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Widespread loss of lake ice around the Northern Hemisphere in a warming world

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Ice provides a range of ecosystem services—including fish harvest[1], cultural traditions[2], transportation[3], recreation[4] and regulation of the hydrological cycle[5]—to more than half of the world's 117 million lakes. One of the earliest observed impacts of climatic warming has been the loss of freshwater ice[6], with corresponding climatic and ecological consequences[7]. However, while trends in ice cover phenology have been widely documented[2,6,8,9], a comprehensive large-scale assessment of lake ice loss is absent. Here, using observations from 513 lakes around the Northern Hemisphere, we identify lakes vulnerable to ice-free winters. Our analyses reveal the importance of air temperature, lake depth, elevation and shoreline complexity in governing ice cover. We estimate that 14,800 lakes currently experience intermittent winter ice cover, increasing to 35,300 and 230,400 at 2 and 8 °C, respectively, and impacting up to 394 and 656 million people. Our study illustrates that an extensive loss of lake ice will occur within the next generation, stressing the importance of climate mitigation strategies to preserve ecosystem structure and function, as well as local winter cultural heritage.

Lake ice is one of the world's resources most threatened by climate change[10]. Long-term lake ice records have been maintained for hundreds of years, signifying the importance of lake ice for transportation, fishing, recreation and local cultural identity[8]. For example, the Shinto religion has recorded freeze dates of Lake Suwa since 1443 because their tradition is that an ice ridge (omiwatari) was left by their god crossing the frozen lake to visit his wife[2]. Indigenous communities rely on winter lake ice roads in northern Canada for food, supplies and social interactions[3]. Warming winters have reduced the duration and quality of ice roads, limiting access to remote communities[3]. In addition, the quality and duration of winter recreational activities is declining with warming winters. Skating seasons in the largest outdoor skating rink have become shorter, with a risk of no outdoor skating opportunities by the late twenty-first century[4]. These are just a few examples of the diverse ways that lake ice contributes to human culture, but stands to be lost.

The importance of lake ice to society is underscored by the existence of meticulous long-term human observations showing that ice cover is being lost at an accelerated rate[11]. Lake ice onset is later and ice breakup is earlier, resulting in shorter annual durations of ice cover[6,8,9,11]. In extreme cases, lake ice has been completely lost in some winters[2,11]. This transitional period from annual winter ice to permanent loss of ice cover may endure for decades[2]. The factors influencing whether or not ice forms are well known; previous research has indicated that air temperature, wind speed, and lake size are essential components to ensure that vertical heat transfer is sufficient to cool surface water temperatures to 0 °C[12,13]. Precipitation[12], snow cover[14], cloud cover, solar radiation[14], distance to coastline[15] and regional differences[7,16] can govern the timing of ice formation and ice growth during the winter season. However, previous research has not identified how the interactions between features such as climate and lake shape (area and depth) will dictate when and where the threat of lake ice loss is greatest. We provide the first global estimate of how many lakes are likely to lose annual winter ice cover as the climate warms.

We used updated lake ice cover records for 346 lakes in North America, 136 lakes in Europe, and 32 lakes in Asia to evaluate the threat of lake ice loss[17] (Supplementary Fig. 1). Lakes were designated as annual or intermittent winter ice-covered lakes. Annual ice-covered lakes experienced complete ice cover every winter, whereas intermittent ice-covered lakes had one or more winters without complete ice cover since 1970. This enabled us to identify when lakes may begin to lose winter ice cover. The extent and timing of intermittent ice cover can be a harbinger of permanent ice loss.

A classification tree analysis using a diverse set of climatic, geographical and lake characteristics (Supplementary Fig. 2) identified that regional climatic conditions and local lake characteristics predict susceptibility to loss of winter ice cover. The tree correctly classified 95% of lakes overall, with a 97% success rate of correctly classifying annual ice cover ($n = 291$) and 75% success rate of correctly classifying intermittent ice cover ($n = 28$; Fig. 1). The mean annual air temperature (1970–2010) was the most important factor explaining whether a lake had annual or intermittent winter ice cover (Fig. 1a). Where mean air temperatures exceeded 8.4 °C, lake ice cover was predicted to be intermittent. As heat inputs increase, the growth and decay of lake ice could be affected[6], shifting lakes from annual to intermittent winter ice cover, with a permanent loss of ice cover at a long-term mean air temperature of 10 °C[9].

Individual lake characteristics also influenced the sensitivity of lakes to warming. Lake depth, elevation and shoreline complexity influenced the likelihood of winter ice cover loss (Fig. 1a–e

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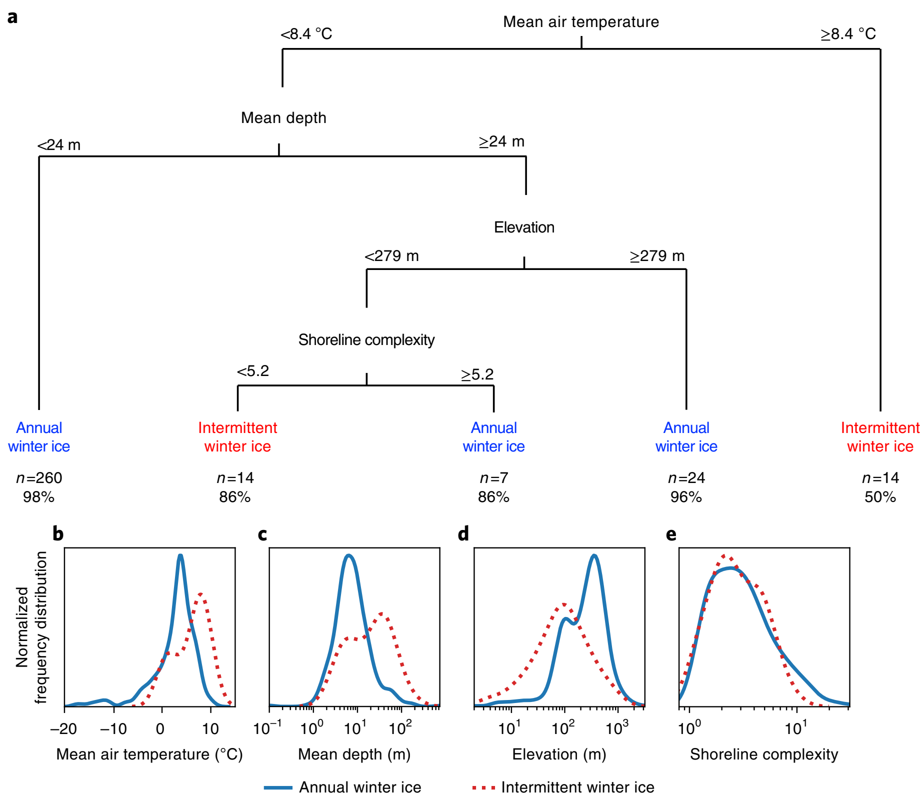

Fig. 1 | Significant geomorphological and climatic characteristics classifying lakes that have annual and intermittent winter ice cover. a, Classification tree predicting lakes that have intermittent winter ice cover (classification success = 95%). Lakes characterized with intermittent ice cover are found in regions with a 1970–2010 mean air temperature ≥8.4 °C. Lakes with intermittent ice cover are also found in regions with mean air temperatures <8.4 °C if the mean depth is ≥24 m, elevation is <279 m and the shoreline complexity ratio is <5.2 (in order of decreasing importance). **b–e**, Normalized frequency distributions for mean air temperature (**b**), elevation (**c**), mean depth (**d**) and shoreline complexity (**e**) showing the distribution of annual winter ice lakes (blue) and intermittent winter ice lakes (red).

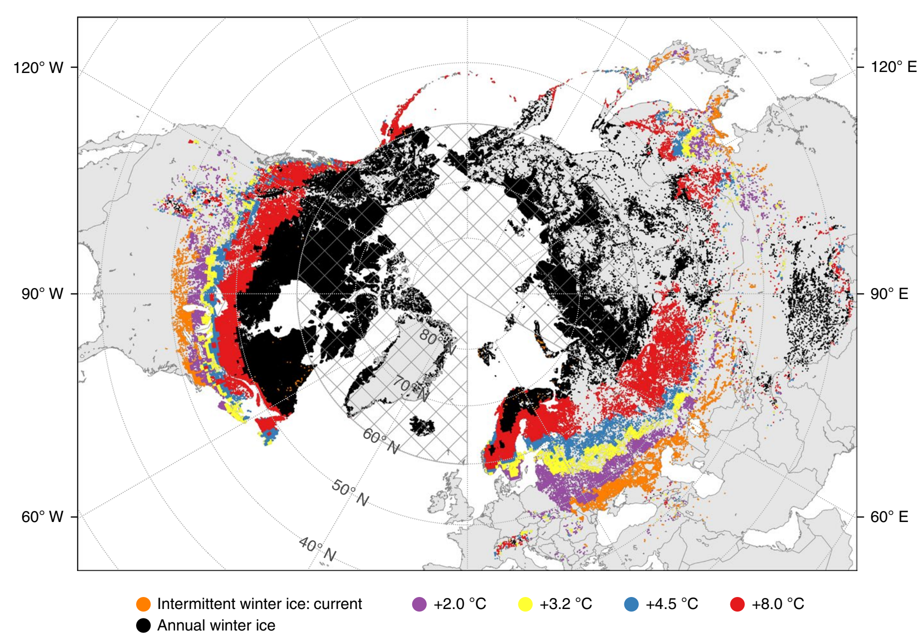

Fig. 2 | Spatial distribution map of current and future Northern Hemisphere lakes that could experience intermittent winter ice cover with climate warming. Projections were generated by applying the classification tree model to the global HydroLAKES database[16] (lakes larger than 10 ha) and limited to the south by 1970–2010 mean winter temperatures below −0.4 °C. We did not project north of 60° N in North America and Asia because of a paucity of ice cover observations (hashed regions). Intermittent winter ice cover projections were based on current conditions (orange) and established air temperature projections of +2.0 °C (purple), +3.2 °C (yellow), +4.5 °C (blue) and +8.0 °C (red). All other lakes are shown in black.

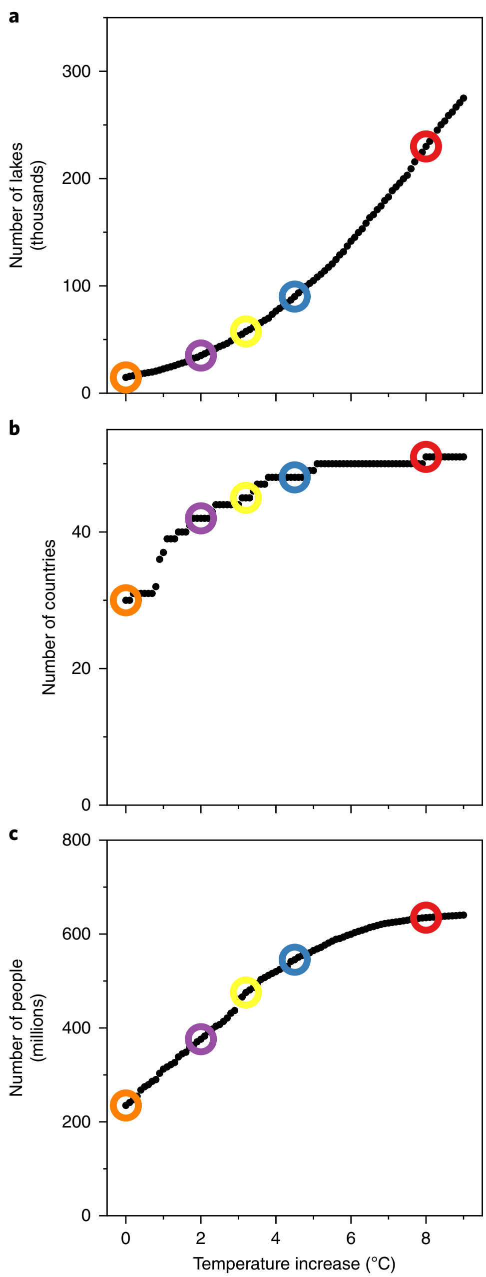

Fig. 3 | Estimated numbers of lakes, countries and people affected by current and future projected lake ice loss. a–c, Numbers of lakes (**a**), countries (**b**) and people (**c**) were calculated based on increases in mean air temperatures using 0.1 °C increments from 0–8 °C. Coloured open circles indicate the warming scenarios depicted in Fig. 2 (+0 °C, orange); +2.0 °C, purple; +3.2 °C, yellow; +4.5 °C, blue and +8.0 °C, red).

and Supplementary Table 1). Where mean air temperatures were below 8.4 °C, deeper lakes at lower elevations were less likely to freeze annually (Fig. 1a–b). Deeper lakes require a longer period with below-freezing air temperatures because they have a greater volume per surface area that must be cooled for ice formation to occur[6,14]. The effects of elevation on ice cover extend beyond air temperatures because short-wave radiation and wind speed also change with elevation and may confound the potential influence of distance to coastline[15]. Finally, lakes of the same area but with more complex shorelines may be more likely to have ice cover than those with simpler shorelines because they have a smaller mean fetch.

Projecting our results to a broader spatial distribution of lakes revealed the potential for widespread shifts in lake ice from annual to intermittent winter ice cover, as well as the northward expansion owing to warming. We estimated that approximately 15,000 lakes may currently experience intermittent winter ice cover (Fig. 2). Spatial heterogeneity in intermittent winter ice cover was evident as our predictions incorporate regional gradients in latitude, elevation and air temperatures with local differences in lake depth and shape. Neighbouring lakes may not shift from annual to intermittent winter ice cover in the same year, even if they are exposed to the same climate, owing to differences in lake depth and shape.

The number of lakes potentially experiencing intermittent winter ice cover is projected to increase exponentially with climate warming (Fig. 3a), reflecting the greater density of lakes at higher latitudes[18]. Although many lakes are still expected to remain annually ice covered at higher latitudes, we forecast that 57,600 lakes (4.6% of ice-covered lakes in the Northern Hemisphere) could experience intermittent winter ice cover given current mitigation trajectories (+3.2 °C). If the goal of a 2 °C increase in air temperature from the Paris Agreement under the United Nations Framework Convention on Climate Change is achieved, 35,300 lakes (2.8%) would potentially experience intermittent ice. With little or no climate change mitigation (+4.5 °C and +8 °C), 90,200 lakes (7.2%) and 215,600 lakes (18.4%), respectively, may experience intermittent ice (Fig. 3a and Supplementary Table 2). Similarly, a suite of general circulation models (GCMs) suggest that 41,000–90,000 lakes could experience intermittent winter ice cover with little climate change mitigation by 2080 (Representative Concentration Pathway (RCP) 6.0; Supplementary Fig. 3). In contrast, climate change mitigation scenarios (RCP 2.6) predict that 27,000–48,000 lakes would lose winter ice cover beginning in 2080 (Supplementary Fig. 3). Northern lakes at high latitudes may be more vulnerable to loss of ice cover with arctic amplification[19]. Because we are not incorporating feedbacks from the loss of lake ice to regional climate, our global estimate of lakes that become intermittently ice covered is probably conservative[7]. Our results underscore the importance of climate mitigation for preserving ice cover in northern lakes.

A loss of winter ice cover has potentially widespread implications for up to 656 million people in as many as 50 countries (Fig. 3b,c). Even small increases in air temperature could affect a disproportionately large population of people living near lakes (Fig. 3c). Loss of lake ice could contribute to decreased availability of freshwater[20] owing to increased evaporation rates[5]. Ecosystem services that are highly susceptible to loss of ice include transportation via ice roads, hydroelectric production, and provisioning[21]. Winter ice fishing can provide sustenance and economic growth to local communities (for example, ice fishing in Lake Peipsi, Estonia can account for up to 40% of the annual fish harvest[1]). In the USA, US$178 million was spent on ice fishing equipment alone in 2011[22]. In addition, lake ice embodies the winter identity of many cultures, as evidenced by the abundance of winter ice festivals each year[10]. For example, 25,000 people participated in an ice fishing competition in Finland[23], and up to 100,000 people attended one of the last remaining traditional ice fishing events in remote China, where the first fish caught is deemed auspicious and fetches tens of thousands of dollars[24]. Many other examples of cultural and socioeconomic consequences of losing lake ice are apparent, but these impacts have not yet been quantified or synthesized.

Shifts towards intermittent winter ice could be rapid. Some lakes in historically cold regions, such as the northern United States, Norway and Sweden, are already beginning to lose annual lake ice. We used GCM climate projections to explore the timing of ice loss for several lakes in the USA and Sweden. For lakes with

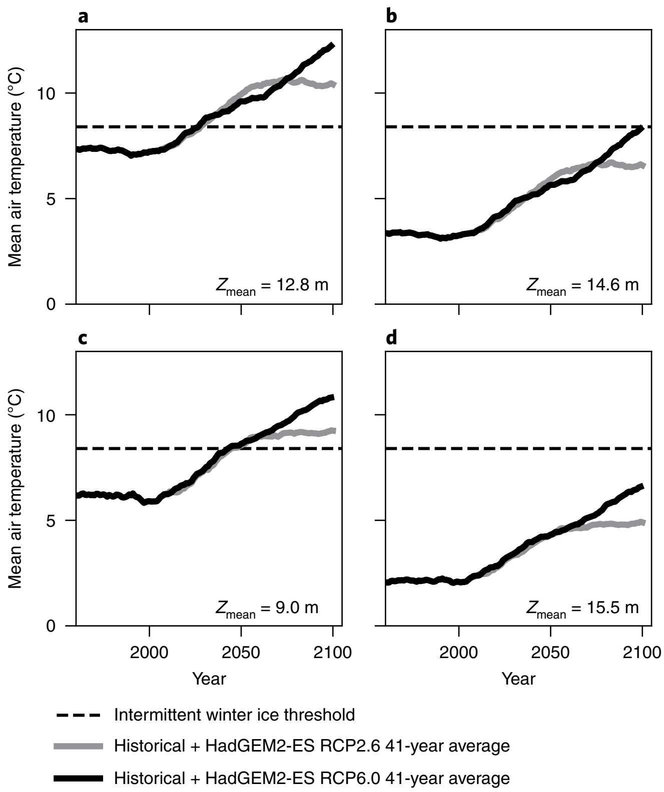

Fig. 4 | Climate projections for the timing of intermittent winter ice cover for shallow and deep lakes in Wisconsin, USA and Sweden. a–d, Forecasts for lakes Mendota (**a**; 43.1° N), Trout (**b**; 46.0° N), Erken (**c**; 59.8° N) and Nackten (**d**; 62.8° N) in Wisconsin, USA and Sweden, where winter activities are a prominent part of cultural identity, using two greenhouse gas emissions scenarios (RCP 2.6 and RCP 6.0) from the HadGEM2-ES global circulation model. Dashed lines represent the last year in the 41-year mean 8.4 °C temperature threshold above which lakes are predicted to begin to lose ice cover.

similar mean depths, latitudinal differences reflecting air temperature gradients influenced the timing of lake ice loss. For example, compared with Lake Mendota, the more northern Trout Lake would not experience intermittent ice cover until the end of the century (Fig. 4a,b). However, if greenhouse gas emissions are mitigated, Trout Lake would retain annual ice cover (Fig. 4b). At substantially higher latitudes in Sweden, shallow lakes such as Lake Nackten could retain annual ice cover through the century (Fig. 4d).

Mean depth influenced the likelihood of ice loss for lakes at similar latitudes. For example, Big Green Lake is a deep lake ($Z_{mean} = 31.7$ m) in southern Wisconsin and has already experienced one winter without ice cover in the past 20 years. Conversely, Lake Mendota is a shallow lake ($Z_{mean} = 12.8$ m) and is predicted to retain annual ice cover through 2020 (Fig. 4a). Similarly, in southern Sweden, deep Lake Vattern ($Z_{mean} = 38.0$ m) was ice-free for 40 of the 48 years since 1970, whereas Lake Erken ($Z_{mean} = 9.0$ m) is predicted to retain annual ice cover through 2035 (Fig. 4c). Thus, not all lakes within a region begin experiencing intermittent winter ice cover at the same time owing to differences in lake depth and complexity. These examples illustrate that within this generation, lake ice recreation, such as ice fishing and ice skating, will become limited to northern regions. The rapid loss of lake ice in locations with a strong winter cultural identity highlights the urgency of this threat in a warming world.

The imminent shift of lakes from annual to intermittent ice cover portends substantial consequences for freshwater ecosystems. Lake ice cover is an important component of how lakes function, impacting their physical, chemical and biological processes[5,25]. Winter conditions, such as biogeochemical cycles and primary production under ice, can influence ecosystem processes in the subsequent summer[25,26]. In years when two Swedish lakes did not freeze, surface water temperatures were warmer and primary production and algal biomass were higher[27]. Shorter, warmer winters are also likely to negatively affect some fish populations through declines in reproductive success[28]. Further research is required to understand how loss of lake ice cover impacts gas exchange between the lake and atmosphere, mixing of the water column, biogeochemical cycling, and ecosystem structure and function. Vulnerable lakes need to be incorporated into long-term research networks to better understand the influence of these intermittent ice cover years.

Our projections reveal the urgency and scope of lake ice loss around the Northern Hemisphere. The socioeconomic importance of winter ice cover has been largely ignored, leaving local communities unprepared for loss of ice[10]. Our analysis provides the first large-scale and spatially explicit representation of where the earliest stages of ice loss will manifest as climate change progresses. This unprecedented view of the global scale of lake ice loss is a conspicuous and tangible sign of the local impacts of climate change on lake ecosystems and the people who depend on them.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0393-5.

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Author contributions

S.S. and J.J.M. conceived the idea for the project. S.S. led the project. S.S., K.B., C.M.O., S.O., M.R.M., D.S., G.A.W., L.W. and R.I.W. collected the data. S.S., K.B. and S.O. conducted the data analysis. S.S., K.B., S.O. and C.M.O. drafted the figures and tables. S.S., K.B., C.M.O., S.O., R.D.B., M.R.M., D.S., G.A.W., L.W., R.I.W. and J.J.M. discussed the results, wrote sections of the text, provided critical feedback and commented on drafts of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Data acquisition. We obtained lake ice phenology records for 514 lakes from the National Snow and Ice Data Center[17]. These records were updated, where possible, to the 2017–2018 season through communications with original data providers. Lakes are broadly distributed around the Northern Hemisphere, with 346 lakes located in North America, 136 lakes in Europe and 32 lakes in Asia (Supplementary Fig. 1). We designated lakes as annual and intermittent winter ice lakes. Annually ice-covered lakes were defined as lakes that consistently froze each year across their complete time series. Intermittent winter ice lakes were defined as lakes that typically freeze, but have at least one recorded instance in the past 40 years in which there was no complete ice cover during one or more winter seasons; 28 lakes experienced at least one year without complete ice cover. The ice phenology time series for each intermittently frozen lake extended from 40–575 years with a median of 132 years.

We acquired a range of lake geographic and morphometric characteristics for each of the 514 lakes with ice phenological records (Supplementary Table 1). Latitude, longitude, elevation, surface area and mean depth data for most lakes were acquired from the National Snow and Ice Data Centre. Google Maps was used to update preliminary values of latitude and longitude. We also used the HydroLAKES dataset[18] 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 (a ratio of the length of the lake shoreline to the circumference of a circle of the same area, such that a completely circular lake would have a value of 1). A HydroLAKES match was not possible for 130 lakes, so these characteristics were updated from the published literature. It is important to note that the HydroLAKES database is the amalgamation of several sources, including remote sensing and government-produced topographic datasets, each with varying degrees of accuracy[18]. The distance to the nearest coastline for each lake was acquired from the National Aeronautics and Space Administration's Ocean Biology processing group (https://oceancolor.gsfc.nasa.gov/docs/distfromcoast/) and the maximum distance to land within a water body was obtained for each lake as an approximation for fetch[29].

We obtained a range of climate variables for each lake. We acquired monthly mean air temperature, mean cloud cover and total precipitation data from 1970–2010, available for all grids on the globe, from the University of East Anglia's Climatic Research Unit (CRU TS4.01). These climate data were derived from meteorological station measurements that were interpolated onto 0.5° latitude and longitude grids[30]. The spatial resolution of our air temperature data is 0.5°, and thus does not consider finer-scale temperature variation owing to altitudinal gradients within a grid cell. For CRU climate data, we used the 0.5° grid cell in which the lake was located. For lakes larger than a single grid cell, we chose the grid cell closest to the centroid of the lake. We calculated the mean air temperature, mean winter cloud cover and total winter precipitation for this 41-year period to minimize the influence of interannual variability in local weather, as recommended by the Intergovernmental Panel on Climate Change when forecasting future climatic changes. In addition, we acquired bias-corrected annual historical (1901–2010) and forecasted (2010–2099) air temperatures for four GCMs (the Geophysical Fluid Dynamics Laboratory's ESM2M, the Institut Pierre-Simon Laplace's CM5A-LR, the Earth System configuration of the Hadley Centre Global Environmental Model, version 2 (HadGEM2-ES) and the Model for Interdisciplinary Research On Climate version 5 (MIROC5)) and two greenhouse gas emissions scenarios (RCPs 2.6 and 6.0) at a spatial resolution of 0.5° from the Inter-Sectoral Impact Model Intercomparison Project. Other commonly used RCP scenarios—RCPs 4.5 and 8.5—were not included in the Inter-Sectoral Impact Model Intercomparison Project as they were either considered too high for evaluating future climate impacts (RCP 8.5) or did not provide enough span (RCP 4.5). Furthermore, we acquired human population counts from the National Aeronautics and Space Administration's Socioeconomic Data and Applications Center Population Count Version 4.10 from 2015 using a spatial resolution of 0.5° latitude and longitude[31].

Data analysis. The non-parametric Wilcoxon test was used to determine whether there were significant differences in geography, lake morphometry and climatic features between annual and intermittent winter ice lakes. A Wilcoxon test was conducted on 514 lakes and is recommended when predictor variables are not normally distributed or are spatially autocorrelated. We applied a Bonferonni correction to account for multiple tests. With 18 statistical tests performed, a P value of less than 0.0028 was required for significance.

We constructed classification trees using a cross-validation approach[32] with lake geography, lake morphology and climate characteristics to identify which factors influenced the susceptibility of lakes to a loss of winter ice cover. We reduced the 514-lake dataset to exclude missing values and used the remaining 319 lakes in the classification tree analysis. The most parsimonious classification tree was selected by pruning the tree to where the complexity parameter minimized the cross-validation error[32]. Classification trees were developed in R using the rpart package.

We applied the results of the classification trees to a global lake database (HydroLAKES) to estimate the current spatial distribution of lakes potentially experiencing intermittent winter ice cover. We used the HydroLAKES database, which summarizes lake attributes for 1.4 million lakes greater than 10 ha[21], as the global spatial extent of lakes in our study. We delineated the southern boundary of winter ice cover using a 41-year (1970–2010) mean winter (January–March) air temperature of −0.4 °C, such that winter air temperatures were low enough for lake ice to form[33]. In North America and Asia, we limited our analyses to below 60° N because of a paucity of historical ice observations above that latitude.

We forecasted potential intermittent winter ice cover with increases in mean air temperature at increments of 0.1 °C from 0–9 °C and using annual forecasted air temperatures from 4 GCMs with 2 greenhouse gas emissions scenarios for the mid- and late century. We generated one spatial distribution map using selected global air temperature thresholds based on projected warming set by the United Nations Framework Convention on Climate Change[34]. The Paris Agreement under the United Nations Framework Convention on Climate Change aspires to hold global air temperature increases below 2.0 °C. Currently adopted mitigation approaches indicate that air temperatures will rise by 3.2 °C (www.wri.org). If little or no climate mitigation efforts are implemented, air temperatures are projected to rise by 4.5 °C. We also chose an extreme warming scenario of 8 °C. We generated the second set of spatial distribution maps of lakes forecasted to experience intermittent winter ice cover using regional climate models for 2040 and 2080.

We counted the number of countries with lakes projected to experience intermittent winter ice cover at temperatures ranging from +0 °C to +9 °C. We summed the number of people within grid cells containing lakes that shifted from annual to intermittent winter ice cover. All population predictions are based on the 2015 population and do not account for any population growth or decline in the future.

For four lakes in Wisconsin and Sweden, we created a 199-year time series (1901–2099) of annual air temperatures by merging bias-corrected historical records and locally downscaled HadGEM2-ES RCP 2.6 and 6.0 mean annual temperature data. From this, we calculated a non-centred 41-year moving average air temperature to identify when lakes could cross the 8.4 °C threshold, at which point they are predicted to begin experiencing intermittent winter ice cover.

Data availability

The ice phenology record, as well as location, mean depth, surface area and elevation data, were sourced from the US National Snow and Ice Data Center Lake and River Ice Phenology database, which was updated through the 2017–2018 winter[11]. We acquired additional information (shoreline complexity and length, residence time, volume, mean discharge, slope within 100m of the lake shore and watershed area) for each of these lakes from the HydroLAKES database[18]. We acquired climate information for each lake (mean annual air temperature for 1970–2010) from the CRU[30]. Data that support the findings of this study are available at https://portal.edirepository.org/nis/mapbrowse?packageid=edi.267.2.

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