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Review article

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Lake ice quality in a warming world

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Abstract

Ice phenology has shifted with anthropogenic warming such that many lakes are experiencing a shorter ice season. However, changes to ice quality – the ratio of black and white ice layers – remain little explored, despite relevance to lake physics, ecological function, human recreation and transportation. In this Review, we outline how ice quality is changing and discuss knock-on ecosystem service impacts. Although direct evidence is sparse, there are suggestions that ice quality is diminishing across the Northern Hemisphere, encompassing declining ice thickness, decreasing black ice and increasing white ice. These changes are projected to continue in the future, scaling with global temperature increases, and driving considerable impacts to related ecosystem services. Rising proportions of white ice will markedly reduce bearing strength, implying more dangerous conditions for transportation (limiting operational use of many winter roads) and recreation (increasing the risk of fatal spring-time drownings). Shifts from black to white ice conditions will further reduce the amount of light reaching the water column, minimizing primary production, and altering community composition to favour motile and mixotrophic species; these changes will affect higher trophic levels, including diminished food quantity for zooplankton and fish, with potential developmental consequences. Reliable and translatable in situ sampling methods to assess and predict spatiotemporal variations in ice quality are urgently needed.

Sections

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Introduction

Lake ice is a critical component of the cryosphere[1] upon which populations in the northern latitudes rely. Societies derive tangible benefits from ice-covered lakes[2], including for transportation[3], fishing for sport and food[4], recreation[5] and entertainment[6]. Ice roads, for example, provide a critical lifeline to northern and Indigenous communities during winter[5,7], as well as support trade and economic activity, including the movement of CAD$500 million in goods per year from the Tibbitt to Contwoyto Winter Road[5,7]. In addition, ice cover strongly modulates the lakes' physical characteristics, including temperature[8,9], stratification[10] and light[11], which, in turn, influence under-ice ecology. For instance, in years with early ice breakup, water temperatures increase from prolonged exposure to solar radiation, warming littoral habitats beyond the thermal tolerance of some fish species and limiting their preferred feeding area[12,13].

Warmer air temperatures and shifting precipitation patterns – a direct consequence of anthropogenic emissions[14] – are changing the extent[15–17] and variability[18,19] of lake ice, affecting these societal and ecological services. Such changes are often typified through ice phenology – the timing of ice growth and retreat – with clear reductions in annual ice cover (later freeze up and earlier melt) apparent in observational records[20,21] and future model projections[14] (Box 1).

Beyond phenology, the transparency and consistency of ice is also of critical importance. These characteristics describe ice quality – the ratio of black to white ice. Black ice (also called clear ice or congelation ice) is solid and transparent, whereas white ice (also called snow ice or superimposed ice) is opaque and structurally weaker, owing to its lower density associated with incorporation of air bubbles and slush during freeze up[22,23]. These properties have strong bearing on the societal and ecological benefits of lake ice. For instance, a decrease in ice quality (representing reduced black ice compared with white ice) has immediate impacts on the safety of individuals moving on ice, either for transportation or recreational purposes[24,25]. In February 2021, 10 individuals lost their lives in Sweden after falling through ice consisting only of a white ice layer[26]; further drownings can be expected as ice quality conditions worsen[25]. Ice quality also dictates the amount of light transmitted to the water column, affecting under-ice water temperature, light conditions and inverse stratification[27], and thereby under-ice ecology across trophic levels[28–30]. Despite its importance, however, limited data have resulted in minimal consideration of ice quality, obscuring the shift towards degraded ice conditions.

In this Review, we investigate the changes in lake ice quality and their resulting impacts. We begin by describing mechanisms that influence lake ice quality, before examining the observed and projected consequences of climate warming on lake ice quality. We subsequently examine the effects of these changes on transportation, recreation and lake ecology. We end with recommendations for future research priorities, including a consistent ice quality measurement method and the potential of cutting-edge technologies.

Mechanisms regulating ice quality

The same physical drivers that control ice phenology – primarily air temperature, precipitation and wind – also govern ice quality, explaining the contrasting bearing capacity and opacity characteristics (Fig. 1). The primary mechanisms that lead to the development of black and white ice are now discussed.

Temperature

Air temperature is the predominant driver of lake ice growth, decay[31], thickness[32] and quality[26]. Prolonged cold air temperatures are required to form the initial ice layer, usually composed of black ice[33]. Once a stable layer is established, the grain size of any subsequent growth is largely dictated by the initial air temperature gradient: a large temperature gradient produces small grains owing to quick freezing[33], whereas a small temperature gradient produces larger grains owing to slower freezing. In both cases, black ice is formed, so-called because it appears transparent as nearly as much light passes through it as through liquid water (although in reality, black ice can be more transparent than water as it tends to have a low concentration of dissolved or suspended matter[23]). If cold, calm conditions remain, this ice continues to grow parallel to the heat flux from the water column, continuing while the conduction of latent heat from ice formation at the ice–water interface is greater than the heat flux into the water[23]. However, fluctuating temperatures inhibit black ice growth and cause formation of white ice (Fig. 1b,c). In particular, temperatures above freezing result in melt–freeze cycles[23], introducing gas bubbles, decreasing grain size and increasing opacity[33] – these small, randomly oriented crystals and impurities create opaque ice, hence white. Such white ice formation is common during spring when air temperatures and solar radiation melt snow and ice cover during the day, but low temperatures refreeze the resulting slush during the night.

Precipitation

In addition to temperature, the timing, amount, frequency and type (rain or snow) of winter precipitation also control lake ice quality through impacts on thermal fluxes and white ice formation. Snow has a low thermal conductivity (generally >0.3 W m^{-2} $°C^{-1}$, varying with density)[34] compared with lake ice (2.14 W m^{-2} $°C^{-1}$ at 0 °C)[23]. Accordingly, it slows the release of latent heat, and delays or inhibits the formation of black ice[23,27], albeit with seasonality. At the beginning of the ice cover period, the temperature gradient between lake water and atmosphere is generally lower than later in the season, meaning that snow accumulation limits black ice growth[35]. However, thick ice also conducts less heat into the atmosphere, and thus, later in the season, snow accumulation can have less influence on black ice growth[35,36].

The snow cover built up by precipitation also has secondary effects by thickening the ice layer through white ice formation[37]. When enough snow accumulates, the weight can submerge the ice layer and fill the pore space in the snowpack; on refreezing, that flooded snow forms white ice[23,38–40]. White ice growth can also occur through rain infiltrating pore space in the snow layer to form slush, which subsequently freezes as a combination of white ice layers and slush[23,27,41]. Moreover, snow can also undergo melt–freeze cycles and promote white ice growth[23,33]. When snow is artificially removed before the formation of white ice, the white ice formation is effectively halted, permitting the growth of a thicker black ice layer[42]. Given that precipitation shows substantial interannual variability, ice quality conditions vary markedly[37].

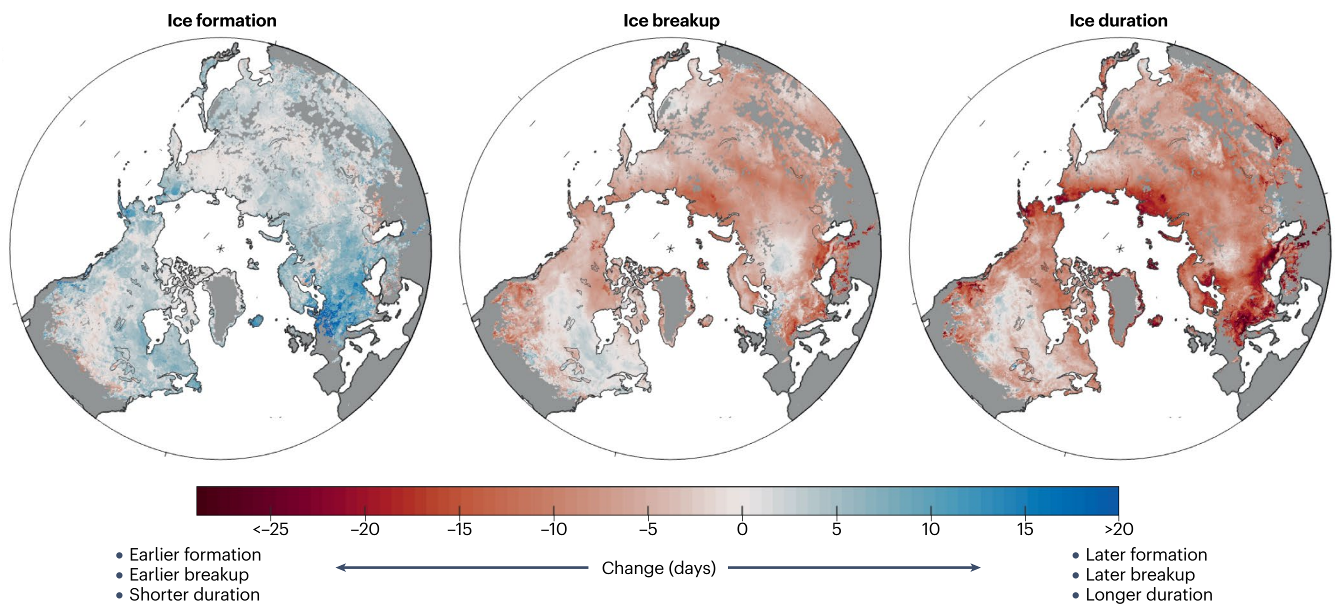
Wind

Wind speed and direction have a further strong influence on ice formation, thickness and quality by interacting with air temperature and snow. When wind advects heat that is conducted through the ice–water interface away from the ice surface, black ice formation is promoted[27,43]. Wind action during the ice formation period can snap thin layers of black ice, the stacking of which produces agglomerated ice and results in thick white ice layers, particularly close to the shoreline[23]. Also, turbulence during ice formation creates frazil ice and slush that can congeal and form an ice layer that incorporates air bubbles, resulting in white ice[44].

Box 1 | Changes to lake ice phenology and duration

Lake ice cover is a sentinel of climate change[149], often quantified using the timing of ice formation and breakup — ice phenology. Phenology records are some of the oldest climate observations in the Northern Hemisphere, in some cases extending long before the Industrial Revolution[126,150]. As a direct consequence of rising temperatures[14], observations generally reveal later lake freeze up, earlier thaw and a corresponding shorter ice season[21]. Indeed, trends over 1981–2019 suggest that ice duration is 9 days shorter[14] when averaged across the Northern Hemisphere (see the figure). On the longer timescale, ice duration has declined by 17 days per century over the past 100–200 years, highlighting amplified ice loss in later years (six times faster between 1992 and 2016[20]).

Future projections suggest that these observed changes in ice cover will continue. By 2100, Northern-Hemisphere-averaged ice formation, ice breakup and ice season are projected to be 20±8 days later, 20±7 days earlier and 38±11 days shorter, respectively, under Shared Socioeconomic Pathway SSP3-7.0 (ref. 16). In a stronger warming scenario, these changes would translate to 230,400 lakes no longer freezing annually in an 8 °C warmer world[151] and almost 5,700 lakes permanently losing ice cover by the end of the century (Representative Concentration Pathway RCP8.5)[152].



Lake ice quality is heterogeneous in space, as snow accumulation can vary on ice depending on the predominant wind direction, lake size and land cover[45,46]. Wind can move snow off the ice[47] or accumulate snow non-uniformly[48]. Lakes with large fetches can experience high wind speeds that remove snow and cool the ice surface, preventing insulation from accumulating snow[23]. Larger lakes can form thicker black ice than small, sheltered lakes where snow can remain on the ice cover[48]. For example, in Lake Baikal, which has a large fetch, wind removes snow and creates black ice reaching 1 m in thickness[49,50]. Artificially removed snow cover for a lake in Wisconsin, USA, increased the proportion of black ice, and reduced the white ice thickness from a maximum of 48 cm during the control year without snow removal to 10.5 cm with snow removal[42].

Observed and projected changes in ice quality

Rather than being a primary source of enquiry, contemporary understanding of ice quality is often linked to the quantification of the under-ice light environment[51], phytoplankton abundance[52] or ice bearing strength[53]. In situ ice quality measurements are therefore rare, seasonally biased and geographically limited[54], with longer-term measurements necessary for change detection largely restricted to a few lakes in Russia[54], Finland[37,55] and Wisconsin, USA[56] (Fig. 2). Observations of total ice thickness are more abundant and offer insight into the behaviour of ice cover owing to the dominant control of temperature and precipitation[26,37]. However, these in situ ice thickness measurements are also relatively sparse, which subsequently limits the opportunity to use remote-sensing methods owing to inadequate validation data[32]. Using available observations and model output, observed and projected changes to ice quality are now discussed. Given limited data sources, caution should be used when interpreting these trends.

Observed changes

Total ice thickness — an indirect indicator of ice quality — has generally declined across the Northern Hemisphere[32], albeit with geographical variability. For instance, statistically significant thinning of $-0.71\ \mathrm{cm\ yr^{-1}}$ has been observed over 1995–2020 in Lake Vendyurskoe, northwest Russia (Fig. 2a). These changes are broadly consistent with changes across Finnish lakes[55], where mean and maximum ice thickness thinned

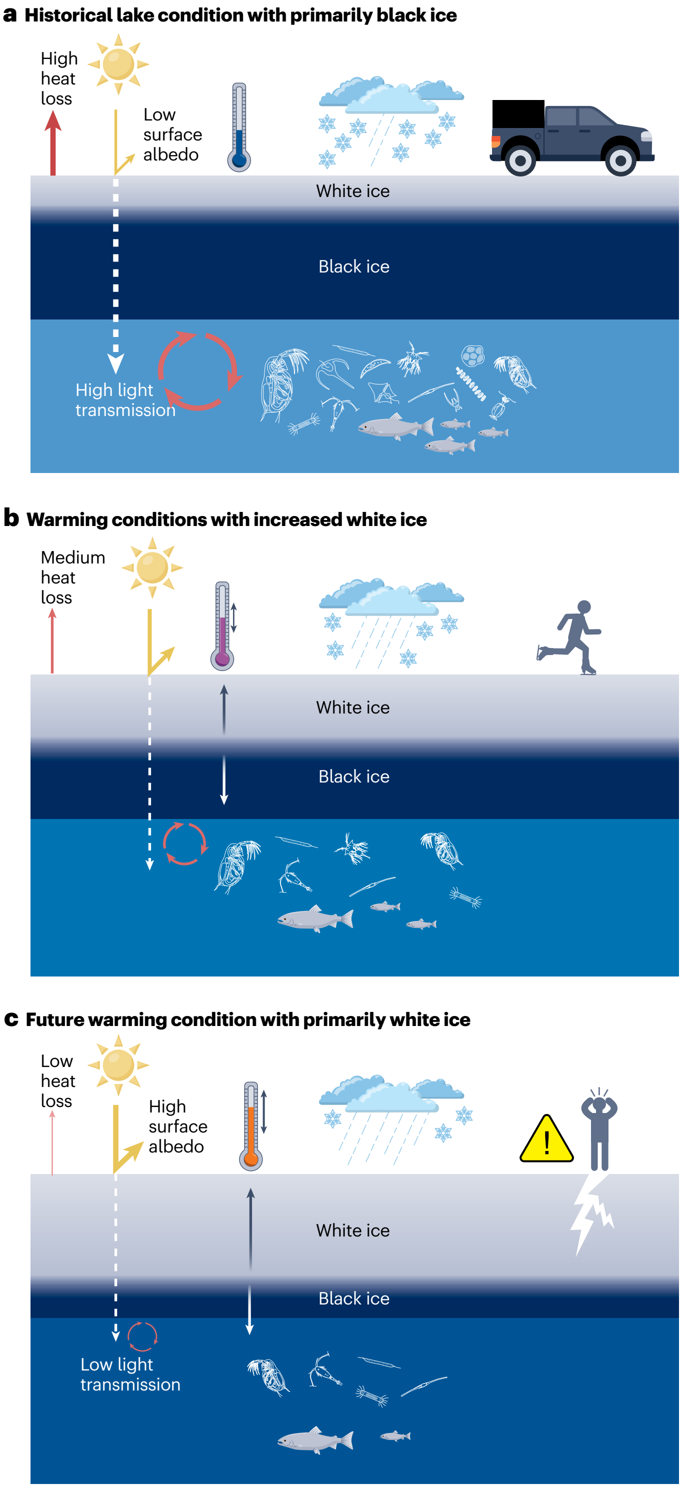


Fig. 1 | Impacts on ice quality in a warming climate. a, The drivers of a high black:white ice ratio and their corresponding physical, ecological and social impacts, broadly representative of a past climate. **b**, As in panel **a**, but for a roughly equal black:white ice ratio, broadly representative of the current climate. **c**, As in panel **a**, but for a low black:white ice ratio, broadly representative of a future, warmer climate. Altered ice quality ratios have a constellation of effects that span human and ecosystem impacts.

by −0.24 cm yr^{-1} and −0.29 cm yr^{-1}, respectively, over a 30–114-year period between 1910 and 2024 (Fig. 2b). More broadly, they corroborate changes in lake ice thickness throughout North America, Europe and Asia over 1990–2018 (ref. 32). In contrast, there have been no significant reductions in ice thickness across 11 lakes in Wisconsin, USA, over a varying 19–47-year period depending on the lake[56] (Fig. 2d). Although these changes hint at a deterioration in ice quality in some locations, resolving them requires explicit records of black and white ice.

Although black ice and white ice data are rare, those that are available imply an overall increase in the ratio of white to black ice and, hence, declining ice quality. For instance, despite an absence of white ice changes in Lake Vendyurskoe (probably arising from interannual variability of snow cover[57,58]), black ice thinning of −0.52 cm yr^{-1} over 1995–2020, in combination with reductions in total ice thickness, highlights an overarching loss of ice quality at this location[55] (Fig. 2a). Black ice measurements in Wisconsin further reveal reductions in ice quality, including at Trout Bog Lake where significant thinning of −0.21 cm yr^{-1} has been observed alongside expansion of white ice (0.05 cm yr^{-1}) (Fig. 2d). Other lakes ($n = 3$) in Wisconsin exhibit thinning of maximum black ice (−0.33 cm yr^{-1}), all pointing toward a decrease in the black:white ice ratio[56]. Although long-term (>30 year) black ice trends are not detectable in Finland, increases in mean (0.33 cm yr^{-1}) and maximum (0.45 cm yr^{-1}) white ice thickness, concurrent with decreases in mean and maximum total ice (Fig. 2b), also suggest reduced ice quality across most Finnish lakes, consistent with overall ice loss[37] and rapidly increasing air temperatures since the 1960s[59]. However, variability is evident, as suggested by a significant decrease in white ice thickness (−0.51 cm yr^{-1}) at one lake in Finland.

The longest available data records indicate that lake ice is generally decreasing in mean and maximum thickness[32,55]. Despite limited explicit quantifications of white and black ice[26], detectable long-term trends in North America and Europe hint at transitions toward increasing white ice ratios[55,56]. However, these trends are geographically concentrated, and further black ice measurements are needed to fully inform ice quality trends.

Projected changes

Consistent with the observed tendency for reduced ice thickness, climate models project an overall decrease in ice thickness in the future[16,60] (Fig. 3), suggesting ongoing ice quality declines. According to the Community Earth System Model Version 2 Large Ensemble (CESM2-LE, which does not distinguish between black and white ice)[61], average Northern Hemisphere lake ice thickness is anticipated to decline by 7 ± 5 cm at 1 °C warming compared with a historical period (1851–1880), with the largest declines in northerly latitudes of North America and Siberia (Fig. 3a,c). Although uncommon, ice thickness is projected to increase in some regions, including the northwestern United States. These overarching reductions in ice thickness are seasonally variable, being strongest in spring (−9 cm) compared with winter (−7 cm) (Fig. 3d).

These characteristics also hold at higher levels of anthropogenic warming but with higher magnitude. For instance, at 2 °C warming, Northern Hemisphere-mean ice thickness is projected to decline by 12 ± 8 cm (Fig. 3b,c), with changes exhibiting the same geographical variability and seasonality; changes are strongest in spring (−15 cm) compared with winter (−12 cm) (Fig. 3d). These characteristics also continue to 4 °C warming, the magnitude of thickness changes rising to decreases of 21 ± 12 cm, including spring changes of 25 cm and winter changes of 20 cm (Fig. 3d). These changes are broadly consistent with other modelling, which suggests a reduced mean ice thickness of 0.23 m by the end of the twenty-first century using Shared Socioeconomic Pathway SSP3-7.0 (ref. 16), or a reduction of maximum lake ice thickness by 0.18–0.35 m for Representative Concentration Pathway RCP2.6-8.5; the geographical patterns of changes are also similar[32].

Very few models, however, are able to explicitly distinguish black and white ice from total ice thickness. From those that are able, a 1D process-based model suggests increases in white ice thickness across the Northen Hemisphere[62], including 1–5 cm in North America[63], by 2041–2070 under SRES A2. The largest increases are apparent in continental regions of northern latitudes, eastern and western Canada, and large swathes of Asia[62,63]. These changes are largely thought to be a response to future snowier conditions. In contrast, coastal regions are expected to experience decreasing white ice, which in the case of North America could exceed 20 cm; latitudes below 50° N are also expected to see strong reductions[63]. This model broadly agrees with the broadscale loss of lake ice thickness suggested by CESM2-LE[64].

Ice quality changes under future anthropogenic climate change can also be inferred from projected changes in key forcing variables: air temperature, precipitation and wind. For instance, warming winter air temperatures[65] will increase the number of days that vary around 0 °C, promoting enhanced white ice growth through refreezing of resulting slush layers[35]. For SSP3-7.0, the projected variability of mean surface water temperatures will exceed the average variability (1850–1900) by 2050 at ~2.4 °C warming[66], implying warming-related degradation of ice quality. Furthermore, as air temperatures become anomalously higher (2–8 °C) throughout the twenty-first century, particularly strong temperature trends (0.1 °C yr^{-1}) throughout Canada[16] could result in large numbers of lakes experiencing warmer winters that lead to white ice conditions[26]. These projected increases in white ice align with observed records of degraded ice quality associated with short-term rising temperatures, as evident at local[58], regional[67] and hemispheric scales[26].

However, these temperature-forced increases in white ice will be modulated by local precipitation regimes. For instance, against a background of rising temperatures, any increases in snowfall will further promote rising white ice concentrations[37,42,67], decreasing ice quality. Such changes are anticipated in the Canadian Arctic and northeastern Siberia[68]. In contrast, locations with reduced snowfall — as in the western United States[69] — would be expected to have larger ratios of black to white ice, provided that temperatures remain cool and melt cycles are limited. Of course, interannual variability would modify these overarching characteristics such that cooler years and reduced snowfall would increase the ratio of black ice, but overall ice thickness is still likely to decline[16,32].

Given the sensitivity of lake ice to air temperature, warming will lead to the decline of lake ice thickness and will degrade ice quality[70]. Modelled lake ice projections using a suite of future climate scenarios suggest reduced ice quantity and degraded ice quality — more white ice. Although ice quality projections are largely inferred from ice thickness models, changing air temperatures and precipitation regimes point toward a future with increasing white ice ratios.

Ecosystem services

Thinner lake ice with a larger proportion of white ice creates less stable ice conditions, influencing transportation and recreation, and limits light availability during ice cover, affecting lake ecology. These impacts of changing ice quality on ecosystem services are now described.

Transportation

Lake ice has a critical transportation function. In Canada alone, approximately 8,000 km of winter ice roads connect remote communities with access to goods throughout the winter, particularly in diffusely populated (<0.5 people km^{-2}) Pan-Arctic regions north of 60° N[71]. Despite the low population concentration, northern communities rely heavily on ice roads to reduce the cost of goods and to maintain relationships outside their immediate population centre, which disproportionally affects the economies and wellbeing of Indigenous communities[72].

Ice thickness, quality and atmospheric conditions are key aspects influencing the load-bearing capacity and, thereby, safety of transportation on ice. Owing to the absence of ice quality data, ice thickness is the most common measure of load-bearing capacity, feeding into ice safety guidelines under the assumption that black ice predominates. However, this assumption could substantially underestimate risk[60] given that white ice (which is generally increasing in thickness; Fig. 2) has a lower density[22] and hence load-bearing strength than black ice[24,73]. Indeed, white ice is 36%, 21% and 51% weaker than black ice at temperatures of −9.5 °C, −5.0 °C and −0.5 °C, respectively[22]. These values also highlight the importance of air temperature in governing ice safety[24]. Rapid drops in air temperature make the ice brittle and thus less safe owing to tensions between the upper and lower surfaces of the ice cover[22,24]. The ice also loses strength if the air temperature stays above freezing for 24 hours or more, or if the average daily air temperature rises above −1.1 °C (refs. 24,74).

The aforementioned changes in ice quality threaten the safety of transportation. Indeed, Indigenous peoples living in the James Bay region of Ontario have noted changes to winter road duration, affecting costs, livelihood and community interconnection[72]. For example, the James Bay Winter Road connects remote Indigenous communities with the supplies from the larger southern city of Moosonee[72]; the decreasing duration of the Winter Road limits access to these goods and increases their cost if increasingly relying on barge or aircraft delivery[72]. These experiences are substantiated by declines in freezing degree days necessary to maintain safe winter road conditions[75]. In February 2024, First Nations communities in northern Ontario and Manitoba declared a state of emergency to address the conditions of the winter roads owing to unusually warm temperatures[76], with similar concerns of increasing temperatures threatening infrastructure also raised in the Sakha Republic in northeastern Russia. Winter road data can be inconsistent, limiting the ability to detect trends in ice road duration; however, changes to the duration of winter roads have been recorded both through Indigenous observations and analysis of freezing degree days[75].

Although contemporary changes might be small, future warming is expected to have a strong influence on transportation infrastructure, although with regional dependencies and temperature sensitivity. The largest capacity losses will be in the Arctic regions of North America and Asia. Under hypothetical ice quality scenarios, allowable loads will decrease on average by approximately 3,600 kg, 16,000 kg and 36,000 kg under white ice, 50% white ice and 100% black ice, respectively at 3 °C warming[61] (Fig. 4, bottom row). Accordingly, the number of days with safe ice for transport trucks might decline by as much as 90–99% with 1.5–3 °C warming[60]. Given that white ice has a much lower carrying capacity[22,24], overall capacity losses are much smaller in 100% white ice scenarios (Fig. 4, top row), but the number of safe travel days will disappear almost completely owing to the additional ice thickness required to support the same weight in the presence of white ice[60].

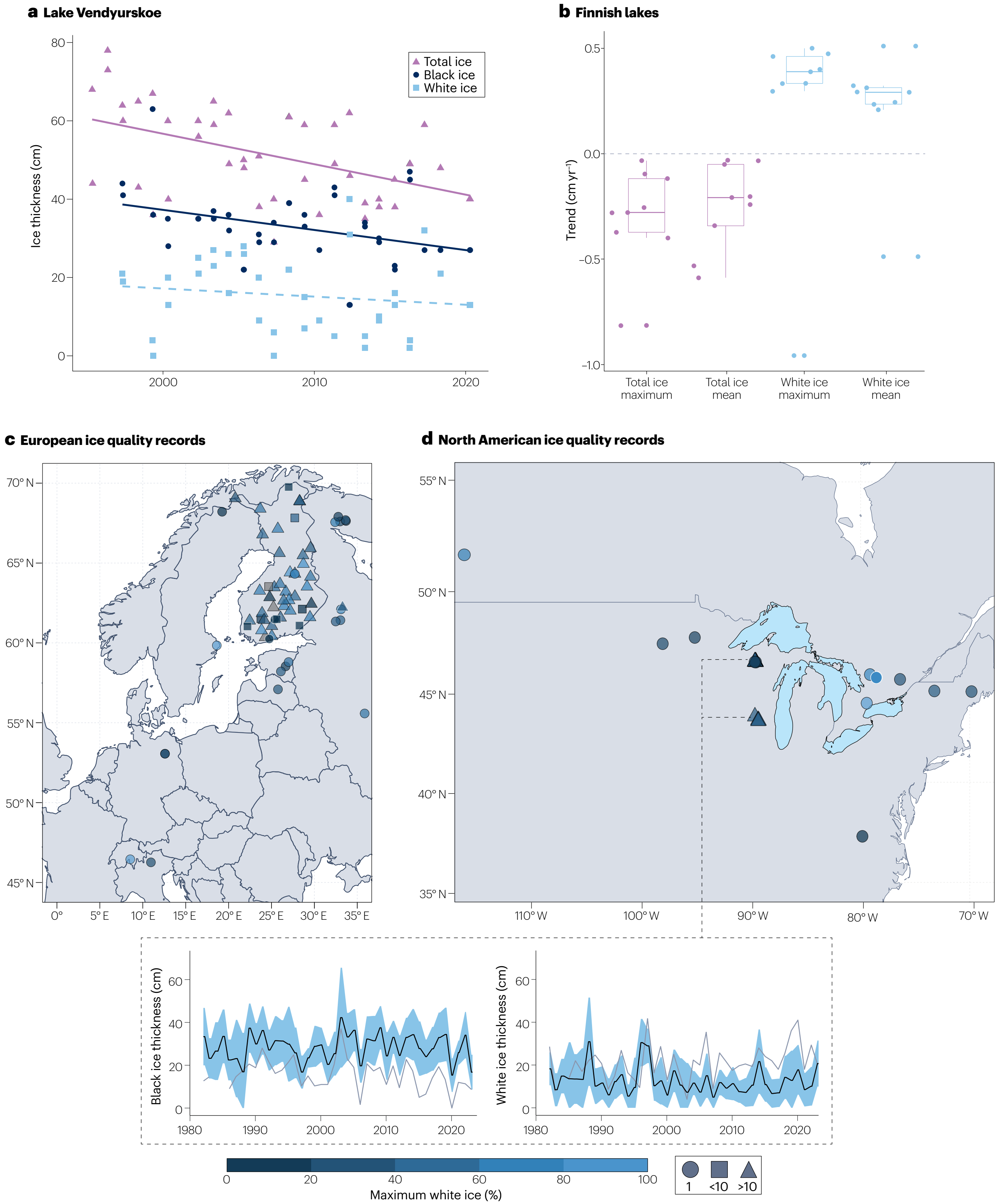

a Lake Vendyurskoe
Total ice
Black ice
White ice
Ice thickness (cm)
80
60
40
20
0
2000
2010
2020
b Finnish lakes
Trend (cm yr⁻¹)
0.5
0.0
–0.5
–1.0
Total ice maximum
Total ice mean
White ice maximum
White ice mean
c European ice quality records
70° N
65° N
60° N
55° N
50° N
45° N
0°
5° E
10° E
15° E
20° E
25° E
30° E
35° E
d North American ice quality records
55° N
50° N
45° N
40° N
35° N
110° W
100° W
90° W
80° W
70° W
Black ice thickness (cm)
White ice thickness (cm)
60
40
20
0
1980
1990
2000
2010
2020
0
20
40
60
80
100
Maximum white ice (%)
1
<10
>10

Fig. 2 | Ice quality observations and trends. a, Total ice, black ice and white ice observations at Lake Vendyurskoe, Russia[54]; solid and dashed lines represent statistically significant and non-significant trends, respectively. **b**, Variability in ice property trends from Finnish lakes with at least 30 years of data (collection ranging from 1910 to 2024)[55]; boxes and whiskers represent the medians, lower and upper quartiles, and minima and maxima of the data. **c**, Ice quality (ice thickness, black ice and/or white ice) measurements in Europe, coloured by maximum proportion of white ice during the Ice Blitz project[26] in winter of 2021, and symbols representing the duration of the ice records in years. Symbols with white borders indicate lakes not sampled during year of the Ice Blitz. **d**, As in panel **c**, but for North America, with a linkedt time series plot specifically for Wisconsin lakes. The linked plot displays the mean (black line), standard deviation (blue shaded region) and the time series for the lake (Trout Bog Lake) that exhibited a significant trend for black and white ice (grey line)[56]. Although there are limited lake quality observations available, those that do exist generally indicate declines in total and black ice thickness and increases to white ice thickness, albeit with variability in magnitude and statistical significance.

Many lower-latitude regions containing winter roads[3,77] will therefore no longer have substantial carrying capacity throughout North America, Europe and Siberia[78,79]. For instance, the Tibbitt to Contwoyto Winter Road (the busiest winter road in northern Canada, responsible for economic activity of CA$500 million per year[77]) is projected to be operationally usable by light and heavy vehicles for 75+ days and 2 days per year, respectively, by 2081–2100 under RCP8.5 (ref. 77); these totals represent reductions of 62 and 50 days compared to 1986-2005. In Ontario, the James Bay Winter Road (320 km) and Wetum Road (170 km) are unlikely to accumulate sufficient freezing degree days by the mid-twenty-first century (2041–2070) for safe winter road construction in all but the lowest warming scenarios (RCP2.5)[3], although more inland regions might remain usable[7] according to CMIP5 simulations under RCP4.5. In other parts of the Arctic, warming will also result in fewer operational travel days[78]. For example, West Siberia is projected to transition from 150–200 travel days under historical conditions (1971–2000) to 100–150 for RCP6.0 and 50–100 for RCP8.5 (ref. 78).

Given these projected changes to the load-bearing capacity of lake ice, adaptation efforts and planning are required to maintain important transportation routes. One strategy includes the construction of permanent roads where seasonal ice roads used to be viable[72]. For example, Highway 10 in Canada, which supplies transportation from Inuvik to Tuktoyaktuk, was constructed to replace a seasonal winter road owing to concern over continued viability[80]. In locations where permafrost degradation is ongoing, permanent road solutions are more of a challenge[81]. Improving ice safety guidelines[25,82], incorporating ice quality into models of winter road capacity, and engineering roads that promote black ice growth into climate adaptation strategies can improve critical infrastructure response[83,84]. Transportation of goods and services might also involve shifting economies to marine shipping as the Arctic Ocean becomes increasingly ice free[85], as already evidenced by rising shipping traffic from 1990 to 2015 (refs. 85,86) and a corresponding reduction in the number of highly strengthened ships[87]. The Arctic is becoming more navigable.

Recreation

Ice-centric recreational activities are a further ecosystem service in cold-weather regions[5]. Lake ice has a long-standing role as a medium for recreation, which includes ice skating, ice fishing and festivals[2,5], often providing revenue. The Harbin International Ice and Snow festival in China, for example, garnered 18 million visitors and generated revenue of US$4.4 billion (ref. 6). Fishing can also have a critical role in the nutrition and economies of Indigenous communities[88]. Changes to ice cover will affect these recreational activities as warmer winters lead to more dangerous ice conditions[25].

Changes in recreation are often considered from the perspective of a shorter ice season. However, ice quality has a critical role in the safety associated with these recreational activities, posing the threat of drowning fatalities. Over 1991–2017, more than 4,000 drownings have been documented across North America, Europe and Japan. The highest numbers of drownings occurred in Latvia and Estonia, but when examining the northern region of Canada, it experienced the highest drownings per capita despite generally cold winter air temperatures, probably owing to the reliance of ice cover for fishing and transportation, which increases frequency of exposure[25]. These fatal drownings are closely linked to air temperature, being 5 times higher when winter air temperatures approach 0 °C (ref. 25). Accordingly, mean spring drownings per capita across all countries are 1.5 times higher than winter drownings, and mean drownings in April 2.6 times higher than in February (Fig. 5). In spring, temperatures are increasing to the point of ice melt and white ice conditions predominate[26]; both these characteristics are expected more frequently in the future. Given these safety concerns, the locations of various outdoor winter events, including the Olympic Games[89] and fishing tournaments[89], have had to be moved or cancelled.

Projected declines in ice thickness and increases in white ice suggest that ice safety will also decline in the future[60]. Accordingly, the number of days during which ice is accessible for activities such as ice fishing, skating or festivals might decrease by as much as a week per degree rise in temperature[60]. However, there is distinct latitudinal and regional variability to these changes: lakes between 40° and 45° N are projected to lose safe ice for the duration of winter, while lakes >60° N are projected to lose safe ice for 13–35 days, with the strongest losses experienced in northeastern North America and Scandinavia[60]. With these changes, the probability of non-fatal and fatal drownings during spring (March and April) might increase, particularly in areas with high rates of unregulated winter activities and/or lenient laws on ice safety such as Canada, Latvia and Estonia[25,82].

Given projected decreases in ice safety and subsequent rising risks, adaptation efforts will be needed. One such opportunity is through stricter ice safety thresholds. Current guidelines indicate that ice 10 cm thick is required for recreation, assuming black ice. In the face of increasingly prevalent rising white ice, these guidelines will probably need to be increased to 20 cm to ensure safe recreation[26]. Local authorities regulating light vehicle use could prevent drownings, as snowmobiles are popular modes of transportation but can result in ice breaks[25]. Additionally, regulation of ice activities when temperatures increase above −5 °C, when ice degrades, could mitigate drowning risks[25].

Lake ecology

In addition to the more societally relevant impacts on transportation and recreation, lake ice quality has a critical role in determining the underlying ecology of the lake. Lake ecology has primarily been researched during the open-water period, but a call to action in 2017

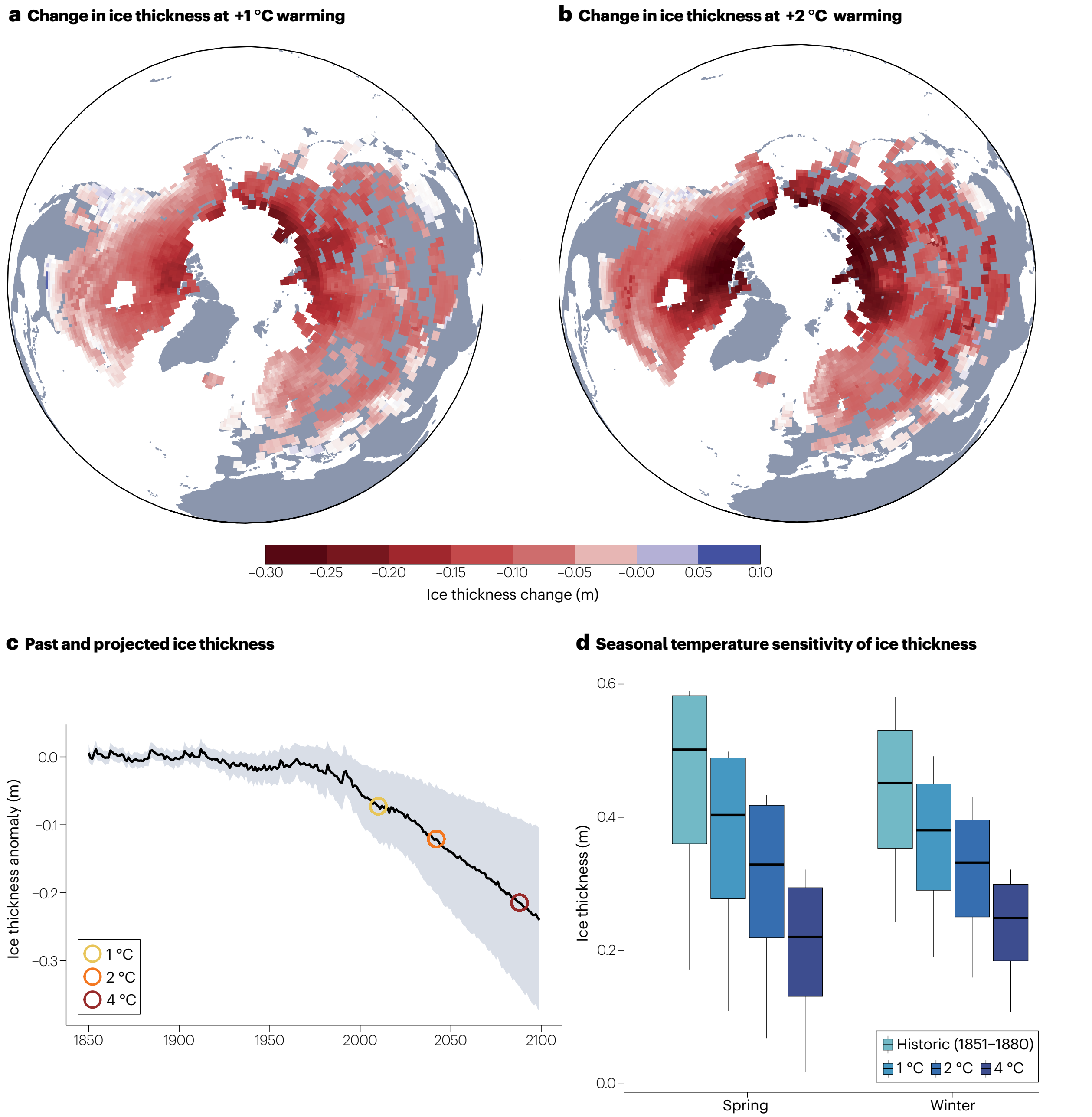


Fig. 3 | Projected changes to ice thickness as a proxy for ice quality. a, Change in average lake ice thickness in the Northern Hemisphere in a 1 °C warmer world. **b**, As in panel **a**, but for 2 °C warming. **c**, Time series of Northern-Hemisphere-averaged ice thickness anomalies with respect to a historical period of 1851–1880, with yellow, orange and red circles representing the times at which warming reaches 1 °C, 2 °C and 4 °C, respectively. Shading represents the standard deviation of ice thickness changes. **d**, Northern-Hemisphere-averaged ice thickness in spring (March–May) and winter (December–February) for the historical period (1851–1880) and for 1 °C, 2 °C and 4 °C warmer worlds; boxes and whiskers represent the medians, lower and upper quartiles, and the minima and maxima of the data. All projections are from the Community Earth System Model Version 2 Large Ensemble (CESM2-LE)[61]. Average yearly lake ice thickness was derived from the mean of 100 ensemble members. Anomaly values were determined by subtracting each year from the historical mean (1851–1880). Ice thickness declines are prominent above 60° N, with stark declines as air temperatures increase throughout the twenty-first century, leading to declining ice thickness in the spring when ice is most dangerous for human use.

highlighted winter-time ecological processes as a necessary field of enquiry[90]. The limitations on light and atmospheric interaction diminish but do not halt phytoplankton activity[51,90], which gives rise to a host of research questions regarding the effect of altered ice cover, such as ice quality, on autotrophic[91] and heterotrophic species[92,93].

Ice cover influences lake ecology largely through the transmission of light. Light transmission depends on the albedo and light attenuation coefficient of the ice cover related to ice quality[94,95] (Fig. 1); snow thickness is also critical[96], but ice thickness is not[51]. In general, black ice allows much larger light transmission than white ice owing to larger crystal structures and limited air bubbles. For instance, roughly 95%

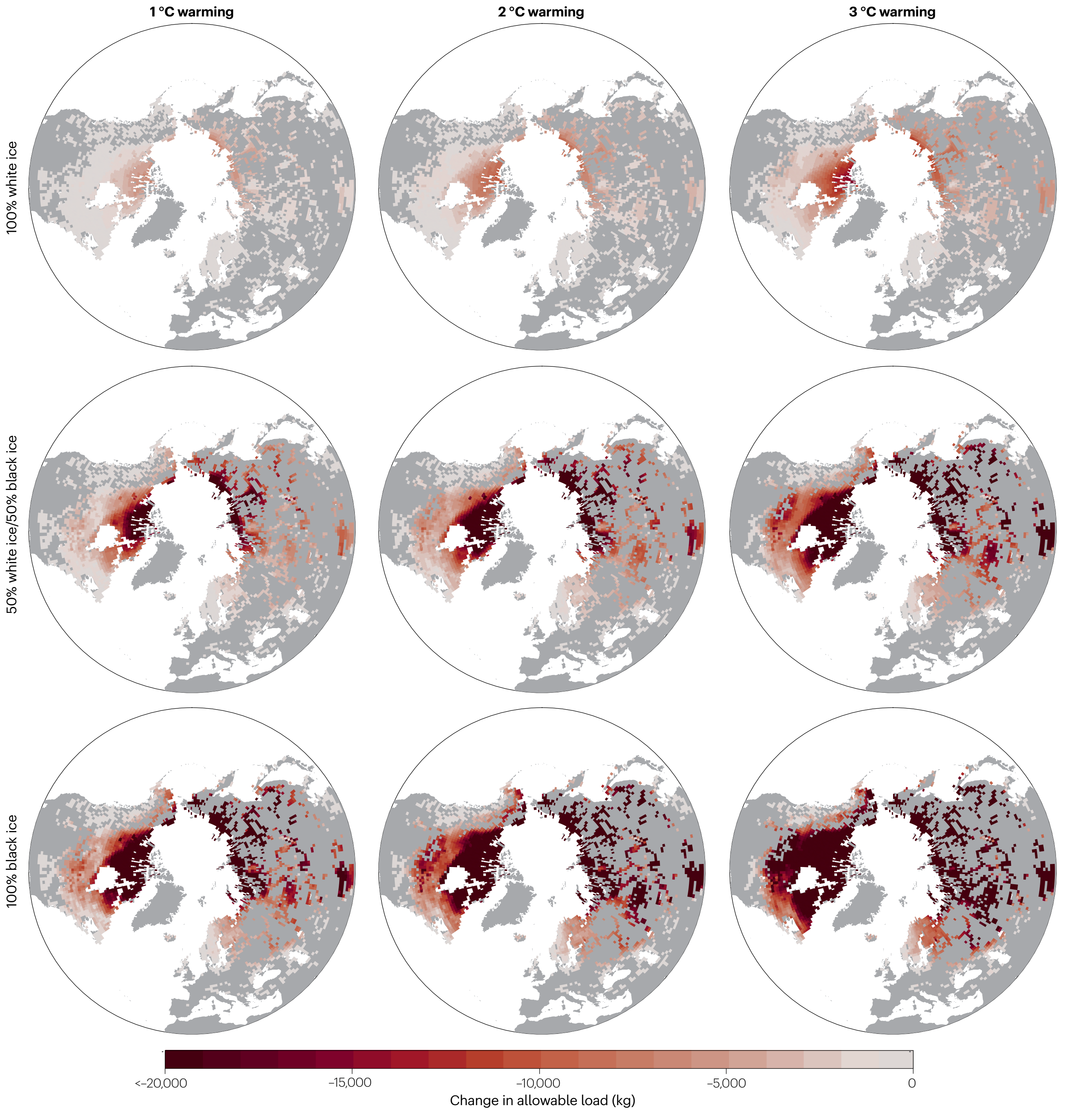


Fig. 4 | Evolving allowable load. Changes in the allowable load on lake ice for 1 °C (left), 2 °C (middle) and 3 °C (right) warmer worlds for 100% white ice (top), 50% white ice and 50% black ice (middle), and 100% black ice (bottom). Ice projections are taken from the Community Earth System Model Version 2 (CESM2-LE), with allowable load calculated using a bearing capacity equation[24,26]. Average yearly lake ice thickness was derived from the mean of 100 ensemble members. The equation for ice bearing capacity was applied to each year[26], and anomalies represent the difference between the climatological historical mean (1851–1880) and each year. Increasing ratios of white:black ice create weaker ice roads with lower carrying capacity; however, ice roads of all quality will be weakened through overall loss in ice thickness in a warmer world.

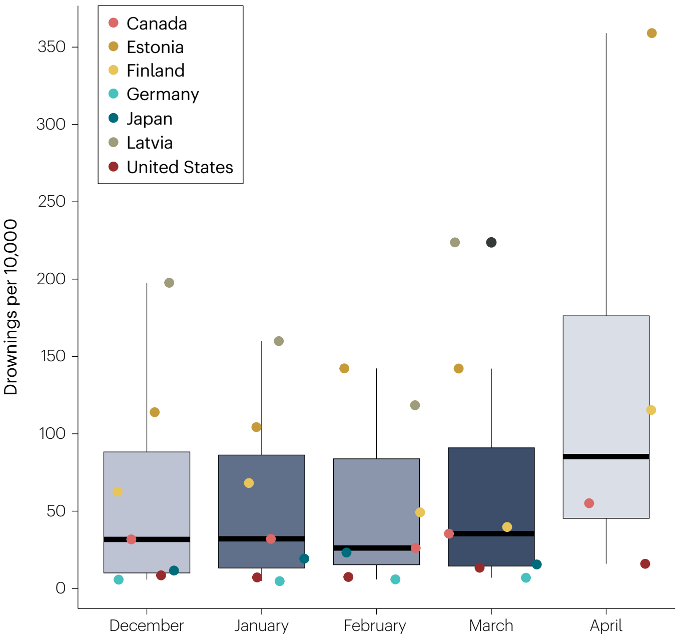


Fig. 5 | Drownings through lake ice collapse. Monthly average drownings in Canada, Estonia, Finland, Germany, Japan, Latvia and the United States[25]. The boxes and whiskers represent the medians, lower and upper quartiles, and the minima and maxima of the data. April had the highest average drownings, with a high of 359 per 10,000 people in Estonia.

of photosynthetically active radiation (PAR; light between the wavelengths of 400 and 700 nm used for photosynthesis) is transmitted in black ice with few bubbles[97], almost as much as in clear water, whereas white ice PAR varies between 20%[51] and 27.2% transmission[96]. Estimates from Grand Traverse Bay, Lake Michigan, reaffirm these contrasts: black ice transmitted approximately 70–80% of surface PAR, whereas a combination of snow cover (8.9 cm) and white ice (1.3 cm) reduced that to ~44%[97]. Similarly, in Lake Haruna, Japan, 60% of surface light was transmitted through 40 cm of clear ice, but the percentage dropped to 20% through 30 cm of white ice[51]. These changes to light transmission will directly affect microbial communities, phytoplankton communities and higher tropic levels, as now discussed[98].

Microbial communities. Large and complex microbial communities thrive beneath ice cover[99], dominated by Verrucomicrobia[29,100,101], Proteobacteria and Actinobacteria[29,101,102]. They perform essential ecosystem services, including: breaking down decaying matter[103,104], transforming dissolved carbon into biomass that can feed other organisms[105], contributing to nutrient cycling[100], and moderating the balance between respiration and productivity during periods when light is a limiting factor[30]. Indeed, all these activities continue under ice[105,106] when photosynthesis can still occur but at a diminished rate compared with the open-water season[90].

However, light availability determines the location of these microbial communities within the water column. Although difficult to disentangle from other influences such as water temperature, nitrogen species and conductivity[102], there is evidence of bacterial communities responding to snow thickness[29] (with snow accumulation possible only when ice cover is present). Yet light limitation does not seem to diminish bacterial growth rates directly[107,108]. For example, in Lake Stechlin, Germany, the termination of an under-ice cyanobacterial bloom that followed snow cover (and therefore light limitation) increased bacterial protein production to five times its typical spring peak, suggesting that phytoplankton community dynamics factor into under-ice bacterial communities[106]. In varying lake environments, such as humic systems, bacterial production responds rapidly to the presence of phytoplankton, even under ice[107]. However, bacterial production can remain higher than phytoplankton production under ice[108]. Therefore, shifts in light abundance seem to affect the productivity of bacterial communities in relation to other factors, such as available phytoplankton biomass to break down[106,107].

The implications of these community shifts remain unclear in the face of changing ice quality. The aforementioned interaction between algal communities and microbial communities offers clues to how microbial communities might behave under variable ice quality environments. Bacterial communities in Lake Erie displayed a preference toward mutualistic interactions with diatoms rather than dinoflagellates, and increased biomass in the presence of diatoms that were more abundant under more transparent ice[109]. Under limited transparency (as expected under white ice conditions), dinoflagellates dominated and bacterial communities were limited[109]. However, in Lake Tovel, Italy, a year with reduced ice transparency reduced competition from algae in the upper euphotic layer that benefited certain bacteria, implying variable direct and indirect effects of ice quality on microbial communities[110]. Ice quality changes throughout the winter period[26] can then demonstrate under-ice cycles of bacterial succession[30] that can have impacts within the food web[109]. Microbial communities, however, demonstrate highly specialized behaviour in ice-covered environments[111], which requires further enquiry to determine how these communities will respond to changes in ice quality.

Phytoplankton communities. Phytoplankton form the basis of the food chain and hence are of vital importance for lake ecology. Their presence provides overwintering species pivotal nutrients during the ice cover period[112]. Phytoplankton growth under ice exhibits strong dependence on light availability, with direct effects occurring through photosynthesis and indirect effects through convection and resuspension of algae in the photic layer[113]. Yet knowledge of phytoplankton growth, community assemblage and succession during the ice-covered period is still nascent[90].

Ice quality influences on light availability are the key mechanism through which impacts on phytoplankton are felt. In general, high black ice ratios are associated with strong phytoplankton abundance, while high white ice and snow cover are linked to declining phytoplankton abundance. Experiments in which snow cover was artificially removed from lake ice to prevent white ice formation reinforce these findings: concentrations of net primary productivity in four lakes in northern Minnesota, USA (Barrs Lake, Pike Lake, Side Lake and South Sturgeon Lake)[91] (Fig. 6a), and chlorophyll *a* in Lake Itasca, Minnesota[114] (Fig. 6b) and South Sparkling Bog, Wisconsin, USA[42] (Fig. 6c) were all consistently higher when snow was removed compared with turbid ice conditions. These findings are consistent with evidence from Lake Haruna, Japan, where chlorophyll *a* concentrations were ~160–180 mg m^{-2} below a transparent ice cover but 70 mg m^{-2} under turbid ice conditions[51].

Although photoautotrophs can grow in low light conditions, it is clear they rapidly respond to light availability associated with black ice[114], whereas potential mixotrophs, unicellular cyanobacteria and Chlorophytes tend to dominate in years with snow and white ice[42].

Relatedly, in Lake Müggel, ice thickness correlates positively with the abundance of the phytoplankton taxa Cryptomonas, Chrysoflagellates, Chrysococcus, Synura and Chlamydomonas, and negatively with the taxa Rhodomonas and Aulacoseira[115]. These taxa represent functional groups where motile taxa have higher relative biomass than non-motile taxa when ice and snow limited light penetration into the water column. However, in some eutrophic systems, some snow and white ice cover benefits photoautotrophs by limiting the photoinhibition that occurs when highly transparent ice allows high surface radiation into the upper water column[91].

Ice quality also influences phytoplankton through mixing. Under black ice conditions, increased light transmission causes thermal convection, in some locations causing mixing as deep as 50 m, as in Lake Baikal[116]. This mixing circulates nutrients[117,118] and keeps non-motile diatoms suspended in the photic zone[113,119,120], benefiting large groups of phytoplankton through access to higher light levels and nutrients. In contrast, weak or absent radiatively driven convection, as is more common in white ice environments, can lead to layered communities of motile phytoplankton[121]; these communities can attune to the light availability within their layer[91] through strategies such as denser pigment packing, altered pigment profiles, higher photosynthetic efficiency and increased chlorophyll *a* content that maximize light absorption and photosynthetic capacity[122,123]. Limited light conditions and narrow light spectra penetration beneath snow and white ice layers provide a competitive advantage for phytoplankton species that absorb light in the green spectrum, indicating a possible community shift under future limited light conditions[91]. These conditions also favour motile taxa that can move nearer to the ice–water interface, or attach to the ice, where the most light will be available[124]. In addition to limited light to promote convection, taxa that rely on convection to move toward the available light can sink in a stilling atmosphere[125], limiting underwater currents[116]. Limited light is additionally likely to affect overall production with cascading impacts to the rest of the under-ice food web[112]. However, some of these impacts could be mediated by shorter ice cover periods in the future[126].

Higher trophic levels. Similar to phytoplankton communities, higher trophic levels have gained attention during winter periods that had been assumed to be a period of quiescence. Invertebrates and vertebrates interact with autotrophs to complete a whole aquatic food web in lakes that continues beneath ice cover. Research on, for example, zooplankton lipid content[93] and fish behaviour[127] demonstrates the importance of winter for aquatic ecosystems as a whole. Higher tropic levels – such as zooplankton, benthos and fish – are also affected by ice quality. These impacts occur both directly through light availability and indirectly through the aforementioned effects on phytoplankton.

Indeed, the impact of ice quality on phytoplankton carries over to indirectly influence biomass and community composition of heterotrophic taxa[128]. One mechanism through which this connection occurs is the availability of phytoplankton-derived energy which, in turn, influences zooplankton growth and survivability. Recall that high black relative to white ice is typically associated with high phytoplankton abundance, providing a food resource that drives high phytoplankton abundance; low black ice relative to white, in contrast, is linked to low phytoplankton abundance and, thus, low zooplankton abundance. Evidence for these relationships is apparent in Lake Atnsjøen, Norway[129], and Lake Kilpisjärvi, Finland[130]: thinner ice and snow cover (black ice conditions) were associated with high zooplankton abundance (specifically high-lipid-content calanoids[131]), whereas thicker ice and snow cover (white ice conditions) were associated with low zooplankton abundance (specifically low-lipid-content cladocerans[131]). Similarly, zooplankton abundance decreased 51% in Lake Superior during a high white ice year (~24% of the ice layer) compared with a black ice year[93]. Projected increases in white ice might, therefore, decrease zooplankton abundance and shift communities to cladocerans over copepods, disrupting the energy transfer to higher trophic levels given low essential fatty acids[131].

The impacts of ice quality on phytoplankton can also influence benthic communities. Benthic organisms benefit from the precipitated biomass of phytoplankton to the sediment, contributing to the diets of benthic invertebrates[132–134] (as well as the degradation of those organisms by bacteria[135]). Diminished autotrophic production from altered ice quality could thereby limit resources and negatively affect the benthos. The importance and potential impact of ice quality changes on benthic communities are unclear owing to limited research, particularly on ice quality[92].

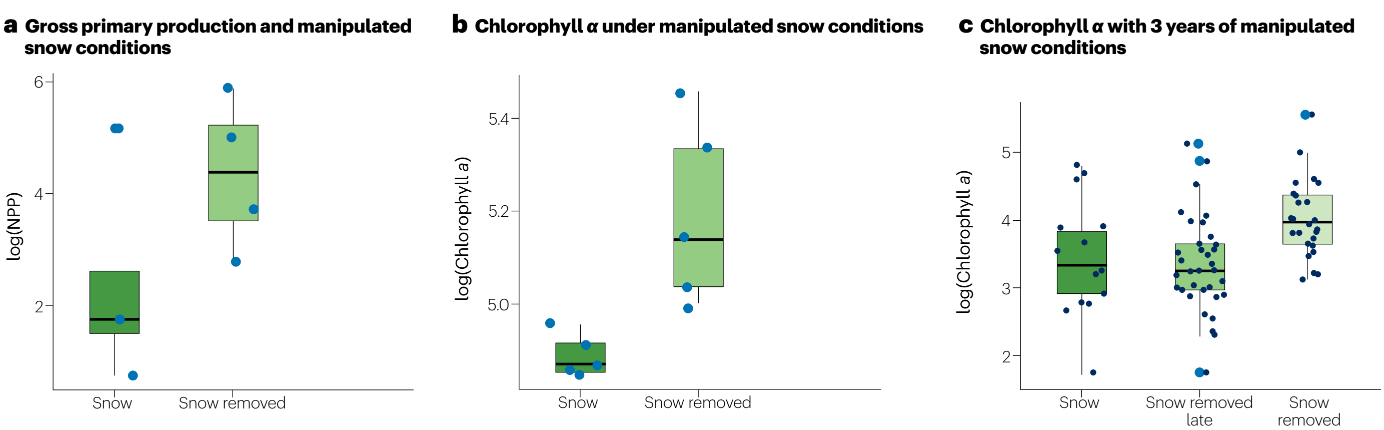


Fig. 6 | Snow cover impacts on lake primary production. **a**, Differences in net primary productivity (NPP) in four different lakes in Minnesota, USA, with snow and those where snow was experimentally cleared[91]. **b**, As in panel **a**, snow was experimentally cleared but points represent individual samples of chlorophyll *a* in Lake Itasca, USA[114]. **c**, As in panel **b**, but samples taken from individual depths in Sparkling Bog, USA, including a year with late and early snow removal, where late snow removal resulted in higher white ice formation[42]. The boxes and whiskers represent the median, lower and upper quartiles, and the minima and maxima of the data. Clearing lakes from snow increases productivity metrics.

Any changes in primary and secondary production can further affect fish populations. In particular, increased white ice in warming winters and subsequent diminished primary productivity[136] can limit food availability and fish growth and reproductive success[137,138]. There are also more direct consequences of changing lake ice on fish populations, but these largely relate to ice phenology and the changing photoperiod rather than ice quality. For instance, desynchronization of seasonal temperatures and photoperiod cues can affect fish gonad development and egg viability[137]. Spawning at inappropriate times (and temperatures) can increase larval mortality or decouple juvenile fish from the start of the spring production pulse[138]. Juvenile fish can miss early zooplankton peaks that follow phytoplankton blooms once light becomes available from reduced snow cover[136], or early snowmelt introduces nutrients to the upper water column[139]. For example, the hatching and juvenile growth of certain species, such as cisco *Coregonus albula*, historically have coincided with favourable zooplankton dynamics[140]. This asynchrony of hatching and prey availability for planktivorous fish leads to high mortality, as early life stages are more likely to deplete energy reserves during winter[138].

There could also be potential benefits to fish. Shorter winter periods, even with diminished under-ice productivity, could benefit fish overall by limiting the overwintering period[141] and oxygen loss. Yet these benefits can be asymmetrical, as coldwater species will lose important developmental periods with climate warming[141]. A more comprehensive understanding of the effects of lake ice variability on ecosystems is required[127].

Summary and future perspectives

Lake ice is well known to have changed over the observational era, particularly from the perspective of ice phenology – the timing of ice growth and retreat. In contrast, ice quality – the ratio of black ice to white ice – has been far less examined, despite its importance for human safety and lake ecology. This absence of knowledge stems, in part, from sparse ice quality observations. However, available evidence suggests that ice quality has declined (increasing white ice thickness and decreasing black ice thickness) in Finland, Wisconsin and Russia (Fig. 2); reductions in ice thickness alongside broader climate changes (in temperature, precipitation and wind) provide further indirect support for declining ice quality reductions across most ice-covered lakes in the Northern Hemisphere. These changes are expected to continue in the future, with ice quality losses strongly scaled to the level of atmospheric warming (Fig. 3). The use of ice for transportation and recreation is, in turn, expected to decline. For instance, even under scenarios of pure black ice, heavy-vehicle use on lakes might completely halt in a 3 °C warming world[60]. Moreover, ice use for recreation in March and April could be greatly reduced owing to increased risk of drowning associated with unsafe ice[25] (white ice prevalence). From the ecological perspective, changing ice might also result in a host of bottom-up trophic interactions that could lead to losses in fitness of young-of-year fish. Yet many unknowns remain, and a rapidly changing climate imposes unprecedented challenges, exposing knowledge deficits regarding how climate change alters ice quality and lake ecosystems.

One of the largest challenges is in the sporadic and spatially limited in situ measurements of ice quality. Limited ice quality records hinder the ability to analyse temporal trends and spatial patterns that can inform research on human and ecological impacts of lake ice quality. With these expanded data retrievals, a standardized ice quality measurement method based on a data collection programme used by the Finnish Environment Institute[55] is recommended. Each year, ice quality measurements should be made a minimum of twice: once at the beginning of the season, as soon as ice is safe to walk on, and again prior to ice breakup. However, more frequent, weekly measurements would be beneficial to assess ice safety. Four essential measurements are recommended: a measure of the total ice thickness in centimetres; a measure of black ice thickness in centimetres; a measure of white ice thickness in centimetres; and a measure of snow and or slush thickness in centimetres, taken as an average of three to five measurements surrounding the site of ice column extraction. Additional quantitative information should be taken when possible, such as the depth of white ice layers that differ in appearance, and impurities from gas bubbles in black ice.

Other data sources highlight the opportunities available to overcome the low temporal resolution of in situ measurements. For example, ice quality could potentially be inferred through the relationship between ice thickness and under-ice light availability[51,97], achievable through using a shallow water ice profiler (for ice thickness) and any number of light sensors[67] (for light availability). However, light attenuation under ice is not yet fully explored. To assess the applicability of this method and its potential error, sensor data need be validated by in situ ice measurements. High-frequency observations can additionally incorporate cross-sectional measurements of the entire lake surface, given the relatively low cost of sensors that can remain under the ice during winter. Incorporating transect measurements from the littoral and pelagic zones, as well as edges, is valuable to understand the risk of travelling onto ice as well as the light conditions for the littoral benthic community under ice.

Spatially diverse measurements would further assist remote-sensing methods that attempt to measure ice thickness on a larger spatial scale. While ice quality measurements are not yet possible using remote sensing[142,143], satellite sensors can begin to accumulate a global database of lake ice thickness. For example, ice thickness was detected on 16 large lakes in North America using altimetry data from TOPEX/Poseidon and Jason-1/2/3 with approximately a 0.2-m accuracy[32]. Aggregating multiple satellite sensors can improve synthetic aperture radar image density to estimate ice quality, for example through the use of satellite constellation missions such as Sentinel-1 A/B and Radarsat Constellation Mission[142] and the development of radiative transfer models such as the Snow Microwave Radiative Transfer (SMRT) model[144,145]. Tools such as synthetic aperture radar and models like the SMRT, in conjunction with lake ice models, can help to predict the presence of non-black ice layers as well as how those layers change throughout the season[144].

Modelling offers an additional avenue to provide ice quality assessment and, importantly, forecasting. Models such as DYRESM-WQ-I account for layers of black ice, white ice and snow cover[146]. The attempts to account for white ice have underpredicted the thickness of the layer and overpredicted the thickness of black ice[147]. This underprediction might result from the DYRESM-WQ-I model isolating the formation of white ice to the intrusion of lake water as a result of ice and snow weight overcoming ice buoyancy[146,147]. A tuning parameter, such as the snow compression rate parameter, might assist this prediction of white ice development[58]. Pairing models that predict black and white ice layers with models that account for spatial heterogeneity of ice thickness, for example the Aquatic Ecosystem Model AEM3D, can help predict complex heterogeneous patterns of ice cover along a lake surface[148]. Ice models that better predict lake ice quality can further contextualize active and passive remote sensing and safety protocols for lakes that commonly hold recreation or transportation activities.

Satellite sensors and models are not easily accessible or interpretable to community members and stakeholders, but tools that project ice conditions on lakes could prevent drownings and transportation issues. Therefore, the combination of in situ, remote sensing and modelling is likely to be necessary to predict real-time ice thickness and ice quality for the purposes of ice safety, similar to weather advisories. For example, models might have large errors that cannot be corrected during formation and breakup, when lake ice is most dangerous. Remote-sensing data could help to correct ice quality models when ice is too dangerous to collect in situ samples. Likewise, consistent ice quality observations during a safe ice cover period can help to adjust models to predict when ice cover will begin to become unsafe, which can be much earlier in the season during warm years and years with high white ice cover[26]. As it stands, data on ice quality are severely lacking, inhibiting the broadscale application of methods to help to prevent drownings and transportation failures as well as under-ice impacts on aquatic ecosystems in a warming world.

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