Lake Ice Will Be Less Safe for Recreation and Transportation Under Future Warming

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Key Points:

- The availability of safe lake ice for recreation will decrease, on average, by 13 and 24 days in response to a global warming of 1.5°C and 3°C
- The most densely populated regions across the Northern Hemisphere are projected to experience the greatest percent loss of safe lake ice
- Without human intervention, the duration of safe ice for winter ice roads is projected to decline by up to 99% within a 3°C warmer world

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Lake Ice Will Be Less Safe for Recreation and Transportation Under Future Warming

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Abstract Millions of lakes from around the world freeze during winter. These frozen surfaces provide essential ecosystem services that are vital to many northern communities. However, the availability of safe lake ice that is oftentimes required to support these services is under threat from climate change. Here we use a 100-member ensemble of climate model simulations to investigate changes in the presence of safe lake ice for different recreation and provisioning activities across the Northern Hemisphere. Our projections suggest that the duration of safe ice for recreational purposes will shorten, on average, by 13, 17, and 24 days within a 1.5°C, 2°C, and 3°C warmer world (relative to 1900–1929), respectively. The projected change in the duration of safe ice will be greater in higher latitudes, but with the most densely populated lower-latitude regions experiencing the greatest percent change. The use of lake ice to support critical transportation infrastructure will also be influenced by future warming through the loss of thicker ice this century. However, our projections suggest that the magnitude of change in the duration of safe ice will differ depending on the ice thickness requirements. For transportation that requires the thickest ice cover, the number of days with safe ice will decline by 90%, 95%, and 99% with 1.5°C, 2°C, and 3°C global warming, respectively. We highlight the need for the development and implementation of adaptation plans to address the imminent loss of critical wintertime transportation infrastructure across the Northern Hemisphere.

1. Introduction

Over half of the world's lakes currently freeze during winter (Hampton et al., 2017; Sharma et al., 2019). However, under climate change, the duration of lake ice cover is shortening at alarming rates (Magnuson et al., 2000; Sharma, Richardson, et al., 2021). Moreover, many lakes in the Northern Hemisphere that historically froze every winter are now experiencing ice-free years (Sharma et al., 2019). The long-term loss of lake ice is projected to continue with future warming (Grant et al., 2021), with some lakes even transitioning to a permanent ice-free state this century (Sharma, Blagrave, et al., 2021). Similarly, lake ice thickness is projected to decline considerably under climate change (Grant et al., 2021; Li et al., 2021; D. J. Mullan et al., 2021). Changes in lake ice dynamics can have widespread ramifications for numerous physical and ecological lake processes, including winter stratification, phytoplankton dynamics, and gas exchange (Hampton et al., 2017; Salonen et al., 2009; Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020; Woolway, Denfeld, et al., 2021). Understanding lake ice responses to climate change is therefore of critical importance.

In addition to influencing key aquatic processes, lake ice also provides essential ecosystem services (i.e., the benefits people obtain from ecosystems) that are vital to northern communities, both culturally and economically (Knoll et al., 2019; Perrin et al., 2015; Wobus et al., 2017). For example, winter ice roads in the Far North provide critical transportation infrastructure for remote communities during the winter months to procure food, fuel, medical supplies, or heavy machinery and minimize the exorbitant costs of air travel to acquire basic necessities (Hori et al., 2017; D. Mullan et al., 2017; D. J. Mullan et al., 2021). However, transportation trucks that use these winter ice roads require ice to be at least one meter thick. In southern locations, such as in Bayfield, Wisconsin (on Lake Superior), an ice road for cars and pickup trucks replaces the ferry to Madeline Island to transport children to school (Magnuson & Lathrop, 2014) but requires ice to be at least 30 cm thick. Cars and pickup trucks are also driven on frozen lakes to access prized ice fishing locations. Ice fishing not only provides recreational opportunities but can provision protein sources in the winter and generate revenue for local economies. For example, 40% of the total catch of perch, roach, and ruffe are angled under-ice in the winter from Lake Peipsi recreationally, but also sold to the local community by retired or unemployed individuals (Orru et al., 2014). In Sweden, the ice fishing industry alone generates $880 million USD of revenue annually. However, it is important to note that declining winter revenue, particularly for ice fishing, could be offset with increasing revenue in the open-water summer season. Finally, ice thickness must be at least 10 cm thick to sustain human weight. Tragically, there has been a documented increase in drownings through lake ice in warmer winters when the ice is anomalously thin (Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020).

Future projections of ice duration, as the subject of most recent lake ice studies, can be used as a proxy for projecting future change in the use of freshwater for winter recreation and some of the provisioning activities described above (Brammer et al., 2015). However, accurately projecting how these ecosystem services might change within a warming world requires a consideration of changes in lake ice thickness and, importantly, the occurrence of "safe ice." While previous studies have explored changes in ice thickness, both in individual lakes (Bartosiewicz et al., 2020; Brown & Duguay, 2011a; Caine, 2002) and across large geographic regions (Grant et al., 2021; Li et al., 2021) no study, to our knowledge, has investigated how different ice thickness thresholds, which are required to predict safe ice for key winter activities, will change this century. To fill this knowledge gap, here we investigate the influence of climate change on lake ice thickness and the occurrence of safe lake ice for different recreation and provisioning activities across the Northern Hemisphere. With this aim, we analyzed daily lake data obtained from an ensemble of historical and greenhouse warming simulations conducted with a state-of-the-art Earth system model.

2. Methods

2.1. Lake Ice Projections

We evaluated the influence of climate change on the duration of safe lake ice by analyzing simulations from the Community Earth System Model version 2 large ensemble (CESM2-LE) (Rodgers et al., 2021). Most notably, we investigated lake ice projections generated by the Lake, Ice, Snow, and Sediment Simulator (LISSS) (Subin et al., 2012), which is a 1-D thermodynamic lake model embedded within and coupled to the land surface module of CESM, the Community Land Model (CLM, version 5) (Lawrence et al., 2019). LISSS is an enhanced version of the Hostetler 1-D lake thermal model (Hostetler & Bartlein, 1990), which has been designed to (a) provide a comprehensive treatment of snow at the lake surface including grain size changes with aging and the effects of aerosol deposition on albedo (Flanner et al., 2007); (b) explicitly simulate freezing, melting, and ice physics; and (c) include the effect of sediment heating on the water column via the inclusion of a sediment thermal sub-model. Furthermore, compared to other thermal diffusion models, LISSS has been designed to include a more accurate parameterization of lake surface properties such as roughness lengths, and to include an improved simulation of density-driven mixing events. In brief, LISSS simulates the thermal environment of lakes by solving the 1D thermal diffusion equation for lake water and ice, overlying snow (when present), and underlying substrate, then simulates vertical mixing caused by wind-driven eddies, convection, molecular diffusion, and unresolved 3D mixing processes (Fang & Stefan, 1996). Atmosphere-lake coupling includes momentum transfer based on fetch-limited friction velocity. After balancing energy fluxes and solving the diffusion equations, LISSS performs full or partial mixing of the water column based on the density of adjacent layers. Importantly, the effect of snow on ice thickness is also incorporated which, depending on the timing and thickness of snow cover, can influence lake ice thickness as well as delay or hasten ice breakup through higher albedo (positive feedback) or greater insulation (negative or positive feedback, depending on the season), respectively. LISSS has been tested extensively in previous studies investigating lake responses to climate change (Butcher et al., 2015; Grant et al., 2021; Subin et al., 2012). LISSS has been shown to provide an accurate representation of water temperature, surface fluxes, and the thickness of ice and snow in previous studies where observational data were available (Subin et al., 2012). In this study, LISSS was used to simulate lake ice thickness at a 30-min temporal resolution and a spatial longitude-latitude grid resolution of 1°-by-1°. Specifically, lakes simulated within each 1° grid in CESM2-LE are based on the mean depth and surface area of all known lakes in that region, aggregated from the high-resolution Global Lake and Wetland Database (Lehner & Döll, 2004) and a global gridded lake depth data set (Kourzeneva et al., 2012). These projections therefore represent an aggregated "typical lake" for each 1° grid, simulating the average lake thermal environment in that location using the grid cell's climate forcing (Grant et al., 2021; Vanderkelen et al., 2020; Woolway, Sharma, et al., 2021), notably by fully coupling LISSS to the grid cell's atmospheric module through two-way interactions. Meteorological forcing required for LISSS includes air temperature, pressure, precipitation, humidity, wind speed, shortwave radiation, and downward long-wave radiation.

The CESM2-LE simulations were conducted under the historical forcing over 1850–2014 and the Shared Socio-economic Pathways forcing scenario, SSP3-7.0, over 2015–2100 (Eyring et al., 2016). Furthermore, an ensemble approach was used in CESM2-LE to account for the chaotic nature of the climate system whereby subtle changes in the initial state can lead to different climate trajectories due to internal variability. The CESM2-LE includes 100 members, with individual members being initialized with a mix of micro- and macro-perturbations (Rodgers et al., 2021). In this study, a subset of 90 ensemble members which had a daily output field of lake ice thickness simulated by LISSS were utilized. Daily simulations of 4,622 lake grids in 90 members spanning 251 years yielded >30 billion total data points. Importantly, this large ensemble provides a mean to deconvolve the forced signal from natural variability, given that natural variability in lake ice is often substantial. Here, we analyzed individual ensemble members independently and then calculated ensemble averages.

2.2. Safe Lake Ice for Recreation and Provisioning Activities

From our model simulations of lake ice thickness, we define the duration of safe lake ice for recreation as the number of days that the projected ice thickness is equal or greater than 10 cm, and is maintained for at least 7 days to ensure that the load capacity of the ice is not compromised (Block et al., 2019). Here, we use the minimal ice thickness that is required to sustain human weight assuming that the ice only consists of the strongest, black, clear ice with air temperatures consistently below freezing for 1-week (Block et al., 2019). Formation of white ice, such as in conditions of recent snowfall or rain-on-snow events can reduce load capacity, and should be considered when interpreting our findings (Block et al., 2019; Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020). The total number of safe ice days within a given year is then calculated as the number of days that this threshold is reached. The spatial variations in the availability of safe lake ice across the Northern Hemisphere are also compared with population density data for each model grid. Specifically, population data for 2020 were extracted from the Socioeconomic Data and Applications Center (Gridded Population of the World, version 4; Center for International Earth Science Information Network, 2018) and then remapped onto the CESM2-LE 1°-by-1° global grids. This analysis was intended to determine if those regions that experience less safe ice per year are also the most populated.

We also investigated the influence of climate change on the use of safe ice for different modes of transportation, which are particularly critical for northern communities. In this study, we selected three thresholds for transportation across safe lake ice, including at least (i.e., a lower limit) 13 cm for snowmobiling, 30.5 cm for cars and pickup trucks, and 107 cm for large transport trucks (Minnesota Department of Natural Resources https://www.dnr.state.mn.us/safety/ice/thickness.html). For each of the ice thickness thresholds, which must be maintained for at least 7 days, we calculated the total duration of safe ice per year, which were then quoted against different levels of global warming (relative to the 1900–1929 base-period average). Notably, we calculated the mean change in safe lake ice within a 1.5°C, 2°C, and 3°C warmer world by first estimating the year in which these global warming levels were reached, and averaged the ice cover anomalies over a 15-year period centered at this time. We used the 1900–1929 period to define the air temperature baseline as it was deemed suitably early to provide a benchmark against any signature of anthropogenic warming over the study period.

The metrics described above were compared across climatic zones, as identified by the Köppen climate classification (Köppen, 1990; Köppen & Geiger, 1930), which provides an efficient way to describe climatic conditions defined by multiple variables (e.g., temperature and precipitation) and their seasonalities. Notably, the Köppen climate classification was developed based on the empirical relationship between climate and vegetation and provides an efficient way to describe climatic conditions defined by multiple variables and their seasonal cycles with a single metric. Here, we used the Köppen climate classification for a long-term average climate (1901–2010), using the same criteria as Kottek et al. (2006) and Chen and Chen (2013). The Köppen classification uses monthly temperature and precipitation data averaged over the 1901–2010 period, on a 0.5° longitude × 0.5° latitude grid. The classification system divides the terrestrial global landscape into five major climatic zones (Tropical, Dry, Mild temperate, Snow, and Polar). In brief, a Tropical climate includes regions where temperature during the coldest month is greater than or equal to +18°C. A Dry climate is where the total annual precipitation is less than 10 times the dryness threshold, which is calculated based on the annual mean temperature and precipitation. A Mild temperate climate is where temperature during the coldest month is greater than

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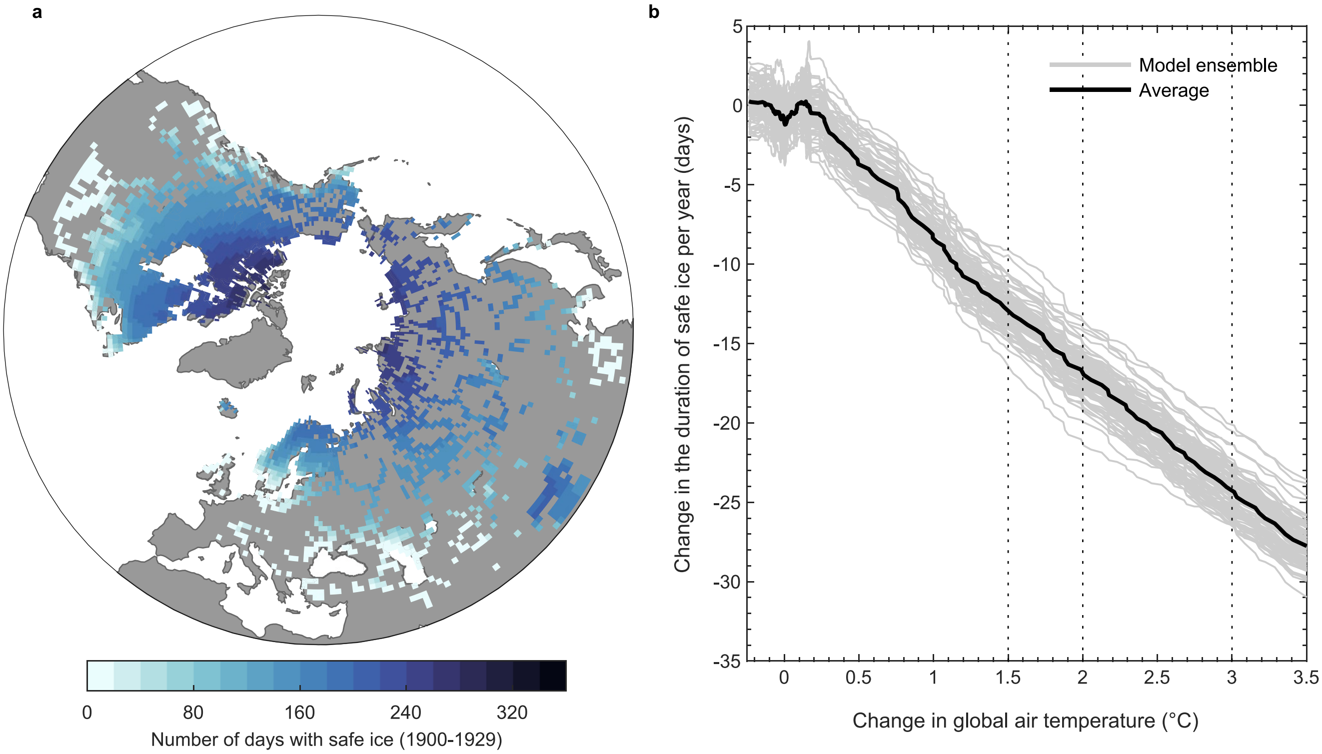

Figure 1. Historic duration of safe lake ice for recreation and the influence of global warming. Shown are (a) the historic (1900–1929) spatial patterns in the average duration of safe lake ice for recreation (>10 cm thick) and (b) the change in the number of days with safe ice under different levels of future global warming. The results in panel (a) are based on the average simulations across a large model ensemble (see Section 2), as also shown by the thick line in panel (b). The thin lines in panel (b) represent the global average from the individual models within the ensemble. All results in panel (b) are smoothed with a 31-year running average. The magnitude of global warming is calculated relative to the 1900–1929 average.

−3°C and less than +18°C. A Snow climate is where temperature during the coldest month is less than or equal to −3°C. Finally, a Polar climate is where temperature during the warmest month is less than +10°C. For a detailed explanation, refer to Chen and Chen (2013).

3. Results

Our long-term simulations suggest that the duration of safe lake ice for recreation (i.e., ice thicker than 10 cm) in the Northern Hemisphere on average lasts 152 days during the historic period (averaged here for all years from 1900 to 1929). The number of safe ice days ranges between 0 and 40 days in warmer southern regions, between 260 and 300 days at higher latitudes, and in some very northern cold lakes, the duration of safe ice can be even longer (Figure 1a). However, our Large Ensemble simulations suggest that the duration of safe lake ice will shorten considerably in response to the projected future increase in global average air temperature (Figure 1b). With a 1.5°C increase (i.e., 2024–2038) of global air temperature since the start of the 20th century (1900–1929), the duration of safe lake ice will shorten, on average, by 13 days. The magnitude of change will be considerably greater under a global warming of 2°C (i.e., 2037–2051) and 3°C (i.e., 2061–2075), with a projected change of 17 and 24 days of less safe ice, respectively. Our projections suggest that the average duration of safe lake ice will shorten roughly by 7.7 days for every 1°C increase in global average air temperature.

The magnitude of change in the duration of safe lake ice will not be similar everywhere (Figure 2). Our projections suggest, under different levels of global warming, that the absolute change in the duration of safe lake ice will be greatest in the coldest regions, including the northernmost latitudes. Specifically, under global warming of 1.5°C, 2°C, and 3°C, our simulations indicate that the duration of safe ice will shorten, on average, by 17, 24, and 35 days, respectively, in lakes situated north of 45°N. At lower latitudes, south of 40°N, the duration of safe lake ice will shorten on average by 5, 6, and 9 days, respectively. However, given that the duration of safe lake ice is often shorter in lower/warmer latitudes during the historic period, the percent change in the duration of safe lake ice can be considerably higher. Notably, many lakes situated between 40°N and 45°N will experience

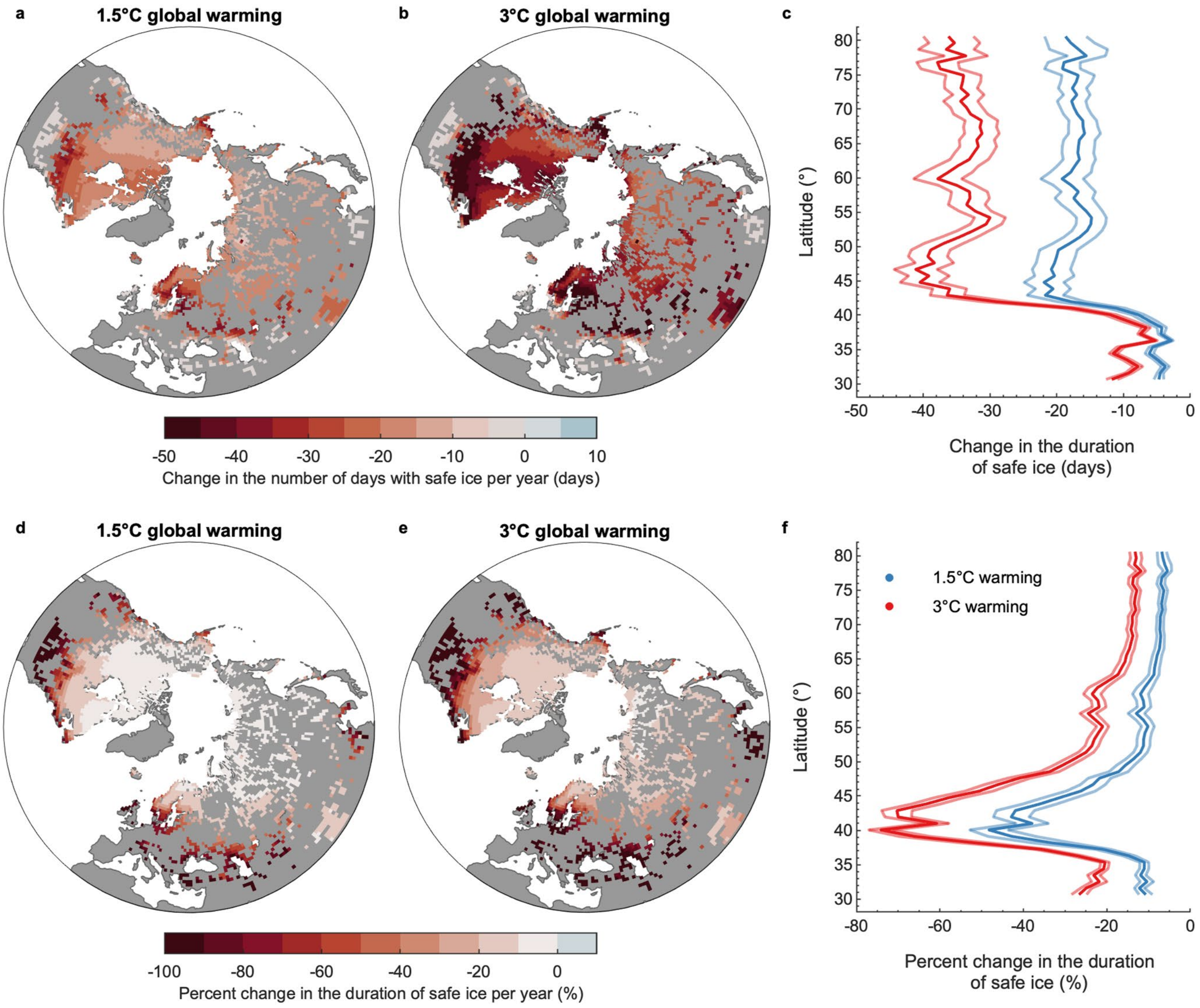

Figure 2. Future change in the duration of safe lake ice for recreation. Shown are changes in the duration of safe ice for recreation (>10 cm thick) under (a) 1.5°C and (b) 3°C global warming, throughout the Northern Hemisphere. The projections are based on the average across the model ensemble. Also shown, in panel (c), are the latitudinal averages in the projected change in the duration of safe lake ice under different levels of global warming (1.5°C and 3°C), showing both the average and spread (standard deviation) across the model ensemble. Panels (d–f) demonstrate similar results to panels (a–c) but shown as a percent change. The magnitude of global warming is calculated relative to the 1900–1929 average.

more than a 40% loss of safe ice under each of the warming scenarios considered. Under a global warming of 3°C, lakes situated in these regions are projected by the model to experience a 66% loss in the duration of safe lake ice, on average. Some southern lakes are projected to experience a 100% loss of safe lake ice under the most severe warming case. Specifically, high-elevation lakes in the United Kingdom that experience ice cover during the historic to contemporary period, will lose all safe lake ice within a 3°C warmer world. A similar loss of safe lake ice is also projected by our model ensembles for many lakes in southern Europe, namely regions surrounding the Black Sea, but also extending to European lakes as far north as southern Sweden and Norway. Most southern United States are also likely to lose safe lake ice within a 3°C warmer world. We stress that our results do not suggest that there will not be any lake ice, but that the ice will not be sufficiently thick, and last a sufficient duration, to support winter recreation according to our criteria within a warming world.

To investigate further the change in safe lake ice across climatic gradients, we grouped our studied lakes according to the Köppen climate region in which they are found. The studied lakes are distributed across four of the major Köppen climate groups (Figures 3a and 3b), primarily within the Dry (number of representative lakes [n] = 160),

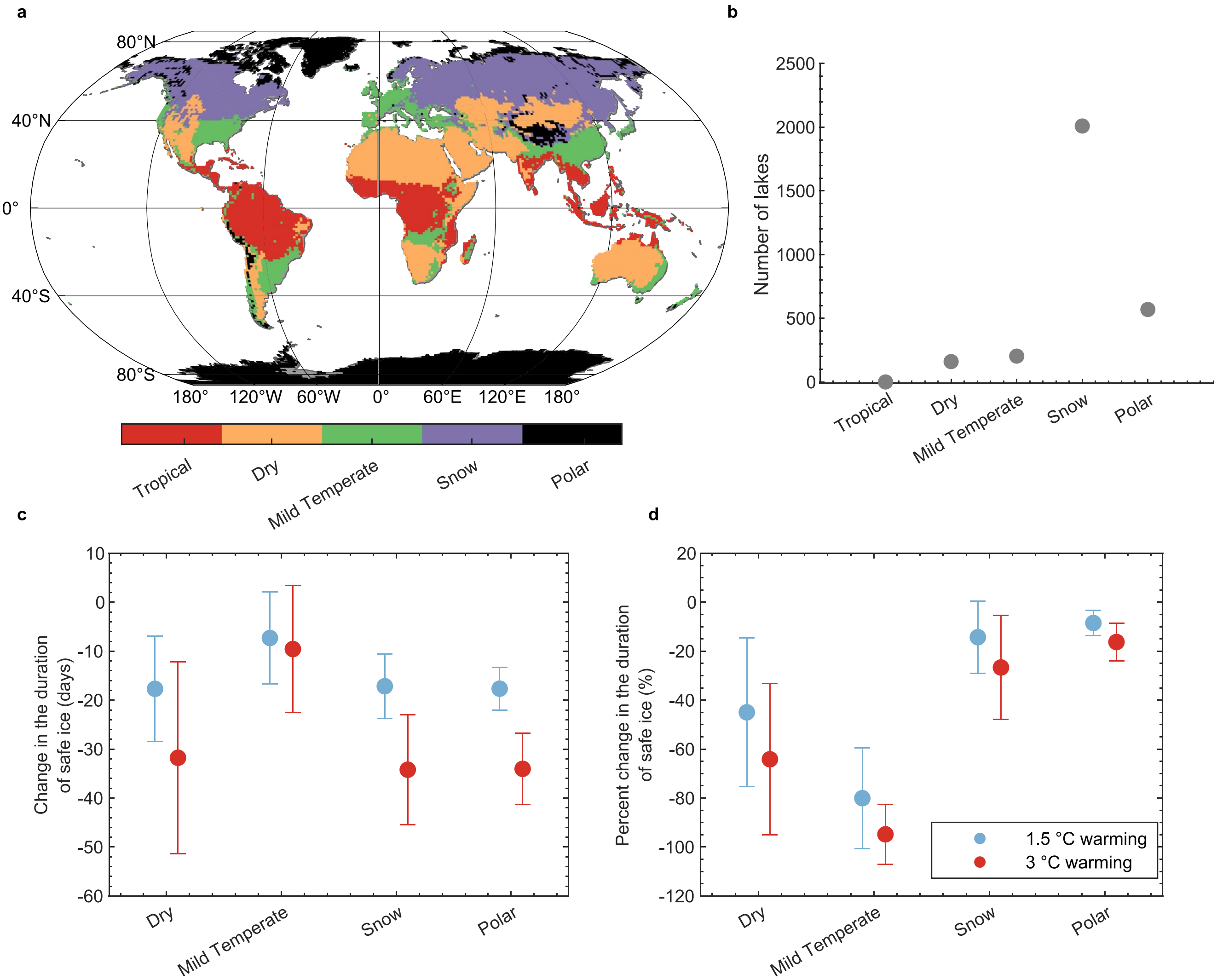

Figure 3. Future change in the duration of safe lake ice across climatic gradients. Shown across Köppen climate zones (a, b), are (c) changes (mean and standard deviation) in the duration of safe lake ice for recreation (>10 cm thick) under 1.5°C (blue) and 3°C (red) global warming. Panel (d) demonstrates similar results to panel (c) but shown as a percent change. The magnitude of global warming is calculated relative to the 1900–1929 average, and the future safe ice projections are based on the average across the model ensemble.

Mild temperate (n = 203), Snow (n = 2009), and Polar (n = 569) climate zones. Within each sub-group, we calculated the average and standard deviation of the total and percent change in the duration of safe lake ice. Our simulations suggest that, within a 1.5°C warmer world, the change in safe lake ice will change similarly among the Dry (−17.7 ± 10.8 days), Snow (−17.2 ± 6.7 days), and Polar (−17.7 ± 4.4 days) climatic zones. The least change is projected to occur in the Mild temperate climate zone (−7.3 ± 9.4 days). The projected changes increase to −31.8 ± 19.6, −9.6 ± 13.0, −34.2 ± 11.2, and −34.0 ± 7.3 in Dry, Mild temperate, Snow and Polar regions, respectively, with 3°C of global warming. Moreover, the percent change in the duration of safe lake ice will be considerably greater in the Mild temperate zone under 1.5°C (80.1 ± 20.5%) and 3°C (−94.8 ± 12.2%) of global warming. Furthermore, we also observe a pronounced latitudinal gradient in population density, and our simulations suggest that the percent change in the duration of safe ice under future warming will be greatest in the most densely populated regions (Figure 4). For example, under 1.5°C global warming, the most densely populated regions (>500 people/km^2) will experience more than a 60% loss in the duration of safe lake ice. The percent change increases to >90% with a warming of 3°C.

Lake ice also provides critical transportation infrastructure for northern communities, including for snowmobiling, driving cars, pickup trucks, and large transport trucks. Figure 5 shows the climatological mean duration

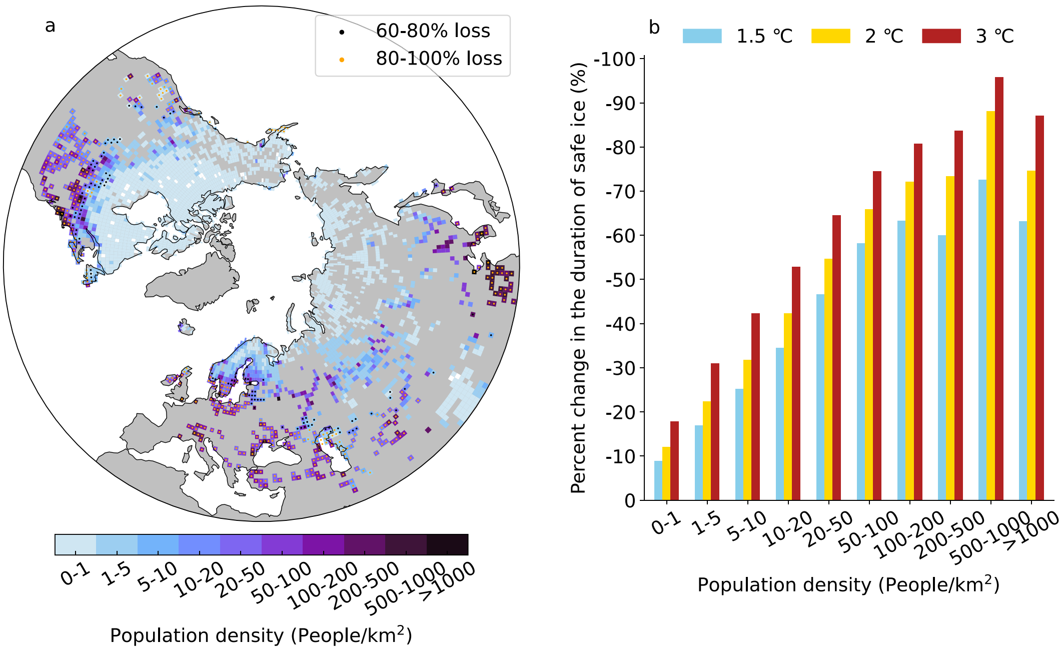

Figure 4. Percent change in the duration of safe lake ice relative to population density. Shown are (a) the population density (in 2020) across the Northern Hemisphere and (b) the projected percent change in the duration of safe lake ice (>10 cm thick) under different levels of global warming, categorized according to population density. All simulations are based on the average across the model ensemble. Black dots in panel (a) denote percent change in the duration of safe lake ice ranging from 60% to 80%, and orange dots denote changes ranging from 80% to 100% under 3°C global warming.

of safe lake ice for these modes of transportation across the Northern Hemisphere during the historic period (1900–1929). The spatial patterns of safe lake ice for snowmobiles and cars/pickup trucks follow closely those for recreation (Figure 1a). However, the projected availability of safe lake ice for transport trucks is largely restricted to higher latitudes (i.e., Canadian Arctic and the northern Siberia). Each of these transportation modes will be influenced by climate change through the loss of thicker lake ice this century (Figures 6 and 7). Our projections suggest that the magnitude of change in the duration of safe lake ice, in the context of these modes of transportation, will differ depending on the ice thickness requirements (Table 1). For example, the safe use of lake ice

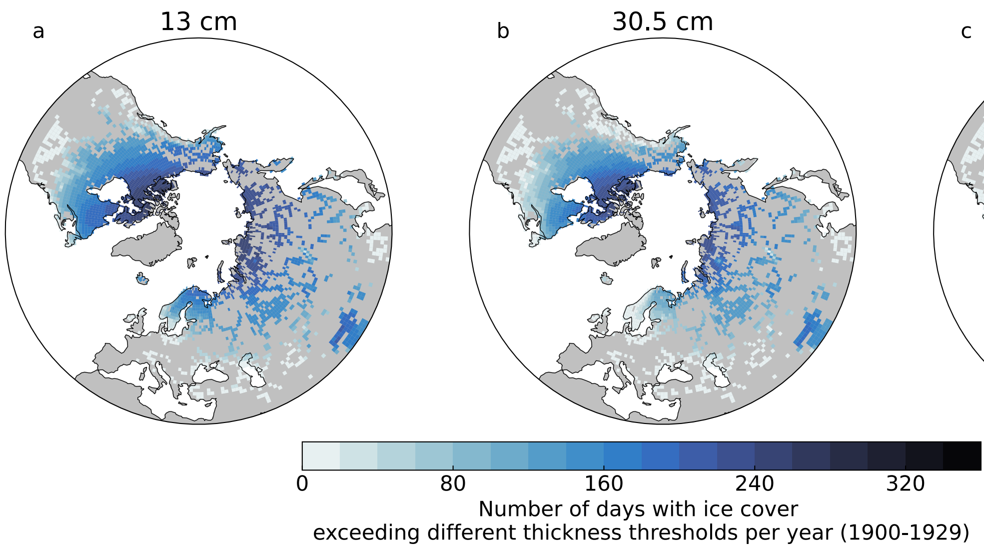

Figure 5. Historic duration of safe lake ice for (a) snowmobiles (>13 cm thick), (b) cars and pickup trucks (>30.5 cm thick), and (c) transport trucks (>107 cm thick). Shown are the historic (1900–1929) spatial patterns in the average duration of safe lake ice, which are based on the average simulations across a large ensemble (see Section 2).

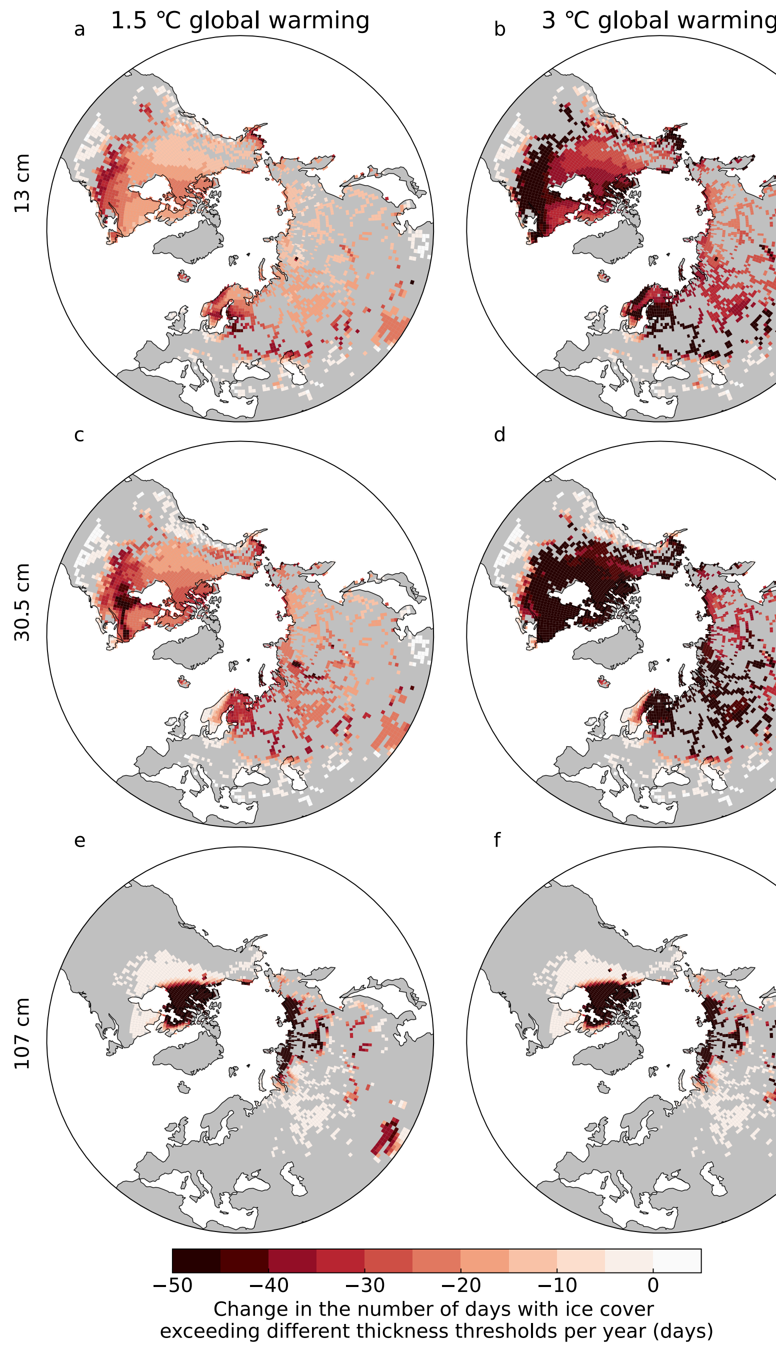

Figure 6. Future change in the duration of safe lake ice for (a, b) snowmobiles (>13 cm thick), (c, d) cars and pickup trucks (>30.5 cm thick), and (e, f) transport trucks (>107 cm thick). Shown are changes in the duration of safe ice for under (a, c, and e) 1.5°C and (b, d, and f) 3°C of global warming relative to the 1900–1929 average, throughout the Northern Hemisphere. The projections shown are based on the average across the large ensemble.

for snowmobiling requires ice to be thicker than 13 cm. Our projections show that the duration of safe lake ice for snowmobiling across the Northern Hemisphere will decrease by 21%, 26%, and 33%. Under the same magnitudes of warming, the duration of safe ice days for driving cars and pickup trucks will decrease by 29%, 36%, and 47%. The greatest projected change in the availability of safe lake ice under future warming is estimated for large transport trucks, which require ice to be thicker than 107 cm and are essential for northern communities. The number of days with safe lake ice for transport trucks is projected to decrease by 90%, 95%, and 99% within a 1.5°C, 2°C, and 3°C warmer world.

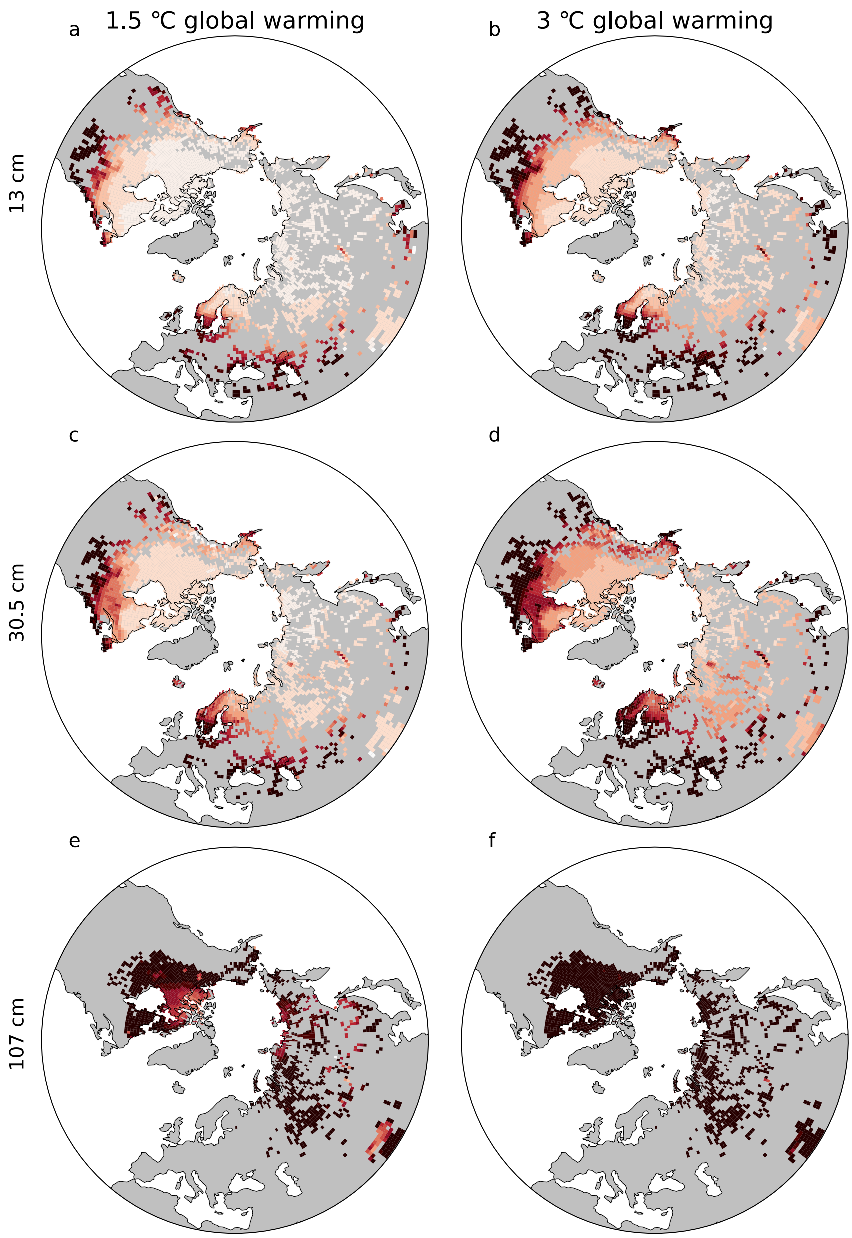

Figure 7. Future percent change in the duration of safe lake ice for (a, b) snowmobiles (>13 cm thick), (c, d) cars and pickup trucks (>30.5 cm thick), and (e, f) transport trucks (>107 cm thick). Shown are changes in the duration of safe ice for under (a, c, and e) 1.5°C and (b, d, and f) 3°C of global warming relative to the 1900–1929 average, throughout the Northern Hemisphere. The projections shown are based on the average across the large ensemble.

4. Discussion

In this study, we provide the first quantitative assessment of changes in the duration of safe lake ice for recreation and provisioning activities in response to future global warming. Intuitively, our simulations suggest that the duration of safe lake ice will shorten across the Northern Hemisphere by 13, 17, and 24 days if global average air temperatures warm by 1.5°C, 2°C, and 3°C, respectively, relative to the 1900–1929 base period. Air temperature is one of the dominant drivers for lake ice properties (Palecki & Barry, 1986; Vavrus et al., 1996; Weyhenmeyer

Table 1
Change in the Duration of Safe Ice for Transportation Under Global Warming

Ice thickness (cm)	Transportation mode	Climate zone	Change in the duration of safe ice under global warming (days, %) 1.5°C	2°C	3°C
13	Snowmobile	All	−17 (−21)	−23 (−26)	−33 (−33)
		Dry	−18 (−48)	−23 (−56)	−32 (−67)
		Mild temperate	−6 (−84)	−7 (−91)	−8 (−96)
		Snow	−18 (−16)	−24 (−21)	−35 (−29)
		Polar	−18 (−9)	−25 (12)	−35 (−17)
30.5	Cars/Pickup trucks	All	−22 (−29)	−30 (−36)	−42 (−47)
		Dry	−17 (−54)	−23 (−63)	−30 (−75)
		Mild temperate	−1 (−90)	−1 (−96)	−2 (−98)
		Snow	−23 (−28)	−31 (−35)	−44 (−47)
		Polar	−25 (−16)	−33 (−20)	−49 (−29)
107	Transport trucks	All	−24 (−90)	−28 (−95)	−31 (−99)
		Dry	−12 (−93)	−14 (−97)	−15 (−100)
		Mild temperate	–	–	–
		Snow	−14 (−94)	−16 (−97)	−17 (−100)
		Polar	−46 (−80)	−56 (−91)	−64 (−98)

Note. We show the calculated duration of safe lake ice for different types of transportation under future climatic conditions. Future lake ice conditions were estimated for different levels of global warming (1.5°C, 2°C, and 3°C) and compared to those estimated at the start of the 20th century (1900–1929). Negative values represent a decrease in the duration for each mode of transportation under future warming, and numbers in the parenthesis indicate the percentage change. Results are based on the average across the model ensemble and are quoted across Köppen climate zones. All values are rounded to the nearest integer. Missing values indicate no safe ice for a particular transportation mode during 1900–1929. Note that the mean change across all climate zones (denoted as "All" in the table) will not always be the same as the mean of the climate zone averages due to the subsets having different sample sizes.

et al., 2011) and has been strongly correlated to ice thickness (Murfitt et al., 2018; Todd & Mackay, 2003), with correlations as high as −0.91 (Murfitt et al., 2018). Our simulations suggest that with every 1°C increase in global average air temperature, the duration of safe lake ice for recreation will shorten by more than 1-week, but with considerably larger changes projected in some regions. As air temperatures warm, and the ice cover season shortens, lake ice has less time to grow leading to a shortening of the safe ice season. Consistently cold air temperatures below freezing are required to form black ice, which has the highest load bearing capacity (Block et al., 2019). Air temperatures hovering around or above 0°C, snowfall, rain-on-snow events, melting and refreezing of water, and ice fracturing can all contribute to the formation of white ice (Brown & Duguay, 2011b; Leppäranta, 2009; Livingstone & Adrian, 2009). In warm and wet/snowy winters, there is more white ice relative to black ice, which is half as strong (Stewart & Magnuson, 2009). The presence of white ice reduces lower load bearing capacity and requires even thicker ice to sustain the same amount of human weight (Block et al., 2019). As extreme warm, wet/snowy winters and freeze-thaw events become more common (Clark et al., 2016), ice will need to be even greater than 10 cm thick to be safer for people to use. Anomalously warm or stormy winters can also cause lake ice to break open in a "blowout" (Perrin et al., 2015).

4.1. Spatial Heterogeneity in the Loss of Ice

Ice thickness will not decline homogeneously across the Northern Hemisphere. At more southern latitudes (and/or Mild temperate regions), the number of days where ice thickness is greater than 10 cm and is deemed "safe" is projected to decline by 9 days under 3°C global warming. This amounts to a 60%–100% reduction in the duration of safe lake ice. Thus, although these lakes may still freeze, albeit intermittently (Sharma et al., 2019), the ice may not be sufficiently thick to support human weight. These southern regions also coincide with the most densely populated regions (>500 people/km^2). In regions with the densest populations,

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our projections suggest a loss of 60%, 75%, and 90% of safe ice use if temperatures warm by 1.5°C, 2°C, and 3°C. Regions where winter air temperatures approach 0°C are associated with highest winter drowning rates (Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020). Thus, climate and behavioral adaptations will be required for residents of these areas to partake in winter ice recreational activities where ice quality has been tested or otherwise traveling to more northern regions where ice will still be safe to use. However, some southern lakes are projected to experience a 100% loss of safe winter ice, suggesting that these lakes, even if they are ice-covered, will not be safe to use for any winter ice recreational activities if global average air temperatures warm by 3°C.

Lakes located at northern latitudes (>60°N) are expected to have a higher absolute decline in ice thickness and lose 17, 24, and 35 days of safe ice cover under scenarios of 1.5°C, 2°C, and 3°C global warming. Although the population density is generally lower at higher latitudes, northern communities rely on ice cover for essential activities, including transportation and sustenance. Cree hunters have remarked on the increased occurrence of weaker white ice in response to more rain events in the winter (Royer et al., 2013). Increased search and rescue events have already been associated with thinning ice cover and warming air temperatures in Indigenous communities in Alaska and Canada's northern territories who rely on traditional hunting and fishing for their livelihoods (Clark et al., 2016; Durkalec et al., 2014). In addition, winter drowning rates through ice for northern Indigenous communities are amongst the highest in the world as ice is less predictable and stable (Brubaker et al., 2011; Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020). Thinning ice is forecasted to continue to increase search and rescue events, injuries, and winter drowning rates in the north in response to climate change (Clark et al., 2016; Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020), as well as threaten wildlife. For example, threatened migratory caribou populations rely on crossing frozen lakes and rivers in the winter. Thin and unstable ice increases the risk of drowning (Leblond et al., 2016). Approximately 10,000 migratory caribou drowned in the Quebec-Labrador Peninsula in the 1980s because of thin ice (Sharma et al., 2009). It is essential to develop multi-stakeholder and participatory adaptation plans which incorporate traditional knowledge, modern technology, and Indigenous-led social awareness campaigns to help further reduce injuries and fatal drownings due to thinning lake ice (Furgal & Seguin, 2006; Giles et al., 2013).

4.2. Implications for Transportation Infrastructure

Critical transportation infrastructure for northern communities over frozen lakes and rivers, such as in the United States, Canada, Russia, and Sweden, will be vulnerable to thinning ice, in addition to shorter duration of ice cover sufficiently thick to support vehicles through the winter months (Arp et al., 2019; Prowse et al., 2009). The loss of lake ice thick enough to sustain snowmobiles, cars, and pickup trucks will all decline within a warming world. Weather conditions, such as air temperature, snowfall, and wind play an important role in the construction of winter ice roads. Several studies have illustrated a delay in the opening date of winter ice roads in warmer winters, in some years almost a 3-week delay and a 25% loss of the winter ice road season (Hori et al., 2017; Knoll et al., 2019; D. J. Mullan et al., 2021). For example, in northern Manitoba, Canada, winter ice roads connect 30,000 people in 28 remote communities for eight weeks of the year. Winter ice roads provide essential infrastructure to allow for the provisioning of food, medicine, machinery, and goods, in addition to social connection critical to the mental health of community members at a third of the cost of air transportation (Blair & Sauchyn, 2010; Hori et al., 2018). The winter ice roads also provide a much-needed economic boost to these communities where unemployment rates can be as high as 80%–90% by employing community members in road construction and allowing the export of goods, such as fish and fur, in the winter months (Blair & Sauchyn, 2010). Our simulations suggest that warmer temperatures may dramatically decrease the duration and extent of winter ice road coverage, by as much as 99%–100%. Although in some areas, such as in Alaska, the freshwater supply for ice roads may increase because of climate change (Arp et al., 2019), the ice may not be sufficiently thick to sustain the heavy loads carried by transport trucks (Prowse et al., 2009). Although, for coastal communities, declining sea and river ice may increase ship navigation (Mudryk et al., 2021; Prowse et al., 2009), land-locked communities may incur additional expenses with declining or disappearing winter ice roads through either the construction of all-weather roads or air transportation, both of which are much more costly (Hori et al., 2017; Prowse et al., 2009). For example, in the warm winter of 1998, winter ice roads could not be built for 12 communities in Manitoba which cost the provincial and federal government an additional $15–18 million CAD to fly in essential goods, such as food, medical supplies, and fuel (Blair & Sauchyn, 2010).

4.3. Perspectives of Implications

Although we consider our results robust and believe that they bridge an important knowledge-gap, there are several caveats to consider when interpreting our key findings. First, for the resolution available with the current generation of Earth system models partaking in CMIP6, it is not possible to resolve individual lakes. Thus, in evaluating lake responses to climate change our model, like others (Golub et al., 2022) represents an aggregated "typical lake" for each 1° longitude-latitude grid, where the modeled representative lake is characterized by the average surface area and depth of all known lakes in that grid and forced by the grid cell's climate forcing. Individual lakes within a 1° grid will likely behave differently to the typical lake considered as, for example, lake surface area and depth are known to influence the duration of ice cover, and thus would also be expected to influence the ice thickness. Specifically, lake depth modulates ice formation and thickness as deeper lakes take longer to cool in autumn and subsequently freeze in winter (Brown & Duguay, 2011b; Sharma et al., 2019). Moreover, air temperatures need to be below 0°C for longer before deep lakes freeze (Nõges & Nõges, 2014). Larger lakes with a longer fetch, and thus higher wind speeds (Woolway et al., 2018), also tend to freeze later, as they are more sensitive to increased wind action breaking up the initial skim of ice on the lake surface (Magee & Wu, 2017; Williams et al., 2004), but also experience earlier ice break-up (Kirillin et al., 2012; Magee & Wu, 2017). These lake-specific processes will not be captured in our modeling approach. However, our simulations do represent changes in the most common lake type within a region, and thus are important to anticipate how safe lake ice will likely change in the future and are particularly useful to capture the large geographic patterns of projected change. We also note that as our projections are generated with a 1-D process-based lake model, horizontal features in lakes and the intra-lake responses to climate change will not be captured (Mason et al., 2016; Woolway & Merchant, 2018). This can be very important for large lakes where the time taken for shallow near-shore regions to freeze is substantially different to the deeper central regions. Projecting within-lake responses to climate change should be a key focus of future studies. It is also important to consider that lake ice thickness, as well as the duration of safe lake ice, will be influenced by the timing and the depth of snow present on the ice surface. While the influence of snow-on-ice is included in the model used in this study, it is important to consider that the uncertainty in the climate driving fields is likely to impact the accuracy of the simulated snow cover. Inaccurate projections of snow thickness can result unrealistic growth of lake ice and this can be considered a major source of uncertainty in the future. Furthermore, our simulations do not consider the influence of human intervention in, for example, the construction of ice roads. One important omission in our projections, that should be considered when interpreting our findings, is that snow on the surface of lake ice can be removed to promote ice growth and thus lengthen the duration of the safe ice season for large transport trucks. Indeed, this method is often adopted on many of the busiest winter ice roads in the Northern Hemisphere, such as the Tibbitt to Contwoyto Winter Road in northern Canada, to ensure that these transport routes are viable for as long as possible (D. J. Mullan et al., 2021). This is not considered in our study and thus regions where winter ice roads are known to exist are missing in, for example, Figure 5. This human factor could also have a considerable influence on the projected changes quoted in Table 1. Also, the ice thickness/duration requirements that we consider in this study are consistent across the study region, which allowed us to isolate the climate change impact on the presence of safe ice. However, some ice roads may have different ice thickness requirements, which are not considered in this work. Lastly, our safety thickness assessment assumes that the ice comprises of black ice. Incorporating additional drivers that influence ice quality will be instrumental in developing more nuanced predictions (Sharma, Blagrave, et al., 2020; Sharma, Meyer, et al., 2020). Despite these limitations, our results provide an important step forward in understanding changes in safe lake ice within a warming world.

The robust strength of this study is that a Large Ensemble of Earth system model projection, which includes a prognostic thermodynamic lake simulator, has allowed us to identify large-scale patterns of trends in lake ice thickness over global scales. The Large Ensemble was invaluable in allowing us to deconvolve the forced (anthropogenic) and natural variability components of the response, enabling (a) identification of the forced signal itself and (b) a timescale over which such changes will emerge over natural variability. It is our hope that in leveraging the strengths of the large ensemble to identify the forced response of lakes and to relate this to natural variability, that our work motivates continued coordination between Earth system model development and lake model development. This should be facilitated by future expansion of computing resources, including increasing spatial resolution and correspondingly improved process representation (non-thermodynamic processes in lakes, improved large-scale hydrological processes etc.). We also believe that the results presented here are robust for emphasizing the potential benefits of meeting international goals of limiting global warming to 1.5°C or 2°C, and that the impacts highlighted here can inform decision making regarding climate mitigation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The outputs of CESM2-LE are available at: https://www.cesm.ucar.edu/projects/community-projects/LENS2/data-sets.html. The code used to produce the figures in this paper is available at https://doi.org/10.5281/zenodo.6984624 (Huang, 2022).

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