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Quantifying the Trends and Drivers of Ice Thickness in Lakes and Rivers across North America

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Abstract: Monitoring the timing of ice-on and ice-off has been instrumental in estimating the long-term effects of climate change on freshwater lakes and rivers. However, ice thickness has been studied less intensively, both spatially and temporally. Here, we quantified the trends and drivers of ice thickness from 27 lakes and rivers across North America. We found that ice thickness declined on average by 1.2 cm per decade, although ice thickness declined significantly in only four waterbodies. Local winter air temperature, cloud cover, and winter precipitation were the most important determinants of ice thickness, explaining over 81% of the variation in ice thickness. Ice thickness was lower in years and regions with higher air temperatures, high percentage of cloud cover, and high winter precipitation. Our results suggest that warming is contributing to thinning ice, particularly at high latitudes, with potential ramifications to the safety of humans and wildlife populations using freshwater ice for travel and recreation.

Keywords: climate change; ice thickness; warmer air temperatures; North American lakes and rivers

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1. Introduction

Freshwater ice acts as the base for numerous winter activities, such as snowmobiling, ice fishing, ice hockey, skating, and winter festivals [1,2]. Ice thickness can be a limiting factor in these winter activities, as lakes must attain a certain level of thickness before these activities are safe to occur [3]. For example, winter ice roads are important for transportation of goods and connecting remote communities during the winter months but require ice to be more than a metre thick [4,5]. An ice fishing tournament can generate ~$1 million USD in revenue over a weekend but requires at least 15 cm of ice for it to be safe for anglers [2]. Understanding the trends and drivers of ice thickness is critical for a preliminary assessment of ice safety for human use [3].

Ice is being rapidly lost from lakes and rivers across the Northern Hemisphere [6–9]. Recent estimates suggest that the timing of ice formation is 11.0 days later, ice melt is 6.8 days earlier, and ice duration is 17.0 days shorter per century for 60 lakes across the Northern Hemisphere [10]. Alarmingly, ice is being lost six times faster in the last quarter century than any other 25-year period over the past 100 years [10]. Trends in ice thickness appear to be less clear or significant. Although remote sensing of lakes larger than 50 km^2 suggested that ice thickness in most lakes was declining, only 10% of these trends were significant [11]. Across Finland, a general trend in ice thickness has not yet been observed, although ice duration is clearly shorter [12]. For example, ice thickness increased in northern lakes with increased snowfall, whereas ice thickness decreased in southern lakes [12]. However, ice thickness has generally decreased in lakes in the Arctic and northern Europe [13], and since 1955, ice thickness has generally decreased across lakes and rivers in Russia [14], and since 1961, ice thickness has decreased by 2.5 cm per decade in lakes from northern Poland [15]. The interplay between local, regional, and global weather and large-scale climate drivers complicates the prediction of changes in ice thickness.

Weather conditions in early winter, such as air temperatures, snowfall, winter precipitation, solar radiation, and cloud cover, in addition to large-scale climate oscillations, all play an important role in ice thickness [3,15–19]. Cold air temperatures are critical to ice formation and growth [16,18,20] and, in temperate lakes, winter air temperatures have been strongly correlated to ice thickness [21]. Winter precipitation, including snowfall and snow depth, are also important drivers of ice thickness and in some studies found to be the most important driver of ice thickness [22,23]. Snowfall can facilitate ice formation at the beginning and during the ice cover season by acting as a source of snow-ice but subsequently can also slow ice growth by providing insulation [16,18,24]. For example, in Alaska, the years with the thinnest ice coincided both with warm air temperatures and heavy snowfall [25], whereas, in Lake Baikal, Russia, the years with the thickest ice corresponded to cold winters with low snowpack [26]. Finally, large-scale climate drivers can impact ice thickness as well [27–35]. For example, a Pacific Decadal Oscillation shift that occurred in 1976 resulted in thinner ice, as well as shorter ice duration in Alaskan lakes [23].

In this study, we used long-term records of ice thickness data for 23 lakes and 4 rivers across North America to ask two questions: (1) Are there changing trends in ice thickness over time? and (2) What are the relative roles of local weather and large-scale climate drivers on ice thickness? Previous observational studies have examined lake ice thickness in detail within single lakes [18,20,24,36] and regionally such as in Alaska [25,37]; Finland [12], and Russia [14]. Here, we expand our study to include observations across North America to understand the empirical drivers of lake and river ice loss at a broader spatial and temporal scale.

2. Materials and Methods

2.1. Data Acquisition

We collected ice thickness data for 23 lakes and 4 rivers across North America, each having at least 8 years of data. These data were collected using data search engines such as 'Google Data Toolbox' and 'Google Search', with key search terms such as 'ice thickness', 'ice depth', 'ice thick', and 'thick'. We only included data that were measured in situ and excluded data collected through satellite methods. Data on ice thickness for most lakes and rivers collected were in Alaska, USA, obtained from the National Science Foundation (NSF) Arctic Data Center from a dataset created by Christopher Arp [38], or Wisconsin from data acquired by the North Temperate Lakes Long-Term Ecological Research Network (lter.limnology.wisc.edu). In Canada, many of the observations were from data collected by the Government of Canada's ice thickness program [39]. The earliest measurement year was in 1962 from Lake Imikpuk and Kuskokwim River, and the latest measurement date was 2020 for 13 of the lakes and rivers included in this study. Each time series began after 1961 and ranged from 8 years to 57 years long (Table 1).

To investigate the weather and climate drivers of ice thickness, we obtained local air temperatures, local cloud cover, local precipitation, and large-scale climate drivers. For each waterbody, we acquired the mean monthly air temperature, monthly cloud cover, and monthly precipitation from the University of East Anglia's Climatic Research Unit (CRU TS4.02). CRU weather variables are measured at a 2 m level above ground and available on a 0.5 grid cell from 1900–present [40]. We extracted weather variables from 1961 to 2020 at the closest grid to the waterbody. To calculate seasonal winter weather conditions, we averaged monthly air temperature, monthly cloud cover, and monthly precipitation from December, January, February, and March. Unfortunately, we were unable to access solar radiation and snowfall and snow cover data for the study lakes and rivers across the length of the time series, so we used winter cloud cover and winter precipitation as a proxy.

Table 1. Waterbodies with ice thickness data collated in North America. Our study included 23 lakes and 4 rivers across North America, with data starting as early as 1961 and going as far as 2020. We summarized the mean and range in ice thickness, in addition to the trends in ice thickness over time. The trend column shows the slope obtained from the Thiel-Sen estimator, with its associated *p*-value in the '*p*-Value' column.

Waterbody Name	Location	Years Range	Ice Thickness Range (cm)	Mean Ice Thickness (cm)	Trend (cm/decade)	*p*-Value
Lake Hood	Alaska, USA	1997–2019	46–84	66.59	2.31	0.67
Imikpuk Lake	Alaska, USA	1962–2019	114–211	167.08	−25.00	<0.001
Kuskokwim River	Alaska, USA	1962–2019	69–159	117.13	−4.37	0.07
Koyukuk River	Alaska, USA	1968–2019	69–182	108.65	−1.33	0.45
Yukon River	Alaska, USA	1999–2019	67–157	116.71	20.97	0.03
Smith Lake	Alaska, USA	1965–2019	54–101	70.21	−1.68	0.07
Lake Minchumina	Alaska, USA	1997–2019	62–123	98.00	−16.92	0.07
Tanana River	Alaska, USA	1989–2019	69–128	104.52	−5.33	0.28
Baker Lake	Nunavut, Canada	1958–2020	92–290	211.15	−4.14	<0.001
Resolute Lake	Nunavut, Canada	1947–2020	94–238	193.51	0.93	0.49
Lake Superior	Wisconsin, USA	1963–2000	34–100	70.50	−6.67	0.01
Primrose Lake	Saskatchewan, Canada	1975–2000	30–118	73.42	−10.00	0.06
Island Lake	Manitoba, Canada	1971–1998	70–137	90.11	0.00	0.97
Macdonald Lake	Ontario, Canada	2009–2017	39.68–66.75	52.26	−1.47	0.92
Little Rock Lake	Wisconsin, USA	1984–2000	35–60	45.59	3.54	0.46
Allequash Lake	Wisconsin, USA	1982–2020	34–78	53.85	0.00	1.00
Big Muskellunge Lake	Wisconsin, USA	1982–2020	40–75	54.49	0.00	0.79
Lake Wingra	Wisconsin, USA	1997–2020	13–45	31.68	−0.44	0.78
Lake Monona	Wisconsin, USA	1996–2020	27–50	37.10	2.18	0.57
Lake Mendota	Wisconsin, USA	1996–2020	17–64	34.73	−3.33	0.47
Fish Lake	Wisconsin, USA	1997–2020	12–52	34.95	4.12	0.09
Trout Lake	Wisconsin, USA	1982–2020	30–77	52.79	0.77	0.68
Green Lake	Colorado, USA	1984–2019	0–150	87.44	13.08	0.19
Sparkling Lake	Wisconsin, USA	1982–2020	32–72	49.29	−0.59	0.62
Crystal Bog Lake	Wisconsin, USA	1982–2020	30–63	44.11	1.25	0.43
Crystal Lake	Wisconsin, USA	1982–2020	28–73	47.86	0.53	0.75
Trout Bog Lake	Wisconsin, USA	1982–2020	27–68	45.88	0.00	0.93

Finally, we gathered annual large-scale climate driver data from the National Oceanic and Atmospheric Administration (NOAA) for 1961–2018. The large-scale climate data that we acquired included the Southern Oscillation Index (SOI), El Nino/Southern Oscillation Index (NINO3), Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), Quasi-Biennial Oscillation (QBO), North Atlantic Oscillation (NAO), and the sunspot cycle. Lastly, global carbon dioxide concentrations were obtained from NOAA (Tans, NOAA). We acquired a combination of these large-scale climate drivers to encapsulate a variety of atmospheric processes that are associated within these indices and because they have been well associated with ice phenology and ice thickness previously in the literature [27–35]. For example, the QBO is associated with equatorial zonal winds and is believed to have a period between 1.5 and 3 years [41,42]. ENSO considers the variation in surface water temperatures of the tropical eastern Pacific Ocean and the variation in pressure of the air surface in the tropical western Pacific Ocean and is hypothesized to have a period of 3–7 years, with an average of 4 years [43]. The sunspot cycle reflects the amount of solar-magnetic activity on the sun. The average length of the sunspot cycle has been identified as approximately 11 years [40,41,44,45].

2.2. Data Analysis

2.2.1. Trends in Ice Thickness

We used a Thein–Sen slope estimator on the time-series for each lake and river using the 'trend' package in R [46], in order to quantify the trends and their significance in the ice thickness and identify whether ice thickness was increasing or decreasing over time for each lake and river. In this analysis, ice thickness was the response variable and year was the independent variable. The Sen's slope estimates the median of slopes of best fit lines fitted through all possible pairs of points, and we chose this estimator as it is an efficient non-parametric approach to fit linear trends, resilient to outliers, and provides a more conservative slope estimate relative to linear regression models [47]. We multiplied the

Sen's Slope by 10 to identify the trend calculated in centimeters per decade for each lake and rivers.

2.2.2. Drivers of Ice Thickness

We first investigated the relationship between ice thickness and our climate variables using the non-parametric Spearman correlations. More specifically, we investigated the correlations between the ice thickness, winter air temperatures, winter cloud cover, winter precipitation, AMO, AO, PDO, QBO, SOI, NINO3, NAO, global carbon dioxide, and sunspot numbers. We used the more conservative non-parametric Spearman correlation because some of our climate variables were not normally distributed and could be spatially or temporally correlated among observations.

We used an ordinary least square multiple regression model to investigate how local winter air temperatures, local precipitation, local cloud cover, and large-scale climate drivers (NAO, SOI, AO, AMO, PDO, QBO, NINO3, and solar sunspot cycles) influence the ice thickness of all of the waterbodies in a single global model. Again, in this case, ice thickness was the response variable, and the predictor variables were local weather and large-scale climate drivers. To identify the most parsimonious model, we chose the model with the lowest Akaike Information Criterion (AIC) [48].

3. Results

The maximum ice thickness in the lakes and rivers considered in this study ranged between 0 cm (i.e., ice free) and 290 cm. Lakes in Alaska and Nunavut had the greatest mean ice thickness, with mean ice thickness values ranging between 70 and 211 cm. Lakes in Wisconsin and other parts of the contiguous US typically had less ice thickness, ranging between 30 and 60 cm (Table 1).

3.1. Trends in Ice Thickness

We found that ice thickness in thirteen of the lakes and rivers in our study declined over time, four experienced no change at all, and the remaining ten waterbodies showed an increase in ice thickness. Thirteen waterbodies exhibited negative Sen's slopes, suggesting decreasing ice thickness over time, albeit only four were significant at $p < 0.05$ (Table 1). Lakes located at higher latitudes were more likely to have a trend of decreased ice thickness, compared to lakes located further south, such as in Wisconsin, which either did not change at all or increased non-significantly. Lake Imikpuk, Alaska had the fastest rate of ice thickness loss over all the waterbodies studied with a trend of losing 25 cm per decade (Table 1; Figure 1). Interestingly, Yukon River, also located in Alaska, had the greatest positive trend in ice thickness of 20.97 cm per decade (Table 1).

3.2. Drivers of Ice Thickness

Maximum ice thickness was strongly and negatively correlated with mean winter air temperatures (r = −0.84, $p < 0.05$), mean winter cloud cover (r = −0.77, $p < 0.05$), and mean winter precipitation (r = −0.74, $p < 0.05$) (Figure 2). Maximum ice thickness was also negatively and significantly correlated with PDO (r = −0.09, $p < 0.05$), AO (r = −0.07, $p < 0.05$), AMO (r = −0.20, $p < 0.05$), NAO (r = −0.11, $p < 0.05$), and global carbon dioxide concentrations (r = −0.27, $p < 0.05$). Warmer winter temperatures, which are shown to strongly predict ice cover [10,34], were positively correlated with winter cloud cover (r = 0.78, $p < 0.05$), winter precipitation (r = 0.79, $p < 0.05$), PDO (r = 0.13, $p < 0.05$), NINO (r = 0.08, $p < 0.05$), AMO (r = 0.25, $p < 0.05$), and global carbon dioxide concentrations (r = 0.34, $p < 0.05$). High cloud cover, which could imply lower levels of solar radiation, was positively correlated with PDO (r = 0.11, $p < 0.05$), NINO (r = 0.08, $p < 0.05$), AO (r = 0.08, $p < 0.05$), AMO (r = 0.25, $p < 0.05$), and global carbon dioxide concentrations (r = 0.38, $p < 0.05$). Increasing cloud cover was negatively associated with sunspots (r = −0.19, $p < 0.05$). Increased winter precipitation was positively associated with AO (r = 0.08, $p < 0.05$), AMO (r = 0.1,

$p < 0.05$), global carbon dioxide ($r = 0.24$, $p < 0.05$), and negatively associated with sunspots ($r = -0.07$, $p < 0.05$).

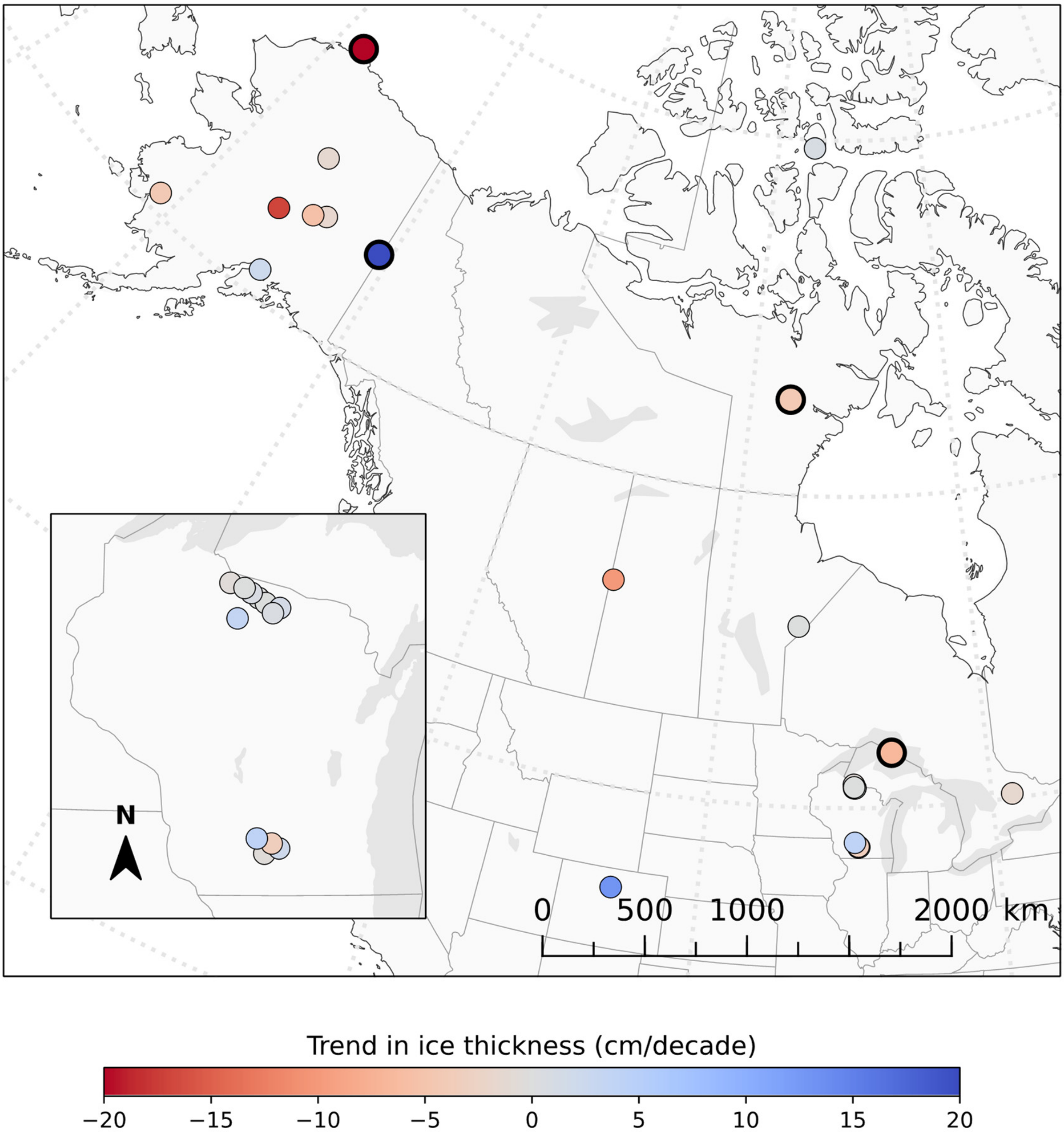

Figure 1. Trends in ice thickness (cm/decade) for lakes and rivers across North America. Spearman correlations for drivers affecting maximum ice thickness (cm) of lakes. Decreasing trends in ice thickness are represented by warmer colors and increasing trends in ice thickness are represented by cooler colors.

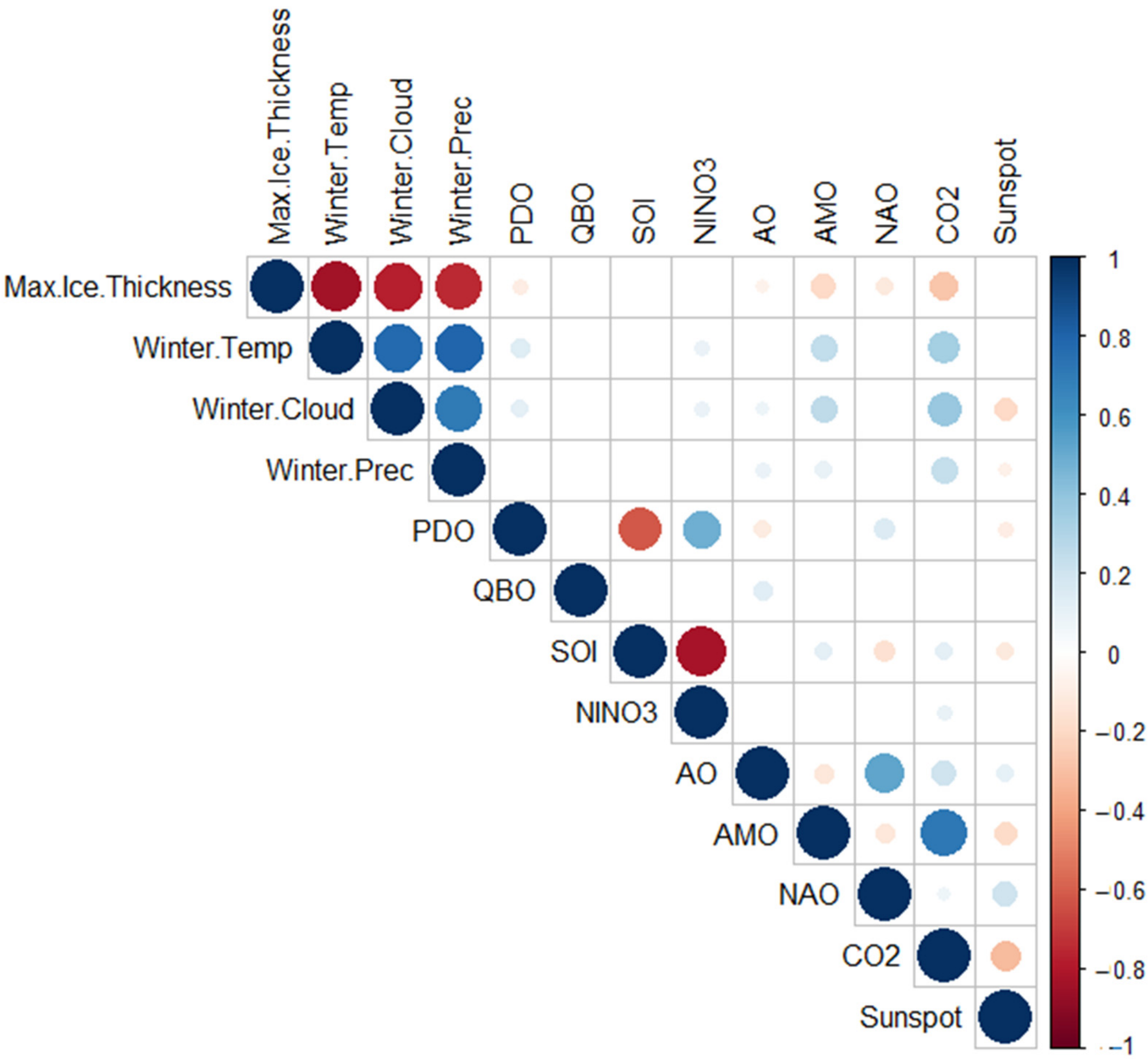

Figure 2. Spearman correlations for drivers affecting maximum ice thickness (cm) of lakes and rivers. The area of the dots and the color intensity are proportional to the strength of correlation of the variables. Positive correlations are represented by cooler colors and negative correlations are represented by warmer colors. Empty grids represent non-significant correlations. Names of variables include: Max.Ice.Thickness: Maximum ice thickness (cm); Winter.Temp: Local winter air temperature, Winter.Cloud: Local winter cloud cover; Winter.Prec: Local winter precipitation; PDO: Pacific Decadal Oscillation; QBO: Quasi-Biennial Oscillation; SOI: Southern Oscillation Index; NINO3: El Nino Southern Oscillation Region 3; AO: Arctic Oscillation; AMO: Atlantic Multidecadal Oscillation; NAO: North Atlantic Oscillation; CO2: Global carbon dioxide (ppm); and Sunspot: Annual sunspot numbers.

Air temperatures, cloud cover, and winter precipitation were significant factors affecting ice thickness and explained 81.1% of the variation (Figure 3). Ice thickness decreased with warming winter air temperatures, increased winter cloud cover, and increased winter precipitation for all waterbodies combined, as shown by the most parsimonious multiple linear regression model (AIC: 8428):

$$\text{Maximum ice thickness (cm)} = 171 - 3.7 * \text{mean winter air temperature} - 2 * \text{mean winter cloud cover} - 0.12 * \text{mean winter precipitation} \quad (1)$$

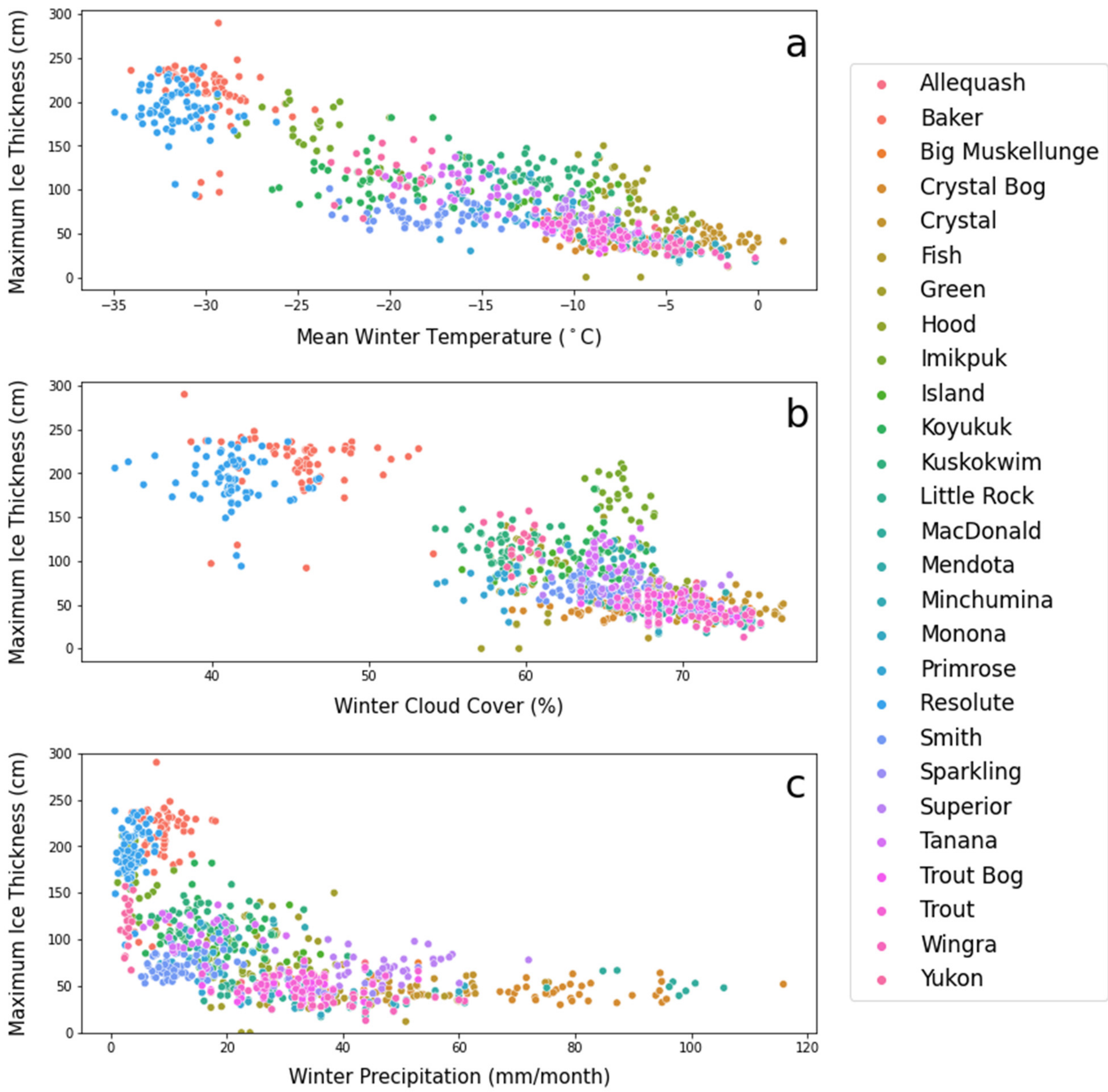

Figure 3. Maximum ice thickness (cm) against (**a**) mean winter air temperatures (°C), (**b**) winter cloud cover (%), and (**c**) winter precipitation (mm/month) for 27 waterbodies in North America. The different colors represent the lakes and rivers considered in the study.

4. Discussion

Patterns of ice thickness in North America since 1962 reflect climate change trends around the continent. Trends analysis revealed that ice thickness is declining by 1.2 cm per decade on average for 27 lakes and rivers in North America with decreasing trends of ice thickness over the years for more than half of our waterbodies. Ice thickness declined most rapidly in lakes and rivers with the thickest ice, generally found at more northern latitudes. Typically, we did not observe significant trends in ice thickness for lakes at more southern latitudes. We found that a combination of warmer winter air temperatures, increased winter cloud cover, and increased winter precipitation explained declining ice thickness and 81% of the variation.

Although ice is forming later and melting earlier in most lakes and rivers across North America [6,7,10], the trends for ice thickness are not as clear, which may be explained in part by the complex interplay of climatic factors governing ice growth and thickness [18], in addition to a relatively short time series [49]. Relatively short time series may have contributed to only 15% of our lakes exhibiting significant trends in ice thickness. In a study of 1313 simulated large lakes and reservoirs across the Northern Hemisphere, ice thickness only significantly declined in 10% of the study systems [11]. Although there is not yet a consistent trend in ice thickness over time, there is considerable variation in ice thickness amongst years with an over 65 cm difference in ice thickness, on average, amongst years. In Baker Lake, Nunavut, ice thickness varied between 92 and 290 cm and in Green Lake, Colorado since 1984, thickness varied from 0 cm and no ice to 150 cm thick ice. Similarly, in MacDonald Lake in central Ontario, the decay of lake ice thickness was higher in 2014 and 2015 (−0.77 rate of decay per year), compared to 2012 (−0.44 rate of decay per year) [20]. However, across a longer time series, ice thickness studies conducted in lakes and rivers across Russia since 1955 found a significant decline in ice thickness over time [14].

Generally, we found that, across 27 lakes and rivers, ice thickness declined by 1.2 cm per decade on average and that the most northern lakes and rivers were most sensitive to the fastest rate of declining ice thickness. Similarly, Li et al. [11] found that ice was thinning fastest in lakes found at high latitude and altitudes. Lakes with the thickest ice cover were experiencing the fastest ice loss across the Northern Hemisphere [11], as we observed in this study. However, we found that, in lakes at southern latitudes, ice thickness was increasing, albeit insignificantly, even though these lakes are experiencing significant rates of ice cover loss through the winter season [10]. Conversely, in Finland, the most southerly lakes were losing ice the fastest, whereas ice thickness increased in the northern lakes because of increased snowfall [12]. However, with climate warming, ice thickness is forecasted to decline in Finnish lakes and even a 2–3 °C increase in air temperatures could yield ice that is too thin to be used by people safely in most lakes across Finland [17].

A combination of winter air temperatures, winter precipitation, and winter cloud cover explained 81% of the variation in ice thickness across 27 North American waterbodies. Decreases in ice thickness in North American lakes and rivers appear to be greatest in years with higher air temperatures. Warmer winter air temperatures were strongly correlated ($r = -0.84$, $p < 0.05$) with declining ice thickness. Similarly, strong correlations ($r = -0.91$) between winter air temperatures and ice thickness existed for a single lake, MacDonald Lake, in central Ontario [20]. The strong relationship between ice and air temperatures is consistent with earlier studies of ice thickness [12,15,20,21,36], although there may be a nonlinear response between air temperature and ice events [50,51]. Detailed long-term analysis of ice growth in Lake Ladoga over a 100-year period suggested that ice thickness is proportional to the square root of accumulated freezing degree days as ice grew linearly until February, then ice growth slows down during the depths of winter, after which ice thickness begins to drop rapidly in late March or April until ice breakup in May [51]. Nevertheless, each study illustrated that warmer local winter air temperatures explained most of the variation in measures of ice thickness as cold air temperatures are required to thicken ice as the lake cools through the winter [14,15]. Not only are low winter air temperatures important to ensure thicker ice, but also the formation of thicker layers of black ice, which has a higher load bearing capacity. At the beginning of winter, consistently cold temperatures, low wind, and no precipitation play a strong role in the formation of thick, strong, black ice [52].

In our study, we found that maximum ice thickness was strongly and negatively correlated with mean winter cloud cover ($r = -0.77$, $p < 0.05$) and mean winter precipitation ($r = -0.74$, $p < 0.05$). Unfortunately, we were unable to acquire direct measurements of snowfall and snow cover on the lake owing to the broad spatial and temporal scales covered in this study. However, we used winter cloud cover and precipitation as a proxy of the amount of light, rainfall, or snowfall reaching the lake's surface [30]. We found that, across 27 North American lakes and rivers, ice was thicker in years and regions with more winter precipitation and cloud cover. Increased cloud cover can reflect solar energy away from the lake surface, trap shortwave radiation, and also limit the solar radiation inputs reaching the lake's surface, thereby contributing to the growth of ice in the winter [14,53], but also can reflect cloudy conditions and precipitation. Decreased snow depth can be associated with thicker ice formation [14] and snow cover can act as an insulator, which influences the rate at which black and white ice forms [22]. However, other studies have found increasing ice thickness with increased snowfall as snowfall can be a source of snow-ice [11,12,54]. For example, ice thickness in Lake Abashiri in Hokkaido, Japan was strongly dependent on snowfall depth, even more so than air temperatures [55]. For this set of lakes and rivers distributed across North America, we found that, on average, thicker ice was generally associated with increased winter precipitation, although responses of individual waterbodies were less consistent. Increased amounts of snowpack on the lake can increase surface albedo, limit the amount of solar radiation reaching the lake's surface, and facilitate the production of ice, which can ultimately yield thicker ice cover [18,32,56]. Winter precipitation in the form of rainfall can reduce surface albedo, increase light attenuation into the water column, melt the snow or ice on the lake's surface, and contribute to the formation of slushy grey ice [18,52]. Although there are contrasting effects of snowfall on ice thickness, there is a much clearer link between snowfall and ice quality. For example, after a heavy snowfall, ice can crack, resulting in some of the lake water coming to the surface and saturating the snow. At negative air temperatures, this wet snow will gradually freeze and form lower quality white ice. However, if temperatures remain above freezing, then a layer of white ice may not form as freezing of the layer of wet snow may not occur. In warmer and wetter winters, the formation of white ice may not occur at all, but rather form a layer of wet snow or slush, which could result in reduced maximal ice thickness [14,57,58]. Under future scenarios of climate change, small lakes in central Ontario are forecasted to result in thinner ice. However, if there is less snow cover, the thinner ice may be stronger with higher load bearing capacity with higher likelihood of black ice, but if winter air temperatures are closer to 0 °C, then the thinner ice will likely be comprised of white ice and much weaker [59]. For future studies, we recommend reporting snow depths on top of the ice, in addition to ice thickness, so that researchers can more fully explore the role of snow on ice thickness and ice quality in empirical models [3,59].

We found that ice thinned on average by 1.2 cm per decade for 27 lakes and rivers in North America. Both wildlife and humans are vulnerable to thinning of lake and river ice. Changes in ice thickness can affect wildlife by changing migration routes and population demographics. For example, the loss of ice can increase the travel distances for caribou that typically would have crossed frozen lakes [60,61]. Although caribou can swim through the frigid open waters in winter, it is not an energetically favorable option and can significantly increase the risk of drowning because of the absence or incomplete formation of ice [61]. In the 1980s, almost 10,000 migratory caribou drowned in the Quebec-Labrador Peninsula because of thin ice [60]. Furthermore, as ice thickness and ice stability decline in warmer winters, more people have drowned through unsafe ice in winter [62]. Extra caution and adaptation will be required for users of freshwater ice as ice continues to change in response to warming winters [3,52]. This may include decreasing winter activity at the beginning and ends of the traditional winter season, although this could result in a loss in revenue for local economies [2]. Further understanding the changes in the patterns and drivers of ice thickness from climate change could help limit ramifications for users of freshwater ice prior to further preventable tragedies.

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Conflicts of Interest: The authors declare no conflict of interest.

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