern Hemisphere from 1900 to 1995. SIL Proceedings, 1922–2010 27(5):2784–2788. https://doi.org/10.1080/03680770.1998.11898172
Sadro S, Sickman J, Melack J, Skeen K (2018) Effects of climate variability on snowmelt and implications for organic matter in a high-elevation lake. Water Resour Res 54:4563–4578. https://doi.org/10.1029/2017WR022163
Sharma S, Magnuson JJ, Mendoza G, Carpenter SR (2013) Influences of local weather, large-scale climatic drivers, and the ca. 11 year solar cycle on lake ice breakup dates; 1905–2004. Clim Change 118:857–870. https://doi.org/10.1007/s10584-012-0670-7
Sharma S, Blagrave K, Magnuson JJ et al (2019) Widespread loss of lake ice around the Northern Hemisphere in a warming world. Nat Clim Change 9:227+. https://doi.org/10.1038/s41558-018-0393-5
Sharma S, Magnuson JJ, Batt RD et al (2016) Direct observations of ice seasonality reveal changes in climate over the past 320–570 years. Sci Rep 6. https://doi.org/10.1038/srep25061

Sharma S, Meyer MF, Culpepper J et al (2020) Integrating perspectives to understand lake ice dynamics in a changing world. J Geophys Res: Biogeosci 125. https://doi.org/10.1029/2020JG005799
Sharma S, Blagrave K, Filazzola A et al (2021a) Forecasting the permanent loss of lake ice in the Northern Hemisphere within the 21st century. Geophys Res Lett 48. https://doi.org/10.1029/2020GL091108
Sharma S, Richardson DC, Woolway RI et al (2021b) Loss of ice cover, shifting phenology, and more extreme events in Northern Hemisphere lakes. J Geophys Res: Biogeosci 126. https://doi.org/10.1029/2021JG006348
Sharma S, Filazzola A, Nguyen T et al (2022) Long-term ice phenology records spanning up to 578 years for 78 lakes around the Northern Hemisphere. Sci Data 9. https://doi.org/10.1038/s41597-022-01391-6
Shuter BJ, Minns CK, Fung SR (2013) Empirical models for forecasting changes in the phenology of ice cover for Canadian lakes. Can J Fish Aquat Sci 70:982–991. https://doi.org/10.1139/cjfas-2012-0437
Stepanenko V, Mammarella I, Ojala A et al (2016) LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes. Geosci Model Dev 9:1977–2006. https://doi.org/10.5194/gmd-9-1977-2016
Surdu CM, Duguay CR, Pour HK, Brown LC (2015) Ice freeze-up and break-up detection of shallow lakes in Northern Alaska with spaceborne SAR. Remote Sens 7:6133–6159. https://doi.org/10.3390/rs70506133
Sutton AO, Studd EK, Fernandes T et al (2021) Frozen out: unanswered questions about winter biology. Environ Rev 29:431–442. https://doi.org/10.1139/er-2020-0127
Vavrus SJ, Wynne RH, Foley JA (1996) Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. Limnol Oceanogr 41:822–831. https://doi.org/10.4319/lo.1996.41.5.0822
Wang T, Hamann A, Spittlehouse D, Carroll C (2016) Locally downscaled and spatially customizable climate data for historical and future periods for North America. PloS One 11. https://doi.org/10.1371/journal.pone.0156720
Weyhenmeyer GA, Livingstone DM, Meili M et al (2011) Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. Glob Chang Biol 17:268–275. https://doi.org/10.1111/j.1365-2486.2010.02249.x
Weyhenmeyer GA, Obertegger U, Rudebeck H et al (2022) Towards critical white ice conditions in lakes under global warming. Nat Commun 13:4974. https://doi.org/10.1038/s41467-022-32633-1
Weyhenmeyer G, Meili M, Livingstone D (2004) Nonlinear temperature response of lake ice breakup. Geophys Res Lett 31. https://doi.org/10.1029/2004GL019530
Williams G, Layman K, Stefan H (2004) Dependence of lake ice covers on climatic, geographic and bathymetric variables. Cold Reg Sci Technol 40:145–164. https://doi.org/10.1016/j.coldregions.2004.06.010
Woolway RI, Kraemer BM, Lenters JD et al (2020) Global lake responses to climate change. Nat Rev Earth Environ 1:388–403. https://doi.org/10.1038/s43017-020-0067-5
Woolway R, Sharma S, Smol J (2022) Lakes in hot water: the impacts of a changing climate on aquatic ecosystems. BioSci. https://doi.org/10.1093/biosci/biac052
Yang B, Wells MG, McMeans BC et al (2021) A new thermal categorization of ice-covered lakes. Geophys Res Lett 48. https://doi.org/10.1029/2020GL091374