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Forecasting the Permanent Loss of Lake Ice in the Northern Hemisphere Within the 21st Century

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Key Points:

- Shallow and deep lakes where winter air temperatures are ~0 °C and large, deep lakes in colder regions are sensitive to losing ice cover
- Large lakes in southern and coastal regions of the freezing zone in the Northern Hemisphere are most vulnerable to permanently losing ice
- Up to 5,679 lakes of 1.35 million lakes studied in the Northern Hemisphere, may permanently lose ice cover by 2100

Supporting Information:

- Supporting Information S1

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Author Contributions:

S. Sharma led the project; A. Filazzola, K. Blagrave, M. A. Imrit, and S. Sharma developed ideas for the project. H. J. H. Franssen provided data for lakes in Switzerland, K. Blagrave compiled all data, A. Filazzola, K. Blagrave, S. Sharma conducted statistical analysis, and K. Blagrave, M. A. Imrit developed figures and tables. S. Sharma led the writing of the manuscript and A. Filazzola, K. Blagrave contributed text. All coauthors revised the manuscript.

Abstract

Lake ice cover is essential to conserving the global freshwater supply for the 50 million lakes that freeze each winter. Here, we ask when lakes across the Northern Hemisphere may permanently lose ice cover. A *K*-means cluster analysis from 31 lakes identified four clusters of lakes vulnerable to losing ice cover, including shallow and deep lakes in regions where winter air temperatures hover ~0 °C and larger and deeper lakes in colder regions. By the end of this century, we estimate that up to 5,679 lakes of 1.35 million HydroLAKES may permanently lose ice cover if greenhouse gas emissions (GHG) continue to be emitted at current levels. In the Northern Hemisphere, lakes in southern and coastal regions, some of which are among the largest lakes in the world and in close proximity to large human populations, are the most vulnerable to permanently losing ice.

Plain Language Summary

Lake ice cover is ecologically important for half of the world's lakes to minimize winter evaporation rates, moderate summer water temperatures, and curtail toxic algal blooms, while also providing recreation, transportation, and food resources to millions of people. In this study, we aimed to identify which lakes around the Northern Hemisphere are most sensitive to permanently losing ice cover and by which decade. Generally, we found that lakes located in southern and coastal regions, some of which are the largest and deepest in the world and close to urban centers, were the most vulnerable to losing ice cover. One hundred and seventy-nine lakes are expected to permanently lose ice cover within this decade, but up to 5,700 lakes by the end of this century if greenhouse gas emissions are not mitigated. We highlight the importance of mitigating GHG emissions to preserve lake ice cover for the conservation of our freshwater ecosystems, in addition to its associated winter cultural heritage for the millions of people who depend on ice ecologically, socioeconomically, and culturally.

1. Introduction

For over 1,100 years, humans have recorded information on lake ice cover because of our dependence on ice for transportation, refrigeration, food harvest, and recreation (Knoll et al., 2019; Magnuson & Lathrop, 2014). Two of the longest ice records began for religious purposes: priests recorded and celebrated the timing of lake ice freeze in Lake Constance, Germany (875-present) and Lake Suwa, Japan (1,443-present). In stark contrast to historical patterns, Lake Constance froze for the last time in 1963 and Lake Suwa has frozen only twice per decade since 1988 (Knoll et al., 2019; Sharma et al., 2016). This loss of ice cover precipitates the question, when will lakes experiencing intermittent winter ice cover permanently lose ice?

Losing freshwater ice is one of the earliest observed impacts of climate change (Magnuson et al., 2000; Walsh et al., 1998) with far-reaching consequences on the global freshwater supply (Woolway et al., 2020). Recent studies estimated that approximately 15,000 lakes around the Northern Hemisphere may be experiencing intermittent winter ice cover (Sharma et al., 2019) and that the frequency of extreme ice-free years is becoming increasingly common in recent decades (Filazzola et al., 2020). Lakes found in warmer regions, such as along the southern edge of the winter 0 °C isotherm or along continental coastlines, are sensitive to experiencing ice-free winters. In colder climates, deeper lakes were more likely to have experienced ice-free years (Sharma et al., 2019) as deeper lakes take longer to cool in the fall (Brown & Duguay, 2010; Jeffries et al., 2012) and air temperatures need to be below 0 °C for a longer time before deeper lakes freeze (Kirillin et al., 2012; Nõges & Nõges, 2014). Such dramatic loss in lake ice cover underscores a need to identify the most vulnerable lakes before irrevocable ice loss.

We provide the first estimate of the number of lakes to permanently lose ice cover in the Northern Hemisphere within this century. We assembled lake ice records extending back 44–1,146 years for lakes currently experiencing intermittent winter ice cover (Table S1) to ask: (1) When are lakes forecasted to experience ice-free years? (2) Which groups of lakes are vulnerable to a higher percentage of ice-free years and why? and (3) In which decade are lakes forecasted to permanently lose ice cover? For the first time, we project in which decade lakes will permanently lose ice cover given a set of climatic and morphological characteristics.

2. Data Acquisition

We obtained lake ice cover records (did the lake freeze or not) for 31 lakes extending 41–1,146 years from the National Snow and Ice Data Center (Benson et al., 2000) and the data portal from the Long-term Ecological Research Network (Sharma et al., 2019). A lake was categorized as ice covered when the lake was partially or completely covered with ice for >1 day of the year following the ice phenology definitions presented in the National Snow and Ice Data Center Lake and River Ice Phenology Group data set (Benson et al., 2000). A year was designated as ice-free if there were no days over the course of a winter with ice formation on the lake. These lakes are distributed across North America (12 lakes), Europe (18 lakes), and Asia (1 lake) (Table S1). We acquired a range of lake geographic and morphometric characteristics for each of the lakes. Latitude, longitude, elevation, surface area, and mean depth for most lakes were acquired from the National Snow and Ice Data Center. We also used the HydroLAKES data set to obtain information on surface area, mean depth, and volume as necessary, as well as additional variables, such as watershed area, shoreline length, residence time, mean discharge, slope, and shoreline complexity for over 1.4 million lakes distributed around the world (Messager et al., 2016). Of the 1.35 million Northern Hemisphere HydroLAKES, 1.25 million are predicted to have seasonal ice cover and 14,688 lakes are currently classified as intermittent, that is experiencing at least one ice-free winter (Sharma et al., 2019). Over 51,000 lakes with similar physical characteristics to the 31 ice-free lakes considered in this study are predicted to have seasonal ice cover. Lakes were defined as permanent freshwater bodies greater than 10 ha in size (Messager et al., 2016). The HydroLAKES characteristics were not appropriate for two sites (Bayfield Bay in Lake Superior and Grand Traverse Bay in Lake Michigan), so these characteristics were updated from published literature where available.

Monthly mean surface air temperatures in December, January, and February were obtained for each lake from the University of East Anglia's Climatic Research Unit (CRU TS4.04; Harris et al., 2020). These climate data were derived from meteorological station measurements that were interpolated onto 0.5° latitude/longitude grids. We calculated winter (December, January, February) temperature for winters between the winter seasons 1901–1902 and 2017–2018 and from this the 1971–2010 average winter temperature for each lake. Finally, we acquired bias-corrected annual forecasted (2010–2099) air temperatures for four general circulation models (the Geophysical Fluid Dynamics Laboratory's ESM2M, the Institut Pierre Simon Laplace's CM5A-LR, the Earth System configuration of the Hadley Center Global Environmental Model, version 2 (HadGEM2-ES) and the Model for Interdisciplinary Research On Climate version 5 (MIROC5) and three GHG emissions scenarios (representative concentration pathways (RCP) of 2.6, 6.0, 8.5) at a spatial resolution of 0.5° from the InterSectoral Impact Model Intercomparison Project (ISIMIP2b; Frieler et al., 2017).

3. Data Analysis

3.1. When are Lakes Forecasted to Experience Ice-Free Years?

A recent study by our team showed that winter temperature is the primary driver for determining whether or not a lake will freeze (Filazzola et al., 2020). We conducted a Mann-Whitney U test to identify if there were significant differences in winter air temperatures between years with ice and no ice. We fit a regularized logistic regression model to each lake using "logit. fit_regularized" from the Python module "statsmodels" (Seabold & Perktold, 2010) to quantify the relationship between probability of freezing and winter air temperatures. We selected a regularization parameter that minimizes the number of false positives (i.e., predicts ice-free when the lake was frozen). Of the 31 regression models for each of the lakes, 28 showed a significant relation (coefficient P-values < 0.05). We defined the mean winter air temperature threshold above which these lakes do not freeze in a winter ("ice-free threshold") based on an ice-free probability of

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0.5 from logistic regression models conducted for each lake (Table S2). Next, we conducted Spearman r correlations between the ice-free threshold and lake morphometric characteristics.

We predicted the probability of ice-free conditions for each year until the 2098–2099 winter season by extrapolating the significant logistic regression models subject to 12 different climate change scenarios. We used annual projections of winter air temperature from three different Representative Concentration Pathways (RCP 2.6, 6.0, and 8.5) and four General Circulation Models (GFDL-ESM2M, IPSL-CM5A-LR, HadGEM2-ES, and MIROC5). The logistic regression model provides a probability that the lake would be ice-free in a given year based on the predicted temperature. Figure S3 summarizes these model results for each of the 28 lakes and each of the 12 climate change models/scenarios, on a spectrum from blue (frozen) to white (uncertain) to red (ice-free) for each winter from 2020 to 2098. We defined the final freeze event for a lake as the year where the frequency of freeze events drops below one per decade.

3.2. Which Groups of Lakes are More Vulnerable to a Higher Percentage of Ice-Free Years and Why?

We performed a K-means cluster analysis using the records of ice occurrence (i.e., did the lake freeze or not) for each year across the time series for each lake. A K-means cluster analysis identifies groups of lakes with similar patterns of ice occurrence histories based on the calinski criterion (Sharma & Magnuson, 2014). We subsequently related the clusters to climate variables, such as the mean 1971–2010 winter temperature, and physical lake characteristics, such as mean lake depth, shoreline length, and lake surface area. Following group assignment, we used a Kruskal-Wallis test to determine if these variables were significantly different among clusters.

3.3. In Which Decade are Lakes Forecasted to Permanently Lose Ice Cover?

Using the four clusters, we calculated the mean and standard deviation for each of the four variables (mean winter air temperature, lake area, mean depth, shoreline length), defining a multivariate normal distribution. We calculated the Mahalanobis distance between each cluster and each of the 1.35 million Northern Hemisphere HydroLAKES (Messager et al., 2016). Mahalanobis distance is a measure of normalized difference in multivariate space, where each lake is measured in units of standard deviations away from the mean of the four clusters (De Maesschalck et al., 2000). We used the smallest distance to select a cluster for a specific lake. Lakes that had a Mahalanobis distance greater than one standard deviation away from any cluster (i.e., 68.3% probability) were excluded. Of the 1.35 million Northern Hemisphere HydroLAKES, 56,344 were identified to a cluster. We only limited our selection of HydroLAKES to lakes with similar characteristics to our original 31 lakes with time series such that our predictions would be conservative estimates.

4. Results and Discussion

4.1. When are Lakes Forecasted to Experience Ice-Free Years?

Winter air temperature is the primary determinant of whether or not a lake will freeze, mediated by lake size (Filazzola et al., 2020). Mann-Whitney U tests revealed that winter air temperatures were significantly warmer in ice-free years ($P < 0.05$; Figure S1). Specifically, the mean winter air temperature threshold above which these lakes do not freeze in a winter ("ice-free threshold") was −0.9 °C and ranged from −4.8 to 4 °C (Table S2). The ice-free threshold was much lower for larger ($r = -0.64$, $P < 0.05$) and deeper lakes ($r = -0.63$, $P < 0.05$), such that generally larger and deeper lakes tend to experience an ice-free year at cooler temperatures (Figure 2a). However, there were a few outliers to this relationship, such as Lakes Sebago, Suwa, and Balaton, which freeze at a lower winter temperature threshold despite being shallow lakes, because they have such large surface areas (Figure 2a). In addition, Lake Balaton, a large, shallow lake which has a high winter air temperature threshold, is undergoing a more extreme transition where many winters have only a few days of ice cover.

Larger, deeper lakes require colder air temperatures to freeze and take longer to cool in the fall. In addition, lakes with longer fetches are more likely to lose the initial skim of ice through increased wind action and are additionally sensitive to experiencing an ice-free year (Sharma et al., 2019, 2020; Woolway et al., 2020).

For example, we found that the ice-free threshold for deeper and larger lakes, such as Lake Champlain and Grand Traverse Bay, Lake Michigan was below −5 °C. In contrast, the ice-free threshold for shallow lakes, such as Balaton, Nehmitzee, and Mueggelsee, exceeded 3 °C (Table S2). Under scenarios of climate warming, within the same region, deeper lakes are expected to be more susceptible to losing ice cover than shallower lakes (Magee & Wu, 2017; Sharma et al., 2019). Further, within a lake, relationships between winter air temperatures, depth, and the timing of lake ice formation and decay can be used to identify when specific regions within a lake could remain ice-free, for those lakes that continue to seasonally freeze each winter, such as Lake Ladoga (Karetnikov et al., 2017).

4.2. Which Groups of Lakes are More Vulnerable to a Higher Percentage of Ice-Free Years and Why?

A *K*-means cluster analysis identified four clusters of lakes sensitive to ice-free years based on their time series of ice occurrence between 1939 and 2016, which explained 97.7% of the variation in ice occurrence histories. We found that there were significant differences between clusters for both climate and morphological lake characteristics (Figure 2b; $P < 0.0001$). For example, both shallow and deep lakes were sensitive to ice-free winters in regions where 1971–2010 mean winter air temperatures hover ∼0 °C. However, in regions with colder winters, the largest and deepest lakes were most vulnerable to ice-free winters. Cluster 1 comprised deep lakes found in cool regions that were ice-free on average 79.5% of the past 78 years. This cluster included Lake Constance and other deep lakes located in central Europe where mean winter air temperatures since 1970 are ∼1.0 °C and now only freeze occasionally when temperatures dip below freezing. Cluster 2 consisted of deep lakes found in cold regions that were ice-free for 35% of the past 78 years,

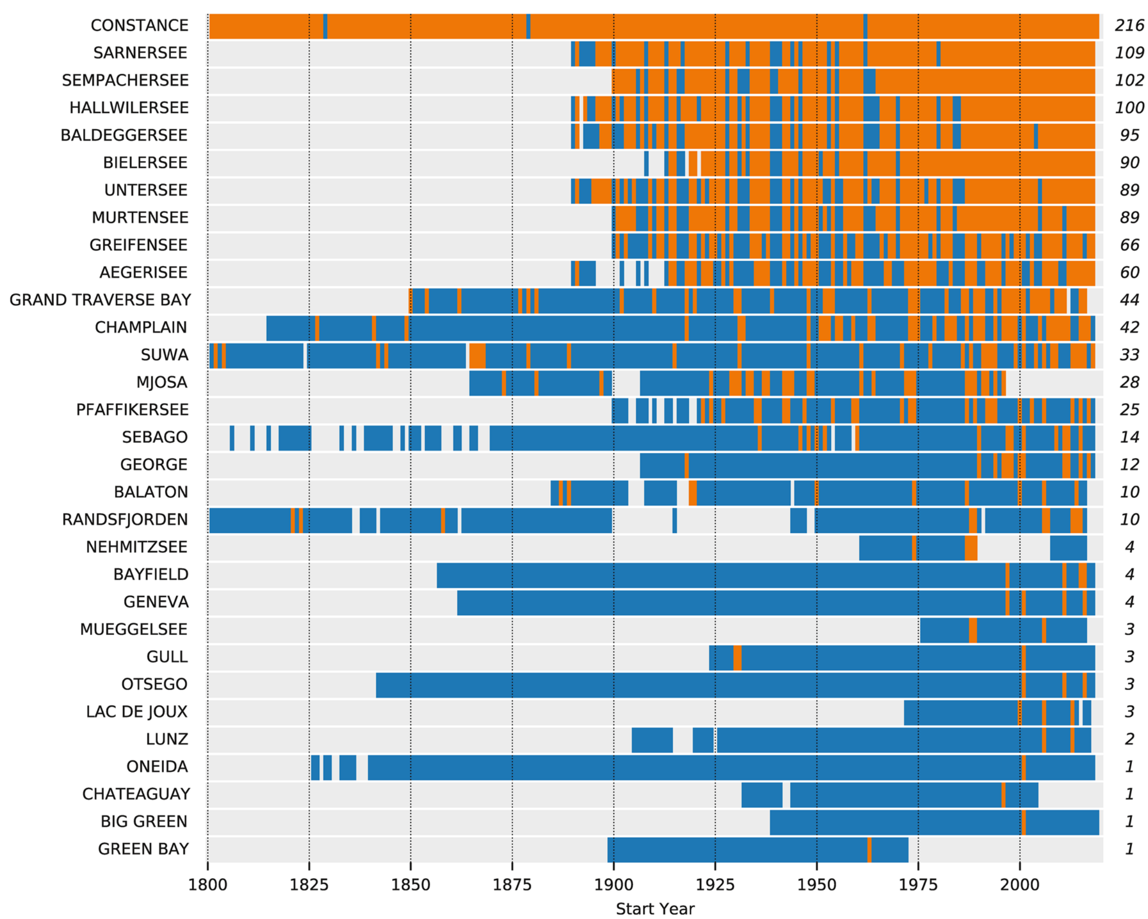

Figure 1. Record of ice-free years (orange bars) for 31intermittent ice covered lakes across the Northern Hemisphere. The number of recorded ice-free events (since 1800) is included for each lake.

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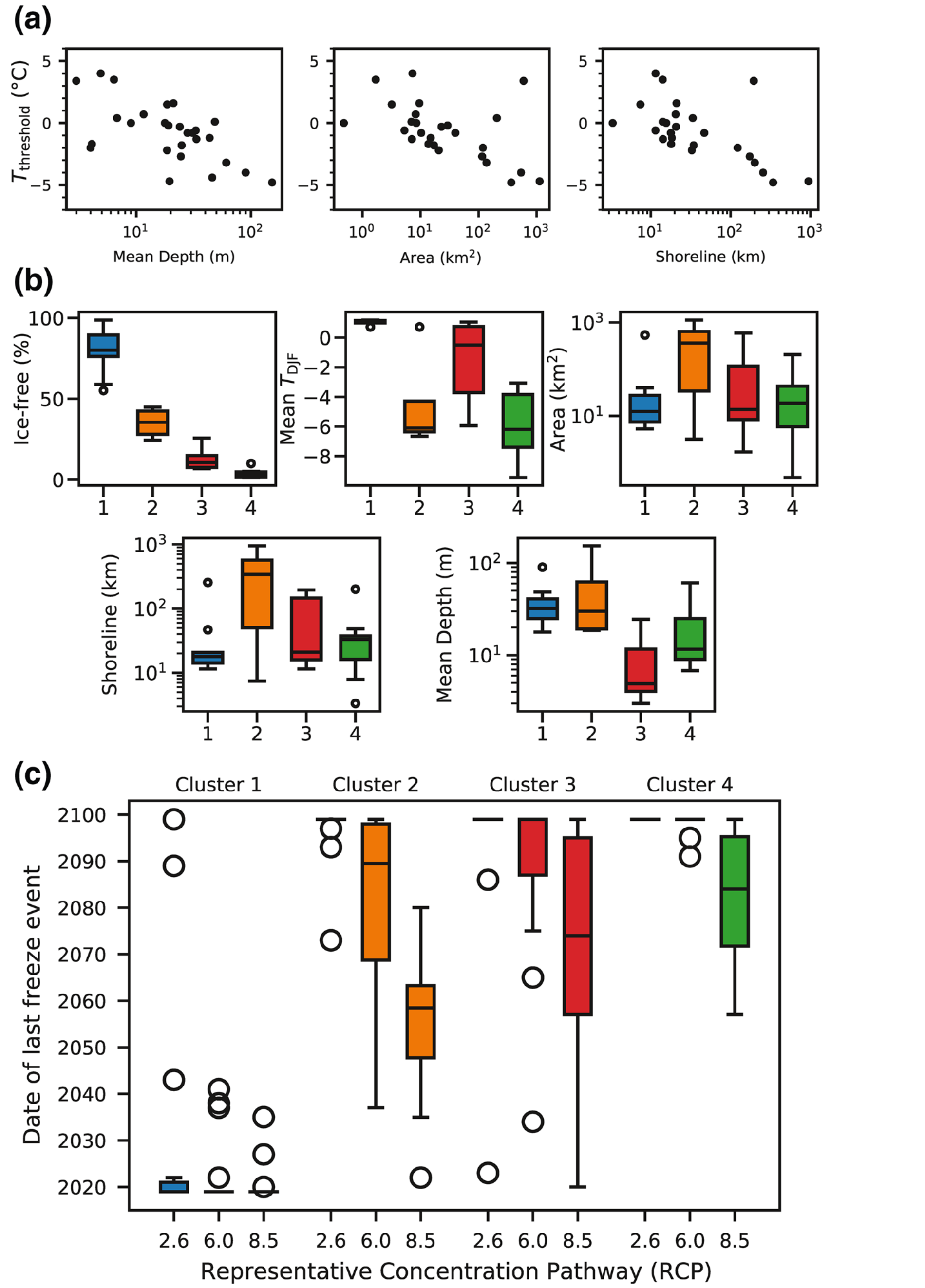

Figure 2. (a) The relationship between the modeled ice-free threshold as a function of each lake's mean depth, surface area, and shoreline length. (b) Boxplots summarizing the significant differences between clusters: percentage of years which are ice-free between 1939 and 2016, 1971–2010 mean winter temperature, lake area, shoreline length, and mean depth. (c) Forecasts of last freeze date (defined as the last decade in which at least 9 years were ice-free; Figure S3) for four clusters of lakes based on four GCM under three different emission scenarios (RCP 2.6, RCP 6.0, RCP 8.5). Lakes in Cluster 1 are currently ice-free ~80% of years ($n = 10$); Cluster 2 are currently ice-free ~35% of years ($n = 4$); Cluster 3 are currently ice-free ~13% of years ($n = 7$); and Cluster 4 are currently ice-free in <5% of years ($n = 7$). The boxes indicate the median, first, and third quartiles of the final freeze event. The whiskers extend beyond the first and third quartiles to include all data at most 1.5 times the interquartile range away. Any data outside of this range are indicated as outliers. GCM, general circulation models; RCP, representative concentration pathways.

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including Lake Champlain and Grand Traverse Bay in Lake Michigan. These large, deep lakes are found in cold regions where mean winter air temperatures are below −4 °C. Cluster 3 is ice-free 12.6% of the years and comprise small and shallow lakes found in regions where mean winter air temperatures hover around −1.6 °C. Finally, Cluster 4 consisted of lakes found in cold climates (mean winter air temperatures ∼−5.9 °C) that have only recently begun to experience ice-free winters (3.5% ice-free winters) and only during abnormally warm winters, such as Bayfield Bay in Lake Superior (Figure 1).

4.3. In Which Decade are Lakes Forecasted to Permanently Lose Ice Cover?

Lake ice may be permanently lost within this century. We forecasted permanent lake ice loss based on extrapolating significant logistic regression models with annual winter temperature projections from 2020 to 2098 and 12 climate change scenarios. First, we compared each lake's modeled ice-free threshold temperature with the distribution of the 40-years mean winter air temperature (1971–2010). From this simple analysis, we noted that 3 of our 28 modeled lakes currently experience an ice-free winter >90% of the time. Increasing winter temperature by 2 °C results in an additional seven lakes becoming ice-free >90% of the time. Increases of 3.2, 4.5, and 8 °C result in a total of 12, 15, and 27 of our 28 lakes becoming ice-free >90% of the time (Figure S2).

We found that deep lakes in central Europe (Cluster 1) are imminently projected to lose ice cover permanently (Figures 2c and 3). For example, not a single climate model forecasted that Lake Constance would ever freeze again (Figure S3). Regardless of climate scenario, the majority of these central European lakes were projected to be permanently ice-free within decades, except for Aegersee and Untersee which may continue to periodically freeze in the lowest greenhouse gas (GHG) emission scenarios. Deep lakes found in cold regions currently ice-free ∼35% of the time (Cluster 2) are projected to permanently lose ice cover by 2085 on average (range: 2,035 and 2,095) based on moderate GHG scenarios (RCP 6.0), and as early as 2055 (range: 2,045–2,065) based on high GHG emission scenarios (RCP 8.5; Figures 2c and 3). Shallow lakes in cool regions currently freezing in fewer than 13% of winters (i.e., Cluster 3) may continue to periodically freeze through the end of this century based on low to moderate GHG emissions scenarios. However, these same lakes may permanently lose ice cover by 2070 (Cluster 3) or 2080 (Cluster 4) under high GHG emissions scenarios (RCP 8.5; Figure 2c). For example, a lake that has been monitored for ∼600 years by Shinto priests, Lake Suwa (Cluster 3), may permanently lose ice cover within this generation (Figure S3). The presence of lake ice is auspicious; when the lake did not freeze three times within the first 250 years of the ice record, there was widespread famine in the region (Arakawa, 1954; Sharma et al., 2016). The complete loss of ice cover in Lake Suwa would also correspond to the loss of a centuries-old spiritual tradition.

Thousands of lakes around the Northern Hemisphere are vulnerable to permanently losing ice cover within this century. However, stringent climate change mitigation would preserve freshwater ice for most lakes.

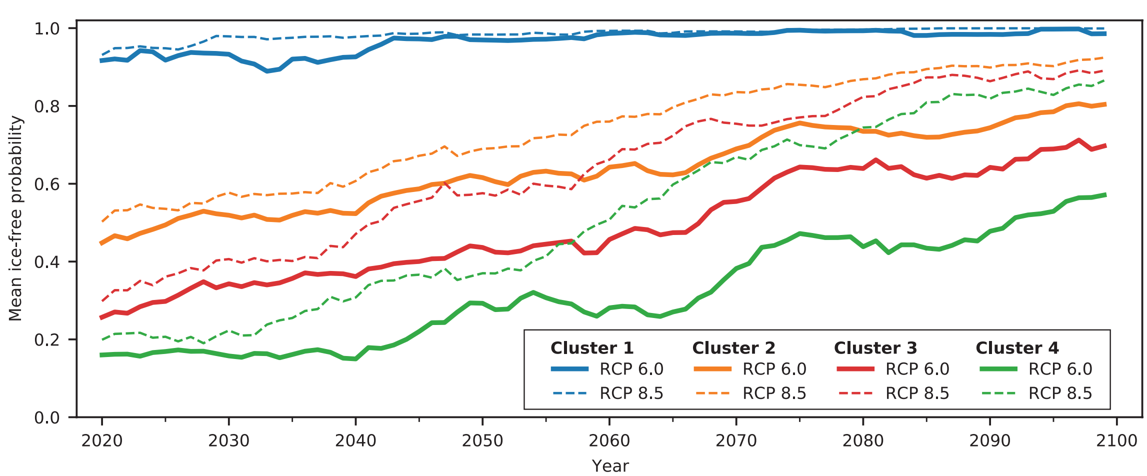

Figure 3. Ten-year rolling mean probability of a cluster of lakes being ice-free from 2020 to 2100 for moderate (RCP 6.0) and high (RCP 8.5) greenhouse gas emissions scenarios. Each time series represents the mean probability of an ice-free year based on four General Circulation Models for all of the lakes in a cluster (based on Figure S3). RCP, representative concentration pathways.

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Table 1
Number of the 1.35 Million Northern Hemisphere HydroLAKES Currently Forecasted to Experience Their Last Freeze Event and by 2060, 2080, and 2090 Based on an Average of 4 General Circulation Models (GCM) and Low (RCP 2.6), Moderate (RCP 6.0), and High (RCP 8.5) Greenhouse Gas Emissions Scenarios

Years	RCP 2.6	RCP 6.0	RCP 8.5
Now	179	179	179
Before 2060	179	179	429
Before 2080	179	179	2,296
Before 2090	179	429	5,679

Of the 1.35 million Northern Hemisphere HydroLAKES, 179 deep lakes in cool regions (Cluster 1) are predicted to permanently lose ice cover within this decade. No further lakes were forecasted to permanently lose ice cover within this century if GHG emissions are severely mitigated and carbon dioxide emissions start declining by 2020 (RCP 2.6; Table 1 and Figure 4). However, the RCP 2.6 scenarios that would limit global air temperature increases below 2 °C within this century are now considered highly unlikely (Sherwood et al., 2020). More realistically, 429 deep lakes from cool and cold regions may permanently lose ice cover with moderate GHG emissions by 2100 (Clusters 1 and 2; RCP 6.0; Table 1 and Figure 4). The projections for freshwater lake ice under high GHG emission scenarios (RCP 8.5) is ominous. By 2080, 2,296 deep and shallow lakes from cool regions and deep lakes from cold regions may permanently lose ice cover (Clusters 1, 2, and 3). By 2100, over 5,679 lakes may permanently lose ice of the 1.35 million lakes in the Northern Hemisphere that we studied (Table 1). Four thousand five hundred seventy-five shallow lakes in cool regions that currently experience annual winter ice cover are forecasted to be permanently ice-free within this century based on high greenhouse gas emissions scenarios (RCP 8.5). Lakes in southern and coastal regions where winter air temperatures are below 0 °C in the Northern Hemisphere are most sensitive to permanently losing ice cover within this century (Figure 4) as they tend to experience the greatest rates of warming in North America and Scandinavia (Jensen et al., 2007; Korho-

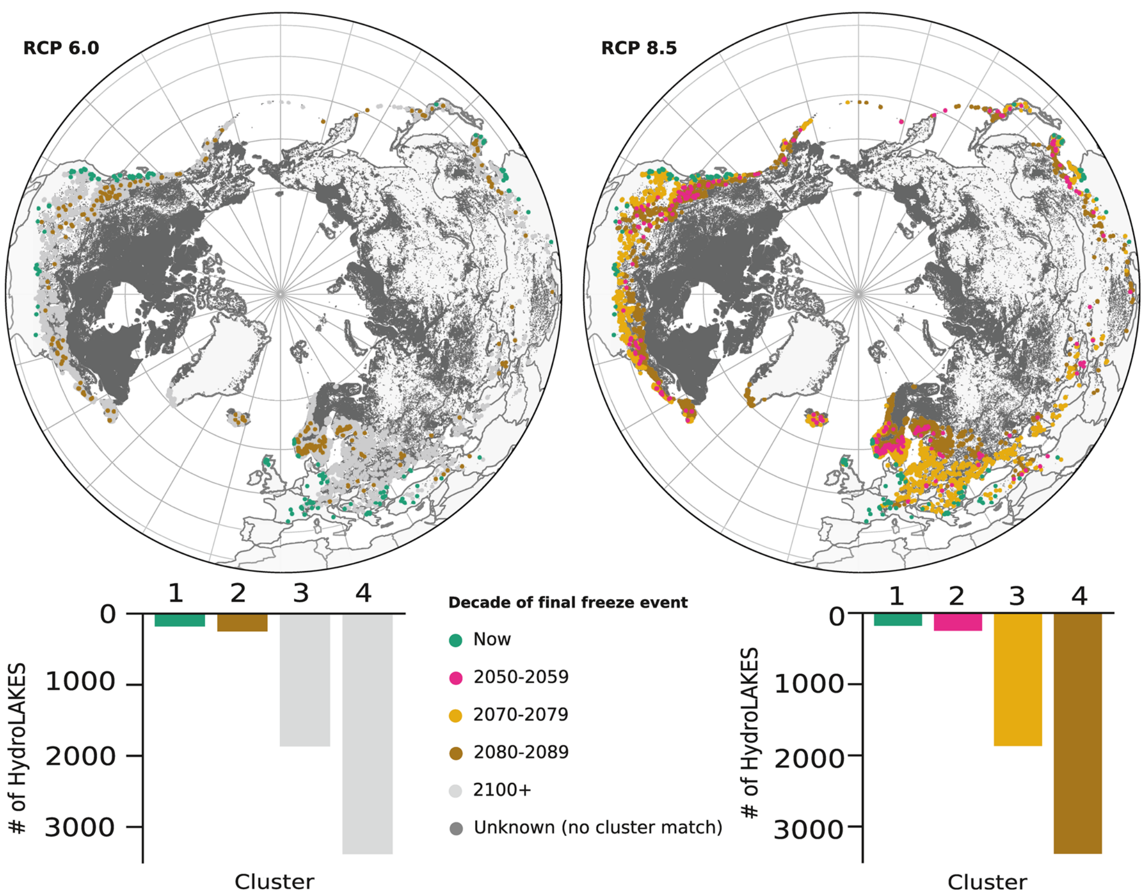

Figure 4. Forecasts of permanent lake ice loss by decade for lakes around the Northern Hemisphere. Freshwater ice is most likely to be permanently lost from southern and coastal lakes within the Northern Hemisphere. One hundred and seventy-nine lakes are forecasted to be ice-free this decade (Cluster 1), 429 lakes are forecasted to be ice-free by 2060 (Clusters 1 and 2), and 2,296 lakes are predicted to be ice-free by 2080 if greenhouse gas emissions remain high (RCP 8.5; Clusters 1, 2, and 3). By 2089, 429 (Clusters 1 and 2) and 5,679 lakes (Clusters 1, 2, 3, and 4) are forecasted to permanently lose ice cover under moderate (RCP 6.0) and high (RCP 8.5) greenhouse gas emissions scenarios, respectively.

nen, 2006; Weyhenmeyer et al., 2011), in part because they are in a transition zone where air temperatures hover around 0 °C (Weyhenmeyer et al., 2004). Coincidentally, the most vulnerable lakes to permanently lose ice cover within this century are also found in close proximity to large human populations and are amongst some of the deepest and largest lakes of the world.

5. Conclusions

The widespread loss of permanent ice cover in freshwater lakes around the Northern Hemisphere would have widespread ecological, cultural, and socioeconomic consequences. Lake ice cover is essential in limiting evaporation rates in the winter, without which lake levels, surface water extent, and ultimately the quantity of available freshwater, would be dramatically reduced (Woolway et al., 2020). Further, in years with decreased or no lake ice cover, surface water temperatures are warmer (Austin & Colman, 2007; Lathrop et al., 2019; O'Reilly et al., 2015), lake mixing regimes are altered (Woolway & Merchant, 2019), primary production is higher (Weyhenmeyer et al., 2008), fish reproductive success is lower (Farmer et al., 2015), and unprecedented algal blooms are observed (Woolway et al., 2020). Millions of people rely on critical ecosystem services provided by ice on the lakes that we identified as vulnerable, including transportation, food provisioning, and recreation; all of which have large cultural and socioeconomic impacts (Knoll et al., 2019; Sharma et al., 2019). Without ice, the multibillion dollar winter recreation industry may collapse in southern and coastal regions by the end of this century. Our analyses provide the first forecasts of widespread permanent lake ice loss within this century and highlight the urgency of mitigating GHG emissions to circumvent a future without lake ice for our grandchildren.

Data Availability Statement

The time series of lake ice cover for all 31 lakes is available at: Sharma, Sapna; Blagrave, Kevin; Filazzola, Alessandro; Imrit, Mohammad; Hendricks Franssen, Harrie-Jan (2020): Patterns of ice cover for 31 lakes in the Northern Hemisphere. Figshare data set. https://doi.org/10.6084/m9.figshare.13043078.v1. Climate data were obtained from the Climatic Research Unit part of the University of East Anglia (CRU TS4.03; http://www.cru.uea.ac.uk/).

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