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Lake Ice From Historical Records to Contemporary Science

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Key Points:

- The extensive study of lake ice began in the 1800s along with the collection of many long-term ice records
- Lake ice has long been used and understood as a sensitive indicator of climate change and variability
- Opportunities abound for harmonizing diverse data, modeling approaches, and connecting research ideas across all cryospheric components

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Abstract Lake ice phenology is a critical component of the cryosphere and a sensitive indicator of climate change that has some of the longest records related to climate science. Records commenced for numerous reasons including navigation, hydropower development, and individual curiosity, demonstrating the value of lake ice as a seasonal event of significant importance to a broad swath of peoples and countries. At the same time, lake ice loss has been rapid and widespread with lakes losing ice at an average rate of 17 days per century. In this Perspective, we examine the earliest known records of ice cover and the scientific studies that developed from that practice of record keeping. Studies in lake ice began in the nineteenth Century and have included relationships between climate, biology, and ice cover. Early studies developed some of the foundational principles that limnologists and climate scientists are still exploring, such as the relationship between ice phenology and climate variables, large-scale climate oscillations, and morphological characteristics, with implications for lake ice physical structure and under-ice ecosystems in a warming climate. We conclude with an examination of the state of the field and how these centuries-long lake ice records can continue to inform cutting edge science by validating satellite remote sensing techniques, in addition to modeling approaches and collaborations across disciplines, that can improve our understanding of the loss of lake ice in a warmer world.

1. Introduction

Frozen lakes are synonymous with winter across much of the Northern Hemisphere. For centuries, lake ice has provided a way of life for northern communities, including for refrigeration, recreation, and transportation. Ice was once harvested from local water bodies to keep food cold (Leppäranta, 2015), prior to the widespread use of refrigerators in the 1930s (Grahn, 2015). Visiting and using ice also provides recreational activity during the cold, dark winters, including ice skating, ice hockey, ice fishing, and attending ice festivals (Knoll et al., 2019). For example, the largest ice festival, the Harbin International Ice and Snow festival in China, attracts 18 million visitors and generates $4.4 billion in revenue annually (Hindustani Times, 2018). Furthermore, ice roads and trails provide essential transportation routes in winter for remote northern communities to access food, fuel, medical supplies, and education (Hori et al., 2017; Magnuson & Lathrop, 2014; Mullan et al., 2021; Woolway et al., 2022).

Fortuitously, long-term in situ observations of ice records spanning centuries exist for lakes around the world owing to the importance of lake ice to northern communities (Magnuson et al., 2000; Sharma et al., 2022). Lake ice has been studied for over 150 years, although its research has proliferated in recent decades. Long-term in situ lake ice records have been instrumental in learning about climate change and variability (Benson et al., 2012; Magnuson et al., 2000; Newton & Mullan, 2021; Sharma et al., 2021). Because of the strong influence of climatic and weather conditions on lake ice dynamics, lake ice is considered a sentinel of climate change (Adrian et al., 2009) and has been included in the Global Climate Observing System (GCOS) as an Essential Climate Variable (ECV; (Zemp et al., 2021), in the Intergovernmental Panel on Climate Change (IPCC) review documents (Magnuson, 2021), and as a clear indicator of climate change by the United States Environmental Protection Agency (Jay et al., 2023).

In this perspective piece, we reviewed the English and Russian literature, in addition to some literature in Japanese and German, where some of the longest lake ice records exist, to understand broad themes historically studied within lake ice research, focusing specifically on in situ observations. Our perspective aims to synthesize the literature, rather than provide a detailed review as others have already done in the past (e.g., Brown & Duguay, 2010; Ozersky et al., 2021; Salonen et al., 2009), to answer three broad questions regarding lake ice: (a) How has the field developed; (b) Which research themes have persisted; and (c) Where is the field headed?

2. History of Lake Ice Research

Lake ice has long held importance for communities in temperate and polar regions, demonstrated by existent, centuries-long ice phenology records. The earliest known written record documented and preserved is from Lake Constance, which began in 875 CE (Dobras, 1992). The earliest known commencement of an ice record comes from Lake Suwa in Japan, where Shinto priests maintained oral records for millennia. However, annual written records of Lake Suwa's ice phenology have been available since 1443 (Fujiwhara, 1921; Sharma et al., 2016; Tanaka & Yoshino, 1982). The ice records for Lake Constance may have begun owing to the irregularity of ice formation; whereas, the ice record of Lake Suwa is steeped in religious significance (Knoll et al., 2019) and potentially used as a predictor of rice crop yields (Arakawa, 1954; e.g., Figure 1).

Upon examination of a broad set of Northern Hemisphere ice records that span more than a century, we found several prominent reasons that gave rise to the detailed ice records of which contemporary scientists have made use. These activities included transportation and navigation, recreation, hydropower development, and local curiosity toward the seasonal event (Figure 2). These individually maintained records seem to have cross-cultural significance, as transnational and transcontinental families and/or cultural groups have independently maintained lake ice records. These records were discovered later through diary entries or passed down within a community to be eventually taken up by an official center, such as a historical preservation society, government agency, or homeowners association (Sharma et al., 2022).

Generations of families started and maintained ice records because of their local interest in ice, keeping records related to weather, and maintaining their family businesses, such as ice fishing. For example, the Smiley family from Lake Mohonk, New York, began collecting weather data in 1896 and included ice phenology dates starting in 1932 (Sharma et al., 2022). Transportation and navigation also frequently catalyzed the collection and maintenance of ice records around the world. For example, information on lake ice cover in Lake Baikal was important for commercial shipping. A complex network of shipping has long been practiced on Lake Baikal, where goods are transported between communities on lake shores, stored in outposts for transfer to Siberia, and traded internationally between Russia and China (Shchukin, 1848). The transportation along these ice roads facilitated the trade of goods and services, owing to the challenges of traversing across mountains and other complex terrain during the winter months (Shchukin, 1848). Finally, the cultural and economic importance of activities on lake ice precipitated interest in recording ice phenological dates, such as in Lake Simcoe, Ontario, where ice phenology dates began in 1852 to plan important socio-economic activities, including winter carnivals, ice fishing, and ice harvesting (Sharma et al., 2022).

As historical ice records were generated, researchers began deriving patterns and relationships between ice records and important drivers of ice, including local weather, large-scale climate drivers, lake characteristics, and human influences (Figure 3). Research beginning as early as 150 years ago highlighted important drivers and themes of ice phenology that continue to be expanded on today. For example, Andreev (1875) highlighted the importance of temperature, snow, and wind on ice phenology in Lake Ladoga. He also examined the characteristics of the shoreline and landscape to identify their role in ice growth (Andreev, 1875). Wedderburn (1908) then showed that deeper lakes tend to freeze later than shallower lakes, followed by Simojoki (1940) who addressed the combined roles of air temperature, lake morphology, and geography, on lakes across Finland (Simojoki, 1940). In a later publication, Simijoki (1960) tracked the tendency for Lake Kallavesi to form ice later and have an earlier breakup over the course of 124 years of observation, which he even connected to warming air temperatures in Helsinki, Finland, signifying an early connection to the impact of climate change on natural phenomena (Simojoki, 1960).

Models predicting ice phenology using weather data proliferated as early as the 1960s (Bilello, 1964; Williams, 1965) and even began to include forecasts of future ice projections based on weather conditions (Williams, 1971). Another important variable recognized in early research was the importance of oscillations as a result of large-scale climate drivers and sunspot cycles, as researchers observed that some winters had shorter seasons of ice cover than others (Fujiwhara, 1921; Voeikov, 1891). Climatic variation and climate change were recognized over 100 years ago in Lake Suwa records as important drivers that shorten the duration of seasonal ice cover and delay ice formation (Fujiwhara, 1921). Physical characteristics of ice and descriptions of ice growth, such as candling ice, ice ridges, and crystal orientation, did not appear in the literature until later (Arakawa, 1954; Knight, 1962; Shostakovich & Drizhenko, 1908). Finally, a synthesis of human drivers of lake ice loss, including climate change, large-scale climate drivers, and land use changes, were identified as important factors affecting

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Figure 1.

ice formation dates in Lake Suwa (Tanaka & Yoshino, 1982). Notably, many of the aforementioned research themes persist within contemporary literature at varying spatial and temporal scales.

3. Prominent Themes in Lake Ice Research

Below, we highlight prominent themes in lake ice research that have persisted in the scientific literature more than 150 years after some of the first published studies. Early research focused on publishing tables—often quite extensive tables—summarizing the data collected, followed by qualitative descriptions of patterns in ice phenology and ice growth. By the 1960s, quantitative evaluations of lake ice were much more commonplace and are now practiced as a normal component of lake ice research. The accelerating loss of lake ice and its ecological, cultural, and socioeconomic importance continue to fascinate researchers, with much more knowledge to gain.

Climatic change has long been associated with the ice phenology literature, particularly as lake ice is a sentinel of climate change (Adrian et al., 2009). Interestingly, the first paper, to our knowledge, relating the ice record to climatic change, published in 1888, actually used the long-term ice record from Lake Constance as counter-evidence against a prevailing idea at the time that winters were warming in response to climate change (Rostron, 1888). However, since that first study, the majority of published studies have revealed the importance of warming climates on later ice-on dates, earlier ice-off dates, shorter ice duration, thinner ice cover, and even the complete loss of ice cover in a winter (e.g., Arakawa, 1954; Benson et al., 2012; Korhonen, 2006; Magnuson et al., 2000; Newton & Mullan, 2021; Sharma et al., 2019; Tanaka & Yoshino, 1982; Williams, 1971). Some of the earliest studies showing evidence of the influence of climate warming on later ice-on dates were from Lake Suwa as scientists documented the clear association between warmer years and later ice-on dates (i.e., Arakawa, 1954; Tanaka & Yoshino, 1982). In fact, ice records have even been used to reconstruct air temperatures, as ice records often extend prior to the use and proliferation of meteorological stations (Assel & Robertson, 1995). Climatic change is a common thread across many, if not all, of the prominent themes described below.

3.1. Long-Term Trends in Ice Phenology and Expanding the Spatial Extent of Study

The long-term nature of in situ ice phenology records (timing of ice-on and ice-off), many of which have existed for over 100 years, permits the calculation of long-term trends and variability in ice dates with sufficiently large sample sizes (Hodgkins, 2013). The overwhelming majority of lakes have exhibited clear trends of ice loss, with later ice-on dates, earlier ice-off dates, and shorter ice duration (Newton & Mullan, 2021). Much research has focused on ice records for single lakes or within a region, such as in Lake Constance (Rostron, 1888), Lake Suwa (Fujiwhara, 1921), Lake Mendota (Robertson et al., 1992), the Laurentian Great Lakes (Assel, 1990), lakes across Finland (Korhonen, 2006; Palecki & Barry, 1986; H. Simojoki, 1940), Estonia (Nõges & Nõges, 2014), and Russia (Rykachev, 1886). To our knowledge, Williams (1970) published the first analysis of trends and variability in ice-off dates for four lakes and rivers distributed across the Northern Hemisphere, namely, the River Neva in the USSR; Lake Kallavesi in Finland; Lake Mendota in Wisconsin; and the Saint John River in New Brunswick (Williams, 1970). The study found that ice-off was 10–15 days earlier in the 1950s compared to the 1870s (Williams, 1970).

In 1996, there was a breakthrough in how long-term ecological time series could be aggregated for regions around the world. John Magnuson invited ice researchers from around the world to a workshop in Wisconsin where participants brought long-term ice phenology records from their respective countries (Magnuson, 2021). This data aggregation led to the publication of a seminal research paper, where Magnuson et al. (2000) calculated trends for 37 lakes and rivers with ice-on and ice-off dates covering a 150 year period (1846–1995). This study found that ice-on dates were 5.8 days per century later and ice-off dates were 6.5 days per century earlier, which was attributed to climate change in part owing to concomitant increases in air temperatures (Magnuson et al., 2000). Furthermore, they made their data freely available, which they continued to update and expand, at the National

Figure 1. Historical images of lake ice use across the Northern Hemisphere. (a) and (b) Shinto ceremony held on the ice celebrating ice freeze and the appearance of the *omiwatari* on Lake Suwa (Photo credit: Suwa Shrine), (c) "Road of Life" on Lake Ladoga during the second world war, 1943 (Photo credit: TASS Archives), (d) Sampling station on the frozen Lake Baikal in 2012 (Photo credit: K. Shchapov), (e) The procession of the bust of John the Evangelist across the frozen Lake Constance from a church in Germany to a church in Switzerland taken in 1963, the last year the lake was entirely frozen (Photo credit: Dobras, 1992), (f) Residents of Rechenauer, Germany crossing the ice and country border to buy ice cream in Mannenbach, Switzerland during the last winter Lake Constance froze in 1963 (Photo credit: Dobras, 1992).

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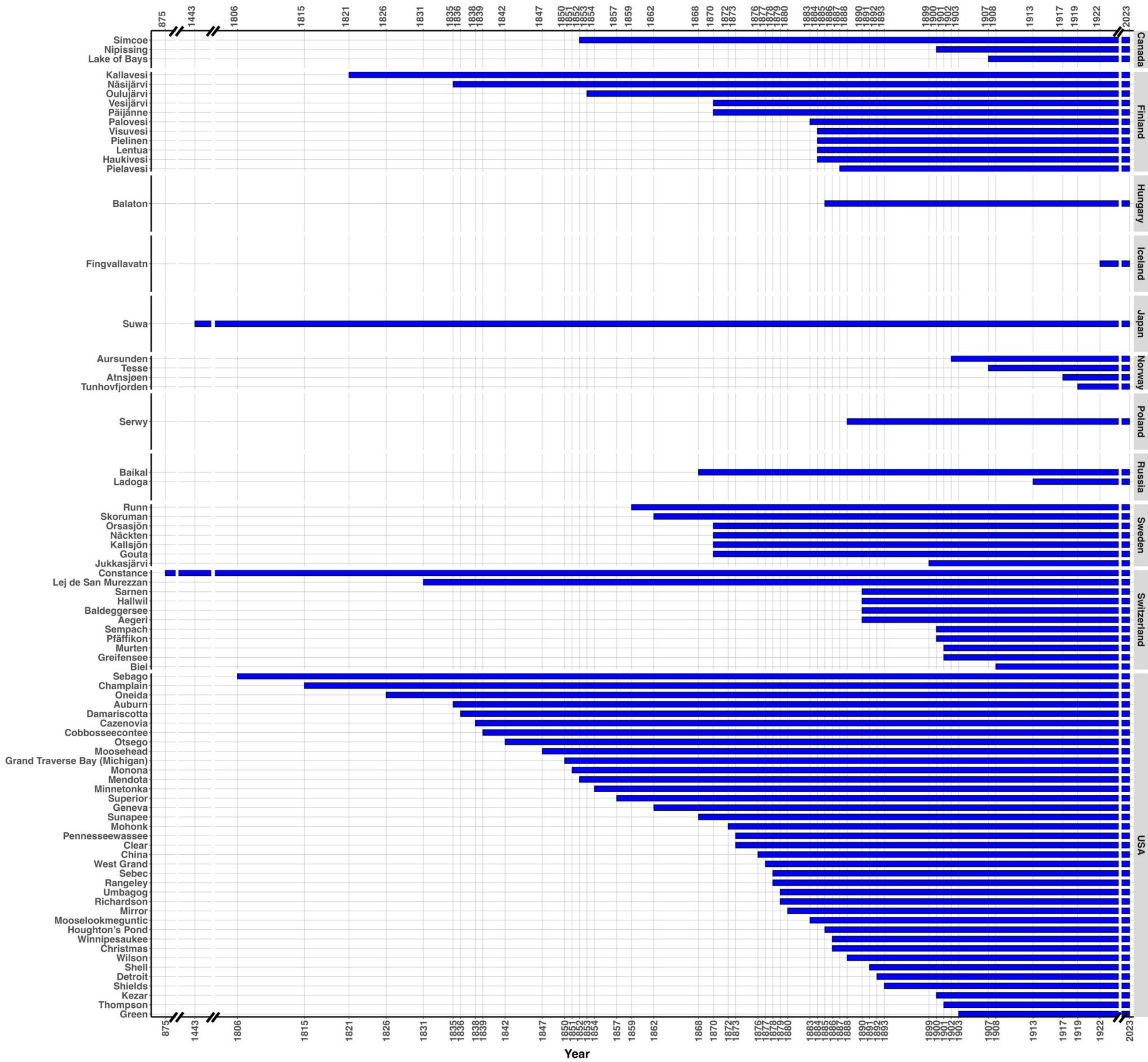

Figure 2. Start dates of the historical records of ice phenology collected by human observers with time series extending over 100 years. These time series have been maintained through the years to present. More specific details on the lake ice phenological records can be found in Sharma et al. (2022). *Scientific Data.*

Snow and Ice Data Center (Benson et al., 2000; updated 2021). Most recently, Sharma et al. (2021) expanded and re-analyzed records from Magnuson et al. (2000) with in situ observations for 60 lakes with 107–204 years of ice phenology records. They observed even more rapid ice loss in the past 25 years (Sharma et al., 2021). More specifically, ice-on dates were delayed by 11 days per century, ice-off dates were earlier by 6.8 days per century, and ice duration was 17 days shorter per century over the 107–204 years record (Sharma et al., 2021). However, in the last 25 years, these lakes lost ice remarkably quickly, such that ice loss was six times faster than the long-term trend at a rate of 106 days per century (Sharma et al., 2021). With the increased prevalence and improvements in remote sensing and modeling approaches, there have been even broader Northern Hemispheric studies quantifying trends in ice loss (Grant et al., 2021; Huang et al., 2022; Li et al., 2021).

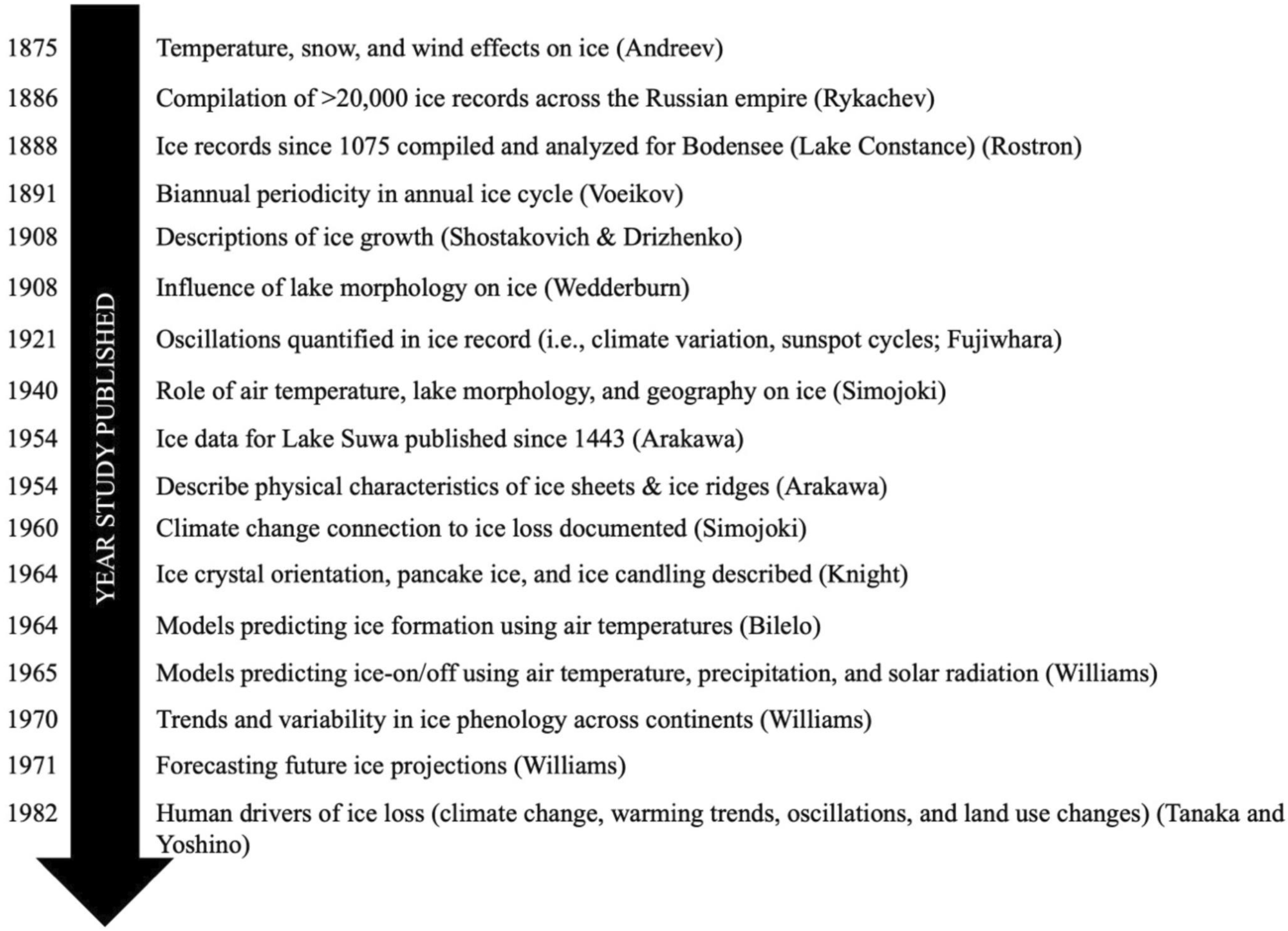

Figure 3. Historical timeline summarizing the dates that key themes and extensive data compilations of in situ lake ice research were presented within the literature.

3.2. Large-Scale Climate Drivers

The long-term nature of in situ ice records permit the evaluation of significant oscillations impacting lake ecosystems (Wynne, 2000). Some of the first quantitative analyses on lake ice records observed oscillations when examining patterns with warmer and colder winters, resulting in shorter versus longer seasons of ice cover (e.g., Arakawa, 1954; Fujiwhara, 1921; Voeikov, 1891). For example, a biennial periodicity in European lake ice records was observed as early as 1891 (Voeikov, 1891). Subsequently, Rogers (1976), Assel (1990), and Sharma and Magnuson (2014) confirmed the biennial oscillations in lake ice datasets and associated the patterns with the Quasi-Biennial Oscillation (QBO). The QBO is associated with equatorial zonal winds and is believed to have a period between 1.5 and 3 years (Salby & Callaghan, 2000; Tangang, 2001). Moreover, over 100 years ago, Fujiwhara (1921) observed cycles and oscillations within the Lake Suwa ice-on dataset, which he connected to solar activity, sunspot cycles, and climatic variation (Fujiwhara, 1921). A persistent 10–12 years cycle has been apparent in ice records across the Northern Hemisphere (Ghanbari et al., 2009; Sharma et al., 2013; Sharma & Magnuson, 2014). The solar sunspot cycle reflects the amount of solar-magnetic activity of the sun with an average cycle length of 11 years (Friis-Christensen & Lassen, 1991; Lee et al., 1995). Shorter seasonal ice cover is associated with years with higher solar sunspots and increased solar radiation (Sharma et al., 2013).

Studies associating large-scale climatic drivers with lake ice, such as the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO) indices, in addition to sunspot cycles and volcanism, began proliferating in the 1990s and 2000s. For example, in North America and Asia, ENSO has been associated with winter ice cover acting at scales of 2–8 years in the contemporary record (Anderson et al., 1996; Bai et al., 2012; Imrit & Sharma, 2021; Livingstone, 2000; Lopez et al., 2019; Robertson et al., 2000; Sharma et al., 2013, 2016; Wynne, 2000). The El Niño phase has been associated with lower ice cover (Bai et al., 2012), but the association can vary regionally and by latitude (Anderson et al., 1996). For example, El Niño events were associated with earlier ice breakup in southern Wisconsin lakes, but not significantly related to ice cover in northern Wisconsin lakes (Anderson et al., 1996). Notably, especially strong El Niño events have been associated with very early ice breakup dates, such as in the 1997–1998 winter (Lopez et al., 2019) and acceleration in ice loss (Imrit & Sharma, 2021). Furthermore, the influence of the North Atlantic Oscillation (NAO) index on ice cover has also been extensively studied in lakes across North America, Europe, and Eurasia (Blenckner et al., 2007; George, 2007; Ghanbari et al., 2009; Imrit & Sharma, 2021; Karetnikov & Naumenko, 2011; Livingstone, 2000; Lopez et al., 2019; Magnuson et al., 2005; Sharma et al., 2013; Yoo & D'Odorico, 2002). The influence of the NAO at multi-decadal scales on winter air temperatures (Blenckner et al., 2007); snowfall (Ghanbari et al., 2009), and alterations in the strength of southerly and westerly winds (Bai et al., 2012) are suggested to influence ice breakup dates. Moreover, ENSO and NAO may also now be interacting such that ice cover in the Great Lakes is further reduced in years with both El Niño and positive NAO events (Bai et al., 2012). Notably, in recent decades, there appears to be a structural change in the periodicities of large-scale climate drivers, such as declining periodicities of ENSO and NAO (i.e., shorter cycle lengths), in response to climate change (Higuchi et al., 1999; Li et al., 2011; Sharma et al., 2016). Continued climatic changes stand to have repercussions for large-scale climate drivers, jet streams, and the Arctic polar vortex with consequential impacts on lake ice cover around the Northern Hemisphere.

3.3. Meteorological and Morphological Drivers of Lake Ice

Researchers observing ice phenology quickly recognized the influence of air temperature on the formation of lake ice, as the connection is relatively intuitive, given the readily apparent relationship between water bodies and the atmosphere. Fujiwhara (1921) highlights the obvious connection between accumulated cold in the weeks prior to lake freezing. Extensive record keeping from lakes across the Russian Empire from Rykachev (1886) preceded Fujiwhara by nearly 50 years and initial analysis revealed relationships between ice cover deviations and the day when temperatures averaged 0°C, as well as observations of wind and snow (Rykachev, 1886). Shortly afterward, Stefan (1891) derived an equation to relate the latent heat from freezing and heat flux away from the ice formation point at the bottom of the ice sheet, which in practice, uses the freezing point of water and the air temperature to model ice growth. The effect of air temperature, then, was quickly established as a leading cause of lake ice growth (Shostakovich & Drizhenko, 1908). Running mean air temperatures were used to predict ice formation dates, where the novel finding was the relationships between the number of days at or below freezing and the depth of the lake (McFadden, 1965). Palecki and Barry (1986) linked lake ice with air temperature variation as well as latitude, but significantly, furthered the relationship between air temperature and lake morphology on ice formation presented earlier by Simojoki (1940). They found that deeper lakes stored more heat and thus froze later than shallower lakes, which had less heat to release (Palecki & Barry, 1986).

Although air temperature has often been shown to be the primary variable driving lake ice cover (Ghanbari et al., 2009; Imrit & Sharma, 2021; Rykachev, 1886; Williams, 1965), other factors, including snow, albedo, solar radiation, precipitation, wind, and cloud cover also play significant roles (Andreev, 1875; Brown & Duguay, 2010; Kirillin et al., 2012; Leppäranta, 1983; Sharma, Meyer, et al., 2020; Williams, 1965). Notably, studies incorporating a suite of meteorological factors into empirical models predicting lake ice began as early as the 1960s (Bilello, 1964; Williams, 1965) and have continued to present. For example, higher fall water temperatures in response to warming air temperatures limit evaporative heat loss and play an essential role in ice formation and ice growth (e.g., Brown & Duguay, 2010; Duguay et al., 2006; Shuter et al., 2013). Solar radiation, though related to air temperature, has two primary functions regarding lake ice. It increases the melt of ice and snow cover (Leppäranta et al., 2010) and causes melt through the convective movement of warmer water beneath the ice-water interface (Bertilsson et al., 2013; Kirillin et al., 2012). Precipitation as snow during the winter contributes to prolonged ice cover and ice growth by enhancing albedo, insulating the ice layer, and enhancing white ice growth (Korhonen, 2006; Preston et al., 2016; Smits et al., 2020). However, precipitation as rain during the ice cover period can cause early melt by adding liquid water to the ice surface (Bartosiewicz et al., 2021). Wind action during ice formation and ice breakup accelerates ice loss. During the ice-on period, wind breaks the initial skim ice, limiting the growth of congelation ice and thereby stable ice cover (Bartosiewicz et al., 2021; Shostakovich & Drizhenko, 1908). During the spring, enhanced winds can mechanically break ice cover and upwell warmer waters, along with melted inflow waters further enhancing ice breakup (Brown & Duguay, 2010; Shostakovich & Drizhenko, 1908; Williams, 1965).

Recent studies continue to show the importance of meteorological factors, mediated by lake morphological characteristics. Warming air temperatures are one of, but not the only factor, contributing to declining ice cover. For example, deeper lakes may respond more sensitively to air temperatures, presumably because deeper lakes take longer to release heat and freeze (Brown & Duguay, 2010; Nõges & Nõges, 2014). Moreover, Nõges and Nõges (2014) found that other meteorological factors, such as winter precipitation, may result in variations in ice cover. Winter snowfall prolonged ice cover and increased ice thickness, while winter rainfall decreased both variables (Nõges & Nõges, 2014). Furthermore, fetch and shoreline complexity can mediate the impacts of wind on ice cover, such that lakes with longer fetches are more sensitive to wind action breaking the initial skim of ice at the time of ice formation (Brown & Duguay, 2010; Sharma et al., 2019; Williams et al., 2004). In Lake Baikal, steep shorelines can absorb more heat in spring, thereby affecting ice melting rates in nearshore regions (Galaziy, 1993). Hydrologic connectivity can also alter ice cover. Groundwater inputs can add warm water at an elevated pressure into the lake that diminishes ice thickness and can create polynias, even in the coldest winters (Choiński & Ptak, 2012). River input may significantly impact ice breakup as well, where for example, input from the Slave River instigates the ice breakup of the Great Slave Lake (Howell et al., 2009). These are just a few examples highlighting the complex interplay between meteorological factors and lake characteristics on ice that researchers are still trying to disentangle even though relationships were noticed in the early studies mentioned above.

3.4. Climatic Variability, Extremes, and Future Projections of Lake Ice Loss

Lake ice is a sensitive indicator of climate, an Essential Climate Variable, and a sentinel of climate change (Adrian et al., 2009; Zemp et al., 2021). Thus, climate has long been associated with lake ice, as evident in many of the themes described in this section. Lake ice has also been directly used to understand climatic variability and extreme events, while also forecasting future projections of ice loss for lakes around the Northern Hemisphere. In recent years, climate change has often been associated with changes in mean conditions, increased frequency of extreme events, and increased interannual variability (IPCC, 2021). While there have been ample studies published on mean trends and interannual variation in ice phenology (see Newton & Mullan, 2021 for a review), few studies have explored the role of climatic variability in lake ice records (Benson et al., 2012; Sharma et al., 2016; Weyhenmeyer et al., 2011). All three of these studies highlighted that variability in lake ice conditions increased over time (Benson et al., 2012; Sharma et al., 2016; Weyhenmeyer et al., 2011). Benson et al. (2000) analyzed lake ice records for a 150-year period and found that variability has been increasing in the 1950–2000 time period, but not earlier. In the ecological literature, increased variability can be used as an early warning indicator of an ecological regime shift (Biggs et al., 2009; Scheffer & Carpenter, 2003; Scheffer et al., 2009). Studying patterns of variability in lakes experiencing shorter durations of ice cover, ice-free years, and even permanent loss of lake ice cover (Sharma et al., 2019, 2021) may portend the possibility of an ecological regime shift to a new ice-free regime.

Early climatologists documented extreme events, such as droughts, heatwaves, and storms, long before extreme events were discussed within the lake ice literature (Lamb, 1977). However, climatologists used the Lake Suwa ice record to identify historically major periods of cooler and warmer air temperatures (Lamb, 1977). Although ice is becoming less certain for lakes around the Northern Hemisphere with shorter duration and in some years, no ice cover at all, extreme events have not been frequently studied to date. To our knowledge, Benson et al. (2012) were amongst the first to examine extreme events in lake ice phenology. They quantified 1 in 10, 25, and 50-year events and found a significant increase in extremely late ice-on, extremely early ice-off, and extremely short ice durations over time, which were associated with warmer climates (Benson et al., 2012). A recent expanded analysis revealed that lakes found in colder regions and lower elevations were the most likely to experience extremely late ice-on and extremely early ice-off dates (Sharma et al., 2021). Moreover, in more recent years, there is an increase in lakes experiencing freeze-thaw events, although this is rarely documented (Sharma et al., 2021), or no ice cover at all (Benson et al., 2012; Sharma et al., 2019, 2021). In fact, there are an estimated 14,800 lakes across the Northern Hemisphere that have reliably frozen for centuries that are now experiencing ice-free winters (Sharma et al., 2019). The occurrence of an extreme ice-free year is highly correlated to warmer winter air temperatures (Filazzola et al., 2020). To date, 179 lakes have been estimated to experience the most extreme condition—permanently losing winter ice cover (Sharma et al., 2021). Much work remains to understand the role of extreme climatic events on extreme ice cover seasons and the consequential impacts on freshwater ecology under the ice and into the open water season.

Whilst there are a number of recent studies that forecast lake ice conditions under future scenarios of climate change (Dibike et al., 2011; Grant et al., 2021; Huang et al., 2022; X. Li et al., 2021; Wang et al., 2022), very few are based on in situ observations (Hewitt et al., 2018; Robertson, 1989; Robertson et al., 1992; Sharma et al., 2019, 2021; Shuter et al., 2013), in part associated with challenges of extrapolating empirical models beyond the data points on which these models were trained. Shuter et al. (2013) used a combination of in situ and remotely sensed observations to project that ice-on dates across Canadian lakes may be an average of 10 days later and ice-off dates may be 0–16 days earlier by 2055 (Shuter et al., 2013). In a study across nine small lakes in Ontario and Wisconsin, Hewitt et al. (2018) projected by 2070 that ice-on could be delayed by 11 days on average and ice-off could be 13 days earlier (Hewitt et al., 2018). Furthermore, Sharma et al. (2019) projected that if global air temperatures rose by 2°C, 235,300 lakes could experience intermittent ice-free years (i.e., no longer reliably freezing every year), whereas 90,200 lakes could experience intermittent ice-free years if air temperatures warm globally by 4°C (Sharma et al., 2019). In the most extreme case, by the end of the century, 179 lakes are forecasted to imminently lose ice cover permanently, whereas 429 lakes may permanently lose ice cover based on moderate greenhouse gas emissions scenarios, and 5,679 lakes may permanently lose ice cover by the end of the century based on the highest greenhouse gas emissions scenarios (Sharma et al., 2021). Much work remains to improve forecasting using empirical models and generate a better understanding of how future climatic changes may impact ice loss using in situ observational data.

3.5. Ice Thickness

Ice thickness and ice growth have long been of interest to researchers, although consistent long-term trends of ice thickness are not yet apparent, with large variation amongst years (Cheng et al., 2014; Imrit et al., 2022; Li et al., 2021; Murfitt et al., 2018; Vuglinsky & Valatin, 2018). To our knowledge, the earliest study evaluating ice formation and ice growth is from Lake Baikal, where Shostakovich and Drizhenko (1908) observed an association between snow depth and ice thickness, such that increased snow depth inhibited ice growth (Shostakovich & Drizhenko, 1908). Ice thickness in lakes is not consistently increasing or decreasing across the Northern Hemisphere or even within a continent or country (Imrit et al., 2022; Korhonen, 2006; Li et al., 2021). For example, across North America and the Northern Hemisphere, lakes found at high latitudes and altitudes often with the thickest ice cover were generally thinning the fastest (Li et al., 2021). Over longer time periods, there appeared to be a significant decline in ice thickness over time as observed in long-term datasets of Russian lakes and rivers beginning in 1955 (Vuglinsky & Valatin, 2018). Notably, the patterns of ice thickness were not so clear in Finland. Ice thickness declined in southern Finland, owing to rapid warming, whereas ice thickness increased in northern lakes with more snowfall, likely due to the development of white ice (Korhonen, 2006). However, forecasts of ice thickness under scenarios of climate warming suggest that the ice thickness in many lakes in Finland may be too thin for people to use safely if air temperatures warm by 2–3°C (Leppäranta, 2010).

A combination of meteorological variables, including air temperatures, wind, snowfall, winter precipitation, and solar radiation, are important drivers of ice thickness (Brown & Duguay, 2010; Cheng et al., 2014; Imrit et al., 2022; Leppäranta, 2010; Nõges & Nõges, 2014). Winter air temperatures have often been observed to be the most important factor influencing ice thickness (Gao & Stefan, 1999; Imrit et al., 2022; Murfitt et al., 2018; Todd & Mackay, 2003). For example, Imrit et al. (2022) calculated that 81% of the variation in ice thickness for 27 lakes and rivers in North America could be explained by winter air temperatures. Warmer winter air temperatures correlate with diminished ice thickness, with correlations as high as $r = -0.91$ in MacDonald Lake in central Ontario (Murfitt et al., 2018). Stefan's Law (1891) predicted ice thickness predominantly by accumulated degree days below freezing, indicating the importance of air temperature to initial freezing and ice growth. Solar radiation also limits ice growth, heating the ice and water surface, and is one of the dominant factors melting ice at the end of the ice season (Leppäranta et al., 2010). Other factors, however, play a significant role in ice thickness. Snow is perhaps the most important of these subsidiary variables and has two important impacts on ice thickness (Jeffries et al., 2005; Morris et al., 2005). Snow provides an insulating layer, inhibiting heat flux from the water-ice layer to the atmosphere, effectively halting downward ice growth at the water-ice interface (Jefferies et al., 2005; Leppäranta, 2015). Snow can, however, have a thickening effect on ice (Korhonen, 2006). Snow can have a high water content and freeze into a white ice layer above the black ice layer (Bolsenga & Vanderploeg, 1992). Rain intrusion into snow cover has a similar effect by freezing in pore spaces above the ice layer at the snow-ice interface (Cheng et al., 2014; Leppäranta, 2015). Snow can also press the ice layer into the water, resulting in lake water intruding into the snow layer and freezing (Leppäranta, 2015). Wind can inhibit initial ice growth by breaking up skim ice (Korhonen, 2006), or it can enhance ice growth in cold conditions where it can move snow away from the ice surface and permit the continued growth of black ice (Bolsenga & Vanderploeg, 1992).

3.6. Ice Quality

Ice quality describes the opacity of the ice sheet that has consequences for both the light environment beneath the ice as well as the strength of the ice sheet to support weight. Black ice forms through cold and calm conditions where ice grows downward into the water column so long as latent heat may be transferred through the ice and into the atmosphere (Leppäranta, 2015); whereas, white ice is formed through a number of methods, including snow and ice melt, rain intrusion into snow, and lake water intrusion into snow (Korhonen, 2006; Leppäranta, 2015). Observations of ice quality began primarily as a consequence of understanding the ability of primary production to occur during the winter ice cover period (Maeda & Ichimura, 1973) or understanding the structural integrity of ice cover for transportation purposes (Gow et al., 1978). To answer whether and to what degree primary production may occur during the ice-cover period, light transmission studies took place for freshwater systems (i.e., lakes), learning from the earlier studies of marine systems (Maykut & Grenfell, 1975). Bosenga et al. (1991) found that black ice transmitted approximately as much light as open water (90% of surface photosynthetically active radiation; PAR), while snow cover limited surface PAR to fewer than 3% directly under the ice. Other ice types (e.g., slush and other white ice formations) varied between those PAR transmission values (Bolsenga et al., 1991).

The use of ice cover as a transportation route during the winter period has resulted in questions regarding the overall strength of ice thickness (Gow et al., 1978) and quality (Barrette, 2011; Weyhenmeyer et al., 2022). Essentially, a load on an ice sheet cannot exceed its flexural strength (Gow et al., 1978). Furthermore, ice quality impacts the bearing capacity of ice cover. Gow et al. (1978) tested the failing point of ice beams through stress tests and determined that white ice that is subject to above-freezing air temperatures lost strength and had a reduced "effective thickness," implying that white ice above 0°C is less structurally sound than black ice. Tests of flexural strength on ice beams cut from the Rideau Canal in Ottawa found that white ice at −0.5°C is 51% weaker than black ice of the same thickness (Barrette, 2011). However, Gow et al. (1978) notes that white ice that is under very cold conditions can be just as strong as the underlying black ice; therefore, ice strength is both a function of ice quality and air temperature.

These early studies in ice quality primarily took individual measurements to contextualize their questions that focused on primary production or weight-bearing capacity. However, few studies have accumulated long-term time series to understand the impact of climate change on ice quality. Korhonen (2006) made use of long-term ice quality data from Finland (Korhonen, 2006). Given that these data were isolated solely to Finland, data must be collected to understand ice quality on a broad spatial scale. The only study to our knowledge that has taken this step launched a concerted ice sampling effort across the Northern Hemisphere, taking measurements of ice quality at different points throughout the winter (Weyhenmeyer et al., 2022). The IceBlitz sampling effort analyzed overall ice thickness, as well as measurements of the ratio of white ice to black ice (Weyhenmeyer et al., 2022). They found that ice tends to form initially as black ice but that the ratio of white ice increases throughout the winter until ice breakup (Weyhenmeyer et al., 2022). The study took place during a particularly warm winter, and many of the lakes sampled had 100% white ice for a prolonged period, indicating that warming winters, owing to anthropogenic climate change, will have an impact on the quality of lake ice (Weyhenmeyer et al., 2022).

3.7. Under-Ice Ecological Dynamics

Although the study of lake ice itself is the primary focus of this perspective, we wanted to take the opportunity to highlight the importance of under-ice biological processes, which has recently become a large area of focus (Bertilsson et al., 2013; Bramburger et al., 2022; Hampton et al., 2017; Sutton et al., 2021). The under-ice environments support a variety of aquatic organisms and have an important role in the whole-ecosystem dynamics. However, historically there was little attention to under-ice biology, and only a few later studies indicated the importance of winter processes under the lake ice. Studies at Lake Baikal (Kozhova, 1961) and Lake Haruna

(Maeda & Ichimura, 1973) showed unusually high phytoplankton biomass and density under the ice, in some cases exceeding summer values. Zooplankton was similarly found to be active and abundant during winter (Kozhov, 1962; Vanderploeg et al., 1992). Despite these findings, winter ecological processes have been understudied and assumed to be dormant until recently.

Algal biomass and primary production under the ice is much higher than expected and can be quite high in some lakes (Bramburger et al., 2022; Hampton et al., 2017; Shchapov et al., 2021). Algal blooms can even be common under the ice cover of many northern lakes, including in Lake Baikal (Jewson et al., 2009; Katz et al., 2015; Kozhova, 1987), Lake Michigan (Vanderploeg et al., 1992), and Lake Erie (Twiss et al., 2012). This spike in primary production under the ice can be crucial for zooplankton communities and, consequently, for higher trophic-level organisms like fish. However, primary and secondary production are generally lower in winter for most ice-covered lakes but not completely absent, in part as a function of ice cover and low light levels associated with a shorter day length. Despite lower abundances of phytoplankton and zooplankton, their nutritional qualities can be high (Syväranta & Rautio, 2010). It was shown that zooplankton species (e.g., copepods) accumulate lipids before and during the ice-cover period in order to survive through winter and reproduce in spring (Grosbois et al., 2017). With warming winters and the shortening of the ice cover period, the development of phytoplankton and zooplankton communities in subsequent seasons can be altered. For example, spring phytoplankton species in Lake Superior were found to shift from lipid-rich diatoms to less nutritious blue-green algae communities (Reavie et al., 2014). There are also evident changes in zooplankton communities across many lakes due to the longer open-water period. Shifts toward cladocerans species that prefer warmer waters were documented in Lake Baikal, Lake Superior, and lakes across Alaska (Bowman et al., 2022; Carter & Schindler, 2012; Link et al., 2004). Considering these changes in plankton communities and their development timing can lead to cascading effects on higher trophic-level organisms.

The duration of the ice-cover period is important for lake stratification regimes, which can influence fish vertical and horizontal distribution and their reproductive periods. Fish life strategies, physiological development, and environmental cues are expected to change due to water temperature increases (Caldwell et al., 2020). Examples of expected changes include an early spawning due to earlier spring onset and later spawning in fall due to a longer open water period, which have been documented in various ecosystems (rivers, lakes, estuaries, etc.) (Lyons et al., 2015; Schneider et al., 2010; Taylor, 2008). Alterations in spawning time for hatched fish due to warmer temperatures at the end of winter can lead to a mismatch with zooplankton development, the main food source for juvenile fish (Thackeray et al., 2013). Furthermore, changes in spawning time and mismatch with main food sources, warmer winters and shortening of the ice-cover period, may enhance niche overlapping between different fish species. The disappearance of ice and the prolonged open water period may be advantageous for warm-water fish species and may limit habitat availability for cold-water fish species (Block et al., 2020; McMeans et al., 2020).

3.8. Societal and Cultural Implications

Although lake ice has been used by people for millenia, the societal and cultural implications of lake ice loss is rarely studied. There is a long history of activities on ice that serve many functions from subsistence to religious significance. Indigenous communities across the Arctic have used ice for subsistence hunting and mobility during long winters for centuries (Beaulieu et al., 2023). Freshwater ice has been used for centuries to keep food cold in ice boxes, long before the proliferation of electrical refrigeration. For example, exporting ice was a large trade in Madison, Wisconsin in the latter half of the nineteenth Century where ice from Lakes Mendota and Monona was exported across the United States on wooden crates delivered by rail as far away as New Orleans (Mollenhoff, 2003). There are records of ice used for religious ceremonies for millennia in Lake Suwa, Japan, and for transporting the bust of John the Evangelist across the frozen Lake Constance as a sign of friendship between churches in Germany and Switzerland over hundreds of years (Knoll et al., 2019; Magnuson & Lathrop, 2014). Although early published papers on Lake Suwa highlight the religious importance of the ice record (Arakawa, 1954; Fujiwhara, 1921), to our knowledge, Magnuson et al. (2000) was one of the first studies to explicitly highlight some of the socioeconomic important uses of lake ice in connection to historically long ice records.

Lake ice is also critical for winter transportation. Transportation across ice is important to access goods and services, and for some remote villages, winter ice cover provides a short window of opportunity for social connections through the year (Hori et al., 2017, 2018). For example, the construction of winter ice roads provides employment opportunities for remote community members and is vital to transport food, fuel, and medical supplies as the cost and dangers of plane travel are much too high in the winter (Mullan et al., 2017, 2021). In Siberia, ice roads have high economic and tourism importance for many remote villages along the shores of Lake Baikal over the past century. For example, the largest region in Russia, Sakha (Yakutia) relies on 40 official roads during the winter spanning 8,000 km in total length across frozen rivers and lakes (Nektegyaev & Kardashevskaya, 2021) because of poor development of the transportation infrastructure (Poleshkina, 2021). These roads are critical for the northern settlements of Sakha (Yakutia) since they lack alternative transportation modes in winter. The longest (20 km) official ice road across Lake Baikal connects Olkhon Island with a population of about 2,000, attracting more than 250,000 tourists only in winter (https://tourism.interfax.ru/ru/news/articles/77699/, accessed on 16 October 2023). Interestingly, Russians hoped to use trains across the frozen lakes during the Russian–Japan war in 1904–1905, but owing to accidents, horses were used instead to transport train carriages, goods (including ice), and people in the winter (Figure 4). Although, large transport trucks may use ice roads to carry oil products, such as fuel, gas, and oil, which in cases of accidents, can leach into aquatic systems. As ice roads become less viable owing to declining ice thickness and safety, alternative forms of transportation, such as shipping with ecosystem impacts such as increased wave action and turbidity, may become more common in the winter months.

Lake ice also provides ample recreation opportunities for northern communities. Millions of people attend ice festivals annually, the largest of which is the Harbin International Ice and Snow Sculpture Festival which attracts more than 18 million visitors and generates $4.4 billion in revenue annually (Hindustani Times, 2018; Sharma et al., 2023). Skating races have occurred for hundreds of years in Europe but became more infrequent over time as ice was lost. A skating race was reinstated in Sweden on Lake Malaren in hopes of regaining the popularity of historical skating tournaments, but after several unexpected truncations or cancellations of the race owing to warmer winters, the race was indefinitely canceled after 2018 (Knoll et al., 2019). Ice fishing not only provides recreational opportunities but also economic activity. For example, retired individuals angle Eurasian perch from Lake Peipsi which not only supplements their pensions but provides the local community with a source of protein in the winter months (Orru et al., 2014). However, in warmer winters, there may be increased risks of winter drowning through ice as has been observed around the Northern Hemisphere (Sharma, Blagrave, et al., 2020). Generally, the rate of winter drownings increases exponentially as winter air temperatures approached 0°C, although there were exceptions in cases where communities who relied heavily on ice for transportation, subsidence, and recreation experienced higher rates of winter drowning (Sharma, Blagrave, et al., 2020). In particular, children and young adults are at highest risk of drowning as these individuals may be the most curious, but also the least experienced in judging unsafe ice (Sharma, Blagrave, et al., 2020). The diverse use of ice and the threat of ice loss provide an incentive to continue monitoring lake ice behavior but also how that change impacts safety for communities who rely on lake ice for these socioeconomic uses and benefits.

4. Future Opportunities

Lake ice is truly the miner's canary of global climate change. Historically, ice records have been collected from lakes primarily found in northern temperate regions where ice has been used by northern communities for a variety of purposes, including recreation, transportation, and refrigeration (Arp et al., 2019; Knoll et al., 2019; Leppäranta, 2015; Magnuson & Lathrop, 2014; Mullan et al., 2021; Woolway et al., 2022). Many of these ice records have been established for over a century, long before the advent of meteorological stations, illustrating their importance to communities, but also serving as long-term direct human observation of climate change (Magnuson et al., 2000; Sharma et al., 2016, 2022). Through in situ observations, we have documented how rapidly lake ice has been lost since the Industrial Revolution (Magnuson et al., 2000; Sharma et al., 2021). However, much has yet to be learned regarding lake ice loss for many regions of the world, as it is impractical to bring intensive in situ sampling to larger numbers of lakes due to funding restrictions and dangerous conditions (Block et al., 2019).

Despite centuries-long observations of ice phenology on a global scale, the diversity of lakes being observed does not fully capture the diversity of lakes present as surface waters across the globe (Verpoorter et al., 2014). Lakes observed are similar in terms of their locations near population centers and lower elevations, which leads to a relatively homogenous group of observations. For example, we have little understanding or observations of lakes found in more remote, alpine regions (Christianson et al., 2021; Kainz et al., 2017; Pociask-Karteczka & Choiński, 2012; Preston et al., 2016), or in the Southern Hemisphere. To branch out and observe a wider

Figure 4. (a) Train and train carriages were used by the Russians during the war between Russia and Japan in 1904–1905 to move the army quickly to the east, but the weight of the trains was much too high for the ice, resulting in accidents. (b and c) Thus, horses pulled train carriages across Lake Baikal; (d and e) Additionally, a combination of ice breakers and horses were used to transport ice, goods, and people across Lake Baikal (Photo credits: FSBI Baikal State Reserve; Baikal Crossing Website-Museum).

collection of lakes for a fuller understanding of lake ice phenology on a global scale, we require the use of newer technologies to fill gaps and expand observations, shifting from an intensive understanding of a single lake or grouping of lakes to an extensive summary of lake observations (Sharma, Meyer, et al., 2020). However, the proliferation of remote sensing techniques and modeling approaches offer promise in a broader view of lake ice loss (e.g., Grant et al., 2021; Huang et al., 2022; Li et al., 2022).

While in situ observations have been one of the most valuable tools in studying the impacts of climate change on lake ice, newer technologies, such as remote sensing and deep learning models, improve our ability to study global patterns of lake ice loss (Grant et al., 2021; Huang et al., 2022; Li et al., 2022). Remote sensing approaches obtain global coverage of lake ice records, but have relatively short time series, limiting our understanding of the long-term ramifications of climate change on lake ice patterns (Sharma, Meyer, et al., 2020). Putting in situ observations and remote sensing approaches in conversation strengthens both approaches. For example, satellite sensors with fine spatial resolution can accurately capture the spatial extent of ice cover across most lakes, including those currently studied with ongoing in situ campaigns (Yang et al., 2022), which is particularly useful for both small and large lakes whereas an in situ observer cannot account for the entire spatial extent on a large lake (Yang et al., 2022). Fine spatial resolution sensors, however, miss the fine timescale at which ice formation and breakup can occur (on the order of days); therefore, combinations with sensors that have as fine as daily overpass times can compensate for what they miss in spatial resolution (Zhang et al., 2021; Zhang & Pavelsky, 2019). Future work in remote sensing must include combining the strengths of these types of sensors alongside modern constellation satellites, such as Planet, that have both fine spatial resolution (<1 m) and roughly daily return intervals but lack the time series that satellites such as Landsat possess. We can then integrate ice observations collected using in situ and remote sensing approaches to inform one-, two-, and three-dimensional models, as well as analyze global circulation models to understand the impacts of climate change on the cryosphere. To date, few studies forecast the impacts of climate change on variability, extreme events, and future climatic changes on lake ice phenology (Grant et al., 2021; Hewitt et al., 2018; Z. Li et al., 2022; Sharma et al., 2019; Shuter et al., 2013; Walsh et al., 1998; Weyhenmeyer et al., 2011), but no studies, to our knowledge, extensively consider the widespread impacts of climate change on lake ice quality, spatial heterogeneity of ice cover, the extent of intra-seasonal freeze-thaw events, or the regional impacts and differences in ecological under-ice processes because of losing ice.

Networking with other cryospheric scientists who work on snow, sea ice, glaciers, freshwater ice, and permafrost may provide a broader understanding of how climate change is affecting the cryosphere globally, of which lake ice is an important component. To date, in broader global cryospheric assessments, lake ice is often an overlooked variable with little or no attention dedicated to its study. The components of the cryosphere are changing quickly with loss of multi-year and permanent ice across lakes in the Arctic and Antarctica (Box et al., 2019; Maksym, 2019), Arctic ice sheet (Duarte et al., 2012), and permafrost (Box et al., 2019; Brown & Romanovsky, 2008), thus quantifying and comparing across cryospheric components will be critical. However, a key challenge is identifying a common currency to evaluate how all components of the cryosphere are changing. This common currency could include variables such as season length, phenology (i.e., the timing of cryosphere on and off), and the percentage loss of spatial extent or the permanence of the cryosphere. By developing a common currency, we could obtain a broader understanding of the rates of cryospheric loss in different environments. We can then develop questions to interrogate the changes to the cryosphere caused by climate warming. For example, which cryospheric component is experiencing the greatest loss? What is the most vulnerable component of the cryosphere? Which component will be lost first? Moving toward integrating the cryosphere, despite the methodological challenges, will be integral in understanding the influence of global ice budgets and their implications for global hydrological, biogeochemical, and climate cycles. Although scientific studies aiming to further understand lake ice through in situ data collection began at the start of the last Industrial Revolution, we are still at the frontier of understanding the widespread impacts of climate change on lake ice dynamics.

Conflict of Interest

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

Data Availability Statement

All data used to generate Figure 2 are available in Sharma et al. (2022). https://doi.org/10.1038/s41597-022-01391-6.

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