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Key Points:
- Lakes at lower elevations, western longitudes, and lower latitudes have been more affected by ice cover loss associated with global warming
- The rate of ice duration loss is also faster for deeper lakes

Supporting Information:
- Supporting Information S1
- Table S1

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Geography and Morphology Affect the Ice Duration Dynamics of Northern Hemisphere Lakes Worldwide

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Abstract Climate change continues to diminish ice cover duration for Northern Hemisphere lakes. However, the differential loss of lake ice duration for various types of lakes across the globe is not well established. In this study, we used time series of ice duration data (average length = 51 years) for 220 globally distributed Northern Hemisphere lakes to determine how local climate trends, geographical location, and physical properties of lakes affect their ice cover trends. Ice duration dynamics were influenced by surface air temperature trends, lake geography, and morphology. Deeper lakes, located at lower elevations, western longitudes, and lower latitudes, experienced the greatest reductions in ice cover over their time series. These results indicate that despite widespread patterns of warming, the individual features of lakes can determine how rapidly they are losing ice cover and may prove informative for future modeling and conservation efforts.

Plain Language Summary Citizen scientists and researchers alike have been visually logging the freezing and breakup dates of lake ice for hundreds of years. Studies have shown that lake ice duration (the number of days between freezing and breakup) has decreased over time due to human-induced climate change. We have used this type of data to determine how the size and geographic location of a lake influence how its ice cover length in winter has changed over time. We found that deep lakes, at lower elevations, western longitudes, and lower latitudes, are losing ice cover at relatively fast rates. Our results demonstrate that even though warming is a general pattern on our planet, these specific types of lakes are being affected disproportionately, which may help to prioritize conservation efforts to preserve freshwater biodiversity and drinking water resources.

1. Introduction

The formation and breakup of winter ice are important seasonal events for lakes. The timing of these episodes, known as ice phenology, has been monitored by humans in some cases for hundreds of years (Magnuson et al., 2000). Shifts in the duration and phenology of ice cover on lakes and streams are a highly sensitive indicator of climate variability, so these records and their trends provide early signs of ecosystem responses to climate change (Adrian et al., 2009; Kling et al., 2003). Ice phenology data are valuable in that they integrate spatial and temporal change as well as variability in climate (Benson et al., 2012; Magnuson et al., 2000; Palecki & Barry, 1986; Robertson et al., 1992; Sharma et al., 2013; Wynne, 2000). The utility of lake ice data is highlighted by the fact that (1) these data originate from middle- to high-latitude regions and incorporate climate signaling during winter and early spring, where and when temperature increases due to climate change are predicted to be the greatest (Hoegh-Guldberg et al., 2018), (2) lake ice records often exist for years and/or regions for which there are no recorded temperature data, and (3) they are observed multivariate signals related to predicted global temperature increases (Maunder, 1992; Wynne et al., 1996). Further, lake ice has been identified as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) (GCOS, 2016).

Air temperatures have been steadily rising with increasing anthropogenic emissions since the industrial revolution (Hoegh-Guldberg et al., 2018), leading to shifts in ice phenology and consistent trends toward reduced ice cover on lakes (Anderson et al., 1996; Benson et al., 2012; Hanson et al., 1992; Jensen et al., 2007; Magnuson et al., 2000; Robertson et al., 1992; Schindler et al., 1990; Sharma & Magnuson, 2014). Freezing events in Northern Hemisphere lakes generally occur in the fall and are associated with decreased air temperatures and heat loss from lakes and therefore depend on the heat storage capacity and volume of a lake (Benson et al., 2012). Spring thawing events are affected by air temperatures; however, they are also influenced by snow and cloud cover as well as wind speed (Palecki & Barry, 1986; Reycraft & Skinner, 1993; Robertson, 1989). Lake ice breakup dates are more variable than fall freezing dates (Schindler et al., 1990) and are more affected by climate forcing due to a positive feedback associated with the removal of insulating spring snow cover (Wynne et al., 1996). Changes in lake ice duration through time are greater than shifts in either individual date, since ice duration incorporates the magnitude of changes in both freezing and breakup dates (Benson et al., 2012).

Variability in lake ice freeze, breakup, and duration influences chemical and biological processes which are important components to ecosystem functioning (Hampton et al., 2017). In years when lakes do not freeze, surface water temperatures can be warmer, leading to increased primary production and algal biomass (Weyhenmeyer et al., 2008). The effects of shorter ice-covered seasons can also manifest at higher trophic positions, as they can reduce the reproductive success of fish populations (Farmer et al., 2015). Additionally, shorter ice cover durations are associated with decreased hypoxic conditions and winterkill for large-bodied temperate fish species (Stefan et al., 2001). Such conditions, however, are critical in maintaining communities of hypoxia tolerant and predation sensitive fish species (Tonn & Magnuson, 1982).

Early studies of ice phenology focused on smaller numbers of lakes located in specific geographic regions, making these results difficult to extrapolate to a global scale (Wynne, 2000). As lake ice studies have expanded their scope to continental and global scales and included lakes of varying characteristics, this variation has become a great strength of freshwater ice phenology data as a climate proxy (Magnuson et al., 2000, 2004). Specifically, Jensen and others (2007) investigated patterns of ice trend variability among 65 water bodies in the Great Lakes region (32 had records for ice duration) over 30-year time scales and found that of the lake characteristics investigated, a combination of lake elevation and air temperature trends or changes to snow cover affected ice duration trends.

Considering the wealth of available ice phenology time series data for hundreds of lakes globally from the Lake Ice Analysis Group (LIAG, Benson & Magnuson, 2000), we still lack an understanding of how global lake ice loss rates are being modulated by geography and lake-specific morphology. Recently, Sharma et al. (2019) used this large data set (LIAG, National Snow and Ice Data Center) plus additional data to identify annually and intermittently freezing lakes and found that air temperature, mean depth, elevation, and shoreline complexity were all significant predictors of whether or not a lake froze every year between 1970 and 2010 or if that lake intermittently froze within that time period. An examination of lake-specific rates of ice phenology change for many lakes worldwide of various morphologies can provide insight into how these systems modulate the general climate change signal. The objective of this study was to identify what types of lakes are losing ice cover at the fastest rates. To do this, we use ice phenology data for 220 globally distributed Northern Hemisphere lakes to determine lake-specific trends in ice duration over time and then use these patterns to infer how lake morphology (mean depth and surface area) and geography (latitude, longitude, and elevation) contribute to the observed rates of change in ice cover duration. Given that the sampling periods of our study lakes did not always overlap and may have fallen within periods of interannual variation (e.g., climate oscillations), we included the annual air temperature and precipitation trend for the sampling interval of each lake in our analysis. This allowed us to quantify the influence of morphology and geography on the ice cover trend of each while accounting for differences in air temperature and precipitation trends that were experienced during that time series. Finally, we performed our analysis on different data set constraints to test the robustness of our results.

2. Methods

2.1. Data Set

We harvested lake ice duration data and lake characteristic data from the global lakes and rivers ice phenology database (Benson et al., 2000). The LIAG database was generated through a 1996 North Temperature Lakes Long-Term Ecological Research Program meeting by Barbara Benson, Dale Robertson, and John Magnuson. LIAG is currently updated by Sapna Sharma at York University in Toronto. This data set contains ice phenology information for northern latitude lakes around the globe, with a focus on North

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America, Europe, and Eurasia. This data set has previously been used to demonstrate freshwater warming patterns caused by climate change (Benson et al., 2012; Magnuson et al., 2000; Sharma & Magnuson, 2014). The database also includes geographic and bathymetric information for most of the lakes featured, which we supplemented using supporting metadata from Sharma and others (2019). We chose ice duration observations for years after 1900 as the transition to current warming trends of later freezing and earlier thawing for lakes started in the late 1800s corresponding with the end of the Little Ice Age (Magnuson et al., 1997). For our analysis we selected lakes for which 25 or more years of time series ice duration data were available. We used a lower limit time series length of 25 years, representing a compromise between including a large sample size of lakes and including lakes that had long enough time series lengths to detect a climate change signal. Time series records used in our analyses had no more than three consecutive years of missing data (as in Jensen et al., 2007), and if a gap of greater than 3 years occurred within a lake's time series record of ice duration observations, we removed all years previous to this gap of missing data. Magnuson et al. (1991) stressed the utility of using the longest possible time series for observations of ice cover records, pointing to records that are greater than 100 years in length in order to avoid describing signals associated with interannual variability as well as the influence of global climate drivers. However, in order to examine prevailing climate trends while also including a large number of globally situated lakes, we chose a minimum time series length based on previous work that has examined variation in lake ice time series (Anderson et al., 1996; Benson et al., 2012; Jensen et al., 2007).

On average, lake ice duration time series were 51 years in length (range 25–113 years). We harvested climate data for all lakes included in our data set from the National Aeronautics and Space Administration GISS Surface Temperature Analysis database (GISTEMP V3 with 250 km smoothing) (Hansen et al., 2010; GISTEMP Team, 2019, https://data.giss.nasa.gov/gistemp/) and from the National Center for Atmospheric Research (Full Data Monthly V.2018 (V8)) (Schneider et al., 2018, https://climatedataguide.ucar.edu/). For each lake, yearly mean surface air temperature anomalies (relative to 1951–1980 means—the three-decade period used to define average temperatures by the U.S. National Weather Service) and total precipitation (September–May; as a proxy for snow cover) were harvested for each year that ice duration data were available.

2.2. Data Analysis

We assessed ice duration trends for the 220 lakes in our data set by calculating the nonparametric Theil-Sen regression for trend estimation and p values (Sen, 1968; Theil, 1950). For each lake we also determined the trends in surface air temperature and total precipitation for freeze-thaw months (to approximate snow cover) for the time series available for that specific lake using the Theil-Sen estimator.

Multiple linear regression models and second-order Akaike's information criterion (AICc) model selection were used to determine the best predictors (and directionality) of trends in lake ice duration. Theil-Sen regression estimates for each lake's time series were used as the response variables in multiple linear regression models which incorporated climate trends for each lake site (surface air temperature and fall-winter-spring total precipitation), lake geography (latitude, longitude, and elevation), and lake morphology (mean depth and surface area). Assumptions of multiple regression were tested following the methods of Zuur et al. (2010). We used variance inflation factor (VIF) metric to identify any potential collinearity between predictors in our selected models. All predictor variables were log10 transformed to approximate normal distributions and reduce skew. In addition, longitude values were standardized to each general sampling area of lakes (east and west) since most lakes were found in North America (west) and in Eurasia (east). To determine whether the significance level of Theil-Sen slope estimates of ice duration trends influenced the results of our multiple regression analyses, we tested multiple data sets by varying the significance threshold for ice duration trends (all significance levels = 220 lakes, ice duration trend $p < 0.5 = 139$ lakes, ice duration trend $p < 0.25 = 96$ lakes, and ice duration trend $p < 0.05, = 41$ lakes). This final threshold ($p < 0.05$) creates a data set of only 41 lakes, which is too few for a multiple regression analysis with our desired predictor terms, so caution should be exercised while examining these results. However, we were eager to examine how significance threshold and the number of lakes included would influence results. We applied automated model selection to each data set, which ranked each possible model (given our predictor variables) by its corresponding AICc score. Next, we combined only those models that ranked with a delta AICc less than 2, which resulted in an averaged model. Predictor variables included in each averaged model determined how, and to

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Table 1
Summarized Ice Duration Trend (Regression) Results, Showing the Number and Proportion of Lakes Losing Ice Duration Over Time (Negative Trend) and Those Gaining in Ice Duration Over Time (Positive Results)

Data set	Lakes losing ice duration	Lakes gaining ice duration
All lakes ($n = 220$)	153 (70%)	67 (30%)
$p < 0.5$ ($n = 139$)	105 (76%)	34 (24%)
$p < 0.25$ ($n = 96$)	82 (85%)	14 (15%)
$p < 0.05$ ($n = 41$)	37 (90%)	4 (10%)

Note. These results are presented as subsets of the full data set ($n_{\text{lakes}} = 220$) created based on ice duration trend significance levels—as less significant results are shed from consideration, a greater proportion of lakes show losses in ice duration.

what degree, each variable affected ice duration change over time. All analyses were performed using R statistical software (R Core Team, 2020).

3. Results

For our largest data set, most lakes (153/220 or 70%) exhibited reductions in ice duration and fewer (67/220 or 30%) showed increases in ice cover throughout their time series (Table 1 and Figure 1). A minority of lakes reported significant (at $\alpha < 0.05$) ice duration trends. However, as we varied the significance (p) threshold of lake ice duration trends, we noticed a trend toward greater proportion of lakes losing versus gaining in ice duration over time (Table 1 and Figure 1).

We examined how lake ice phenology time series length influenced the number (and proportion) of lakes losing and gaining in ice duration over time. While we expected the data set including lakes with shorter time series to have higher proportions of lakes exhibiting gains in ice duration (due to shorter-term oscillations in weather driving patterns as opposed to longer-term climate change), there was a remarkable consistency in the proportion of lakes losing ice cover regardless of lake time series length (62–80%, supporting information Table S1 and supporting information Figure S5). Averaged model selection based on ΔAICc < 2 chose a variety of combinations of predictor variables, depending on the data set considered (Figure 2 and Table 2). However, five of our seven predictor variables (air temperature trend, latitude, longitude, elevation, and mean depth) were consistently selected in averaged models for each data set used (Figure 2 and Table 2). The proportion of total variation explained by these averaged models varied among data sets ($R^2 = 0.17$–0.33, Table 2) and increased as the significance level of lake ice duration trends used in our analyses increased (Table 2).

The standardized (β) coefficients of predictor terms (Figure 2) from averaged multiple regression models for each data set indicate the relationship between each predictor variable and lake ice duration dynamics. The three selected lake geographic variables, latitude ($\beta_{\text{range}} = 1.01$–$1.70$), longitude ($\beta_{\text{range}} = 0.06$–$0.09$), and elevation ($\beta_{\text{range}} = 0.05$–$0.44$) are all positive predictors of ice duration trends; lakes at lower latitudes, more western longitudes, and lower elevations had more negative trends (faster loss rates) for ice duration. Lake surface air temperature trend ($\beta_{\text{range}} = -2.03$ to -4.12) and lake mean depth ($\beta = -0.07$ to -0.12) are both negative predictors of ice duration trends; lakes with greater increases in air temperature and deeper lakes have had more negative trends (faster loss rates) for ice duration.

Although there was general agreement in predictor variables selected and the directionality of those predictors among data sets, there were still slight differences. For example, Data Set 4 (DS4 Figure 2) only included air temperature, latitude, and elevation in the averaged model. This discrepancy may have resulted due to low sample size, since this data set only included 41 lakes, much fewer than should be employed for a multiple regression with seven predictor variables in the initial model. In addition, although elevation was selected in each data set's averaged model and was consistently positive, for one of the sets (DS1 Figure 2) elevation was not a significant factor in ice duration rate. Finally, although mean depth was selected for three of the four data sets and consistent in direction, it was also only marginally significant for two of those (DS2 and DS3 Figure 2).

4. Discussion

Our results reflect the important but poorly understood ecological reality that not all lakes are experiencing rates of ice loss equally. Here, we show that air temperature, geographic location (latitude and standardized longitudes for "eastern" and "western" lakes), elevation, and mean depth best explain interannual variation in ice cover for a 220 lake data set that spanned long time periods and a broad geographic range. These results add to a growing body of work that is uncovering just how climate change is affecting the ice cover phenology of lakes throughout the world. Our results parallel the more geographically constrained study of Jensen et al. (2007) who found that lakes in areas of higher air temperature, lower elevation, and more western longitude in the Laurentian Great Lakes region lost ice cover at higher rates. The results of our

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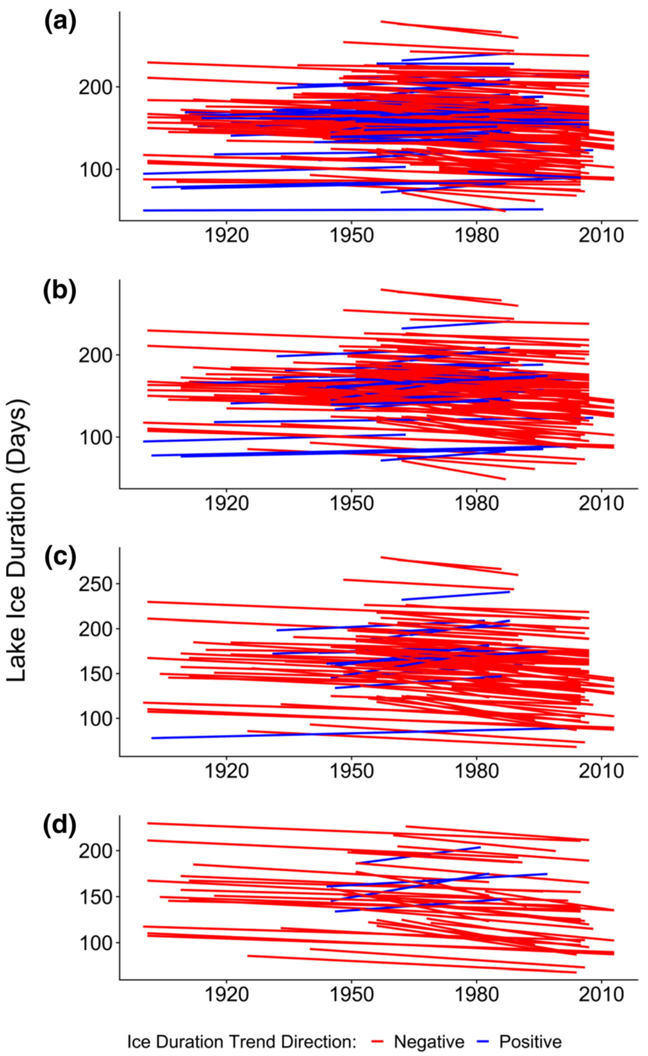

Figure 1. Summary of ice duration trend directions for (a) the entire data set of 220 lakes, (b) the data set with a significance threshold for ice duration trends at $p < 0.5$ ($n_{\text{lakes}} = 139$), (c) the data set with a significance threshold for ice duration trends at $p < 0.25$ ($n_{\text{lakes}} = 96$), and for (d) the data set with a significance threshold for ice duration trends at $p < 0.05$ ($n_{\text{lakes}} = 41$).

more expansive study differed from theirs in that lakes of greater mean depth experienced greater ice duration loss (whereas they found that increased mean depth resulted in earlier ice-off dates, a related but distinct trend). Sharma and others (2019) used a data set similar to ours to ask how warming relates to the degree of intermittent freezing winters for lakes (rather than lengths of ice duration change as we have done), finding that lake elevation and mean depth affect ice cover intermittency but not addressing geographic location of the lakes.

An observation made here that merits some exploration is that some lakes showed increases in ice cover over time in our study. One plausible explanation for this observation is the relatively short minimum threshold that we employed for time series lengths (≥25 years). Given this, decadal trends in temperature driven by meteorological phenomenon could be responsible for these observations of increased ice cover over time. However, the proportion of lakes that experienced increases and decreases in ice duration remained consistent regardless of time series length (Table S1 and Figure S5), suggesting that other factors might be responsible.

In agreement with previously published findings (McFadden, 1965; Palecki & Barry, 1986; Tramoni, 1985), our results showed that local air temperature trends over time had the greatest impact on lake ice cover phenology (Figure 2). More interesting are our findings that lake location (latitude, longitude, and elevation) and morphology (mean depth) affected trends in lake ice cover duration beyond the effect of air temperature. The spatial dependence of lake ice duration data was noted in many early ice phenology studies (Magnuson et al., 1997; Wynne et al., 1996; 1998), with this dependence most often related to the influence of latitude (as a covariate of air temperature) and local snowfall trends.

We found that trends of shorter ice-covered seasons for lakes are occurring faster in lower-latitude regions of the globe (Figure 2), running counter to prevailing patterns of more intense warming occurring in northern regions (arctic amplification, Serreze & Barry, 2011, supporting information Figure S6). These results, however, are congruent with latitudinal patterns of ice phenology over smaller spatial scales (Jensen et al., 2007; Mishra et al., 2011), indicating that this pattern is more universal than previously thought. Greater ice duration loss rates for more southern lakes may result from the nonlinear relationship between ice breakup date and air temperature (Weyhenmeyer et al., 2004); a small increase in temperature may switch a lake from freezing to open when it occurs near 0°C (Jensen et al., 2007).

When lake longitudes in our data set were scaled to two general global regions (North America versus Europe/Russia/Asia or “western” and “eastern”), lakes in western regions of both continental areas were found to be losing ice cover at the fastest rates (Figure 2). This longitudinal trend was qualitatively noted for the Laurentian Great Lakes region by Jensen and others (2007). Stronger trends for earlier ice breakup in western lakes were also found in a study analyzing ice phenology data for Canadian lakes between 1951 and 2000 (Duguay et al., 2006). In North America (our “western” region), lakes losing ice cover faster at more western longitudes match the disproportionate warming of those areas between 1900 and 2015 compared to eastern areas of North America (supporting information Figure S6). In the “eastern” part of our global study area which includes Eurasian lakes, we noticed the same pattern of lakes losing ice cover faster at the western areas of the region. Although temperature anomalies between 1900 and 2015 (supporting information Figure S6) indicate that eastern regions of Eurasia have become warmer compared to western areas, we note that a disproportionate amount of lakes from this part of our data set is situated in Sweden and

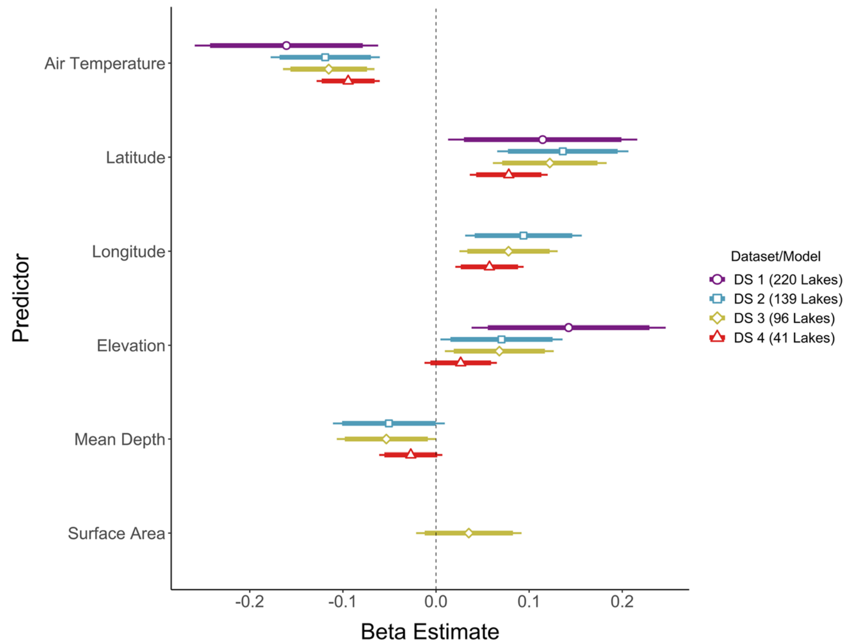

Figure 2. Standardized β coefficients from averaged multiple regression models illustrating the consistency in results across data sets of different ice duration trend inclusion criteria.

southern Finland. It is possible that the many lakes from these countries, which have experienced high increases in winter temperatures over this time period compared to other areas in Eurasia, could indeed be driving this trend.

The longitudinal signatures noted in our results could also be related to large-scale climatic oscillations resulting from atmospheric variations in the Atlantic and Pacific Oceans which affect 0°C isotherm dates (Bonsal & Prowse, 2003) across longitudinal ranges during spring and autumn. These anomalies exist over large areas, affecting regional climates and are called "teleconnections" (Wallace & Gutzler, 1981). Since

Table 2
Averaged (Models With ΔAICc < 2) Multiple Regression Models of Ice Duration Trends and Geographic/Morphological Lake Characteristics, for Each Data Set Considered (1-4)

Data Set 1 (all ice duration significance levels, 220 lakes)					
Air temperature trend	**Latitude**	**Longitude**	**Elevation**	**Mean depth**	**R^2 range**
−2.03***	1.01***	0.06***	0.05	−0.07	0.17–0.18
Data Set 2 (ice duration slope p values < 0.5, 139 lakes)					
Air temperature trend	**Latitude**	**Longitude**	**Elevation**	**Mean depth**	**R^2 range**
−2.53***	1.70***	0.08***	0.14*	−0.11*	0.19–0.24
Data Set 3 (ice duration slope p values < 0.25, 96 lakes)					
Air temperature trend	**Latitude**	**Longitude**	**Elevation**	**Mean depth**	**R^2 range**
−2.55***	1.70***	0.09***	0.16*	−0.12*	0.21–0.26
Data Set 4 (ice duration slope p values < 0.05, 41 lakes)					
Air temperature trend	**Latitude**	**Longitude**	**Elevation**	**Mean depth**	**R^2 range**
−4.12***	1.44*	NA	0.44**	NA	0.33

Note. Results shown are raw beta coefficients (β) for each predictor variable and for each data set (1-4) used.
*0.1. **0.05. ***0.01.

both our "east" and west" sets of lakes are composed of nonoverlapping time series, it is difficult to determine exactly which types of teleconnections are acting on eastern or western lakes and at what times. However, ice phenology data are known to correlate with these large-scale drivers which vary over longitude, including El Niño–Southern Oscillation (ENSO) (Anderson et al., 1996; Bonsal et al., 2006; Livingstone, 2000; Magnuson et al., 2004), the North Atlantic Oscillation (NAO) (Livingstone, 1999; Magnuson et al., 2004), the Pacific Decadal Oscillation (PDO) (Bonsal et al., 2006; Magnuson et al., 2004), the Pacific North American Pattern (PNA) (Benson et al., 2012; Bonsal et al., 2006), the Western Pacific Pattern (WP) (Benson et al., 2012), the North Pacific Index (NP) (Magnuson et al., 2004), and the Arctic Oscillation (AO) (Bonsal et al., 2006).

We found trends of reduced ice cover for lower elevation lakes globally (Figure 2). This finding runs counter to predictions of ice cover models that faster losses in ice duration will occur at higher elevations (Thompson et al., 2005). However, that model predicts absolute (not relative) changes in ice duration. Since lower elevation lakes have shorter ice-covered periods than higher elevation lakes to start with, the maximum absolute levels of change will be greatest for high elevation lakes. Slower rates of change for ice duration trends at higher elevations that we have noted here may be related to the effects of adiabatic cooling at higher elevation sites or may involve other climate factors that we were unable to include in our model such as wind speed and snow cover. We found no trends between total precipitation trend in the fall, winter, and spring months and lake elevation (range 2–1,797 m); however, this proxy for snow cover is not as informative as total snow cover days or snow thickness would have been and may have helped illuminate the direct mechanisms for why lower elevation lakes are losing ice cover at faster rates.

Lake depth is an important physical factor in ice formation and therefore ice cover duration for Northern Hemisphere lakes (Vavrus et al., 1996). Deeper lakes require more time to lose heat to cooler air temperatures and come to thermal equilibrium with the atmosphere (Wynne, 2000). Our analyses revealed that deeper lakes are experiencing ice cover loss at greater rates than shallower lakes (Figure 2). Although lake mean depth was only selected as part of the averaged model in three of four data sets, it was found to be negative in all three and was marginally significant ($p < 0.1$) in two of those three. This negative trend may result from the greater thermal inertia of deeper and larger lakes compared to smaller lakes (Assel, 1986), which harbor greater amounts of heat energy throughout the summer months, taking longer to cool and freeze in the winter and therefore showing greater reductions in ice cover duration. The greater effective fetch of larger lakes (Assel, 1986) and the fact that insulating snow tends to be retained on smaller lakes and more likely blown off of larger lakes (Vavrus et al., 1996) may accelerate the loss of ice cover for larger lakes by causing breakup earlier in the spring. Larger lakes are known to house greater species diversity for fish (Barbour & Brown, 1974; Eadie et al., 1986; Eckmann, 1995; Magnuson, 1976), breeding waterfowl (Elmberg et al., 1994), and macroinvertebrates (Zhengda et al., 2015). Large lakes being disproportionately affected by warming climates therefore represent an increased threat to these repositories of high species diversity and integral sources of freshwater.

Our multiple regression models demonstrate informative and useful trends in climate change effects on freshwaters, but they also explained a relatively small proportion of the overall variation in ice cover dynamics (R^2 range = 0.17–0.33). A great amount of variation went unexplained, probably owing to a lack of comprehensive local climate data for each time series used. Ice duration is affected by the extent and thickness of snow cover (Vavrus et al., 1996), the thickness of the ice itself (Robertson et al., 1992) as well as wind speeds (Palecki & Barry, 1986), cloud cover, relative humidity, and air pressure (Gebre et al., 2014), all of which could have improved model fit. In addition, our lake ice duration time series were often nonoverlapping or did not include the same set of years in analyses. Although we addressed this issue by using local climate data (air temperature trend as well as fall, winter, and spring total precipitation trend), the aforementioned unused climate factors may have varied widely between our time series. Large-scale climate oscillations also act to change local climate at various timescales and have been shown to explain variation in lake ice phenology (Benson et al., 2012; Ghanbari et al., 2009; Sharma et al., 2013).

The winter ice-covered period is decreasing for the majority of Northern Hemisphere lakes (Sharma et al., 2019). Although freshwater ice cover loss is ubiquitous, our results suggest that rates of lake ice loss are also affected by the geographical location and morphology of lakes themselves. Interestingly, our results expand on and agree with previous work that has attempted to identify lake-specific differences in the rate of lake ice phenology dynamics (Jensen et al., 2007; Sharma et al., 2019). Working toward the ability to classify lakes or regions that are at greater risk to reduced ice cover is essential, as lake ice loss could contribute to decreased freshwater availability (Xiao et al., 2018). Lake ice cover is important to the physical, chemical, and biological processes of lake ecosystems (Hampton et al., 2017; Wang et al., 2018). The loss of winter ice affects lake biology in subsequent summers (Blank et al., 2009; Hampton et al., 2017), and earlier spring ice loss increases algal biomass and primary production (Weyhenmeyer et al., 2008), accelerating the problem of eutrophication in freshwaters. Warming and ice phenology changes also affect higher trophic levels by potentially reducing fish population size by decreasing reproductive success (Farmer et al., 2015). The loss of inland ice cover inevitably reduces the use of lake ice cover by people, thus reducing the value of services that these lake ecosystems provide. Apart from the economic value of ice cover, cultural ecosystem services including education, ceremonial activities, ice fishing, and skating (Knoll et al., 2019) will also be eroded as climate warming decreases the length and extent of ice cover on lakes.

5. Conclusions

Ice phenology time series data were used to determine relative rates of lake ice duration change and to examine how those responses are related not only to air temperature trends but also to lake size (mean depth) and geography (elevation, latitude, and longitude). Our results suggest that while the relentless pace of climate change is causing Northern Hemisphere lakes to warm and lose ice; this signal is more strongly experienced by large lakes at lower elevations and situated at western longitudes and lower-latitude regions. These results can inform local to global conservation priorities for lake ecosystems and direct precious rehabilitation and research funding under future climate warming scenarios.

Data Availability Statement

For now, supporting information data are available in Table S2. We plan to deposit this data set into a repository at Open Science Framework (https://osf.io).

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