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Climate-related thresholds in lake ice and the associated environmental and social systems

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Abstract

Nearly half of the world's lakes freeze periodically. In the past few decades, lakes in the northern hemisphere are increasingly recording unusually short or no annual ice season due to climate variability and change. This is raising concerns about the potential impact of short annual ice cover season on lake ecosystem structure, stability, and function. Here we develop a tentative framework that delineates the connection between winter climate variability, shorter lake ice season, and related environmental and social impacts with focus on winter thermal thresholds in lake ice. This framework organizes existing knowledge on this topic and presents a systems-scale view. The integrative system's scale view presented in this study seeks to inform: (a) usability of seasonal climatic information to understand timing of ice out and thresholds therein, and (b) efforts seeking to develop adaptive lake related management and planning policies in a changing climate.

Keywords: Lake Ice, Winter Thresholds, Environmental systems, Social Systems

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1. Introduction

Of the world's 117 million lakes, nearly half freeze over periodically [1]. The freezing of the lake surface creates a unique physical environment such that its annual appearance and characteristics have societal and ecological significance. For hundreds of years, the Shinto priests who live at the shrine near the edge of Lake Suwa (Japan), have held their religious purification ritual following the complete freezing of the lake [2]. Van Assche et al. [3] describes how over the past 60 years, winter ice fishing at Lake Mille Lacs,

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Minnesota (USA) can be linked to technological (from shacks to augers to fish finders) and institutional (resorts as owners of the ice) innovations, infrastructure development (e.g., ice roads), employment (e.g., guides), and booming winter tourism industry (e.g., resorts, ice fishing gear). In remote northern Canadian regions, lake ice sheets have been used as aircraft landing sites, thus allowing for uninterrupted access to and from local communities during the winter season [4]. On the environmental systems end, lake ice acts as a lid restricting the transfer of light, oxygen, wind movement from the overlying atmosphere to the lake (Figure 1). Consequently, lake organisms and biogeochemical processes that can operate under relatively cold, dark, calm, and oxygen limited lake environment often dominate during the ice cover season [5, 6].

In recent decades,however, lakes in northern hemisphere are recording unusually short annual ice seasons including no ice season and no complete ice cover [7, 8, 9]. Recent studies point to both inter-annual climate variability, for example, due to El Niño-related weather [8, 10], and long-term climate warming trends [11, 12, 13, 7] as causative factors. The shortening of the annual ice season can have cascading, cross-seasonal effects on the lake characteristics including its water quality. For instance, in the summer of 2012, the surface of Lake Auburn—a southern Maine (USA) lake with no history of water quality issues—turned green stemming from severe algal blooms [14]. In subsequent weeks, severe anoxic conditions developed at the lake bottom and killed the lake's entire cold-water trout population. Williams [14] suggests that the 2012 event at Lake Auburn were triggered by the early end to the ice cover season and high summer water temperatures caused by the unusually mild winter and high sediment flux into the lake due to heavy springtime rains. Weather- and climate-induced contrasts in lake physical conditions and trophic status during spring and summer seasons are also evident in European lakes, wherein milder winters with shorter ice periods or ice-free conditions appear to lead to larger algal biomass, thus contributing to water quality declines [e.g., 15, 16]. Large interannual swings towards warmer temperatures, and continued warming trends portend higher incidence of unusually short ice cover season and underscore the need to attend to the following knowledge gaps: (a) nature and predictability of unusually short ice season, (b) implication of short ice season on lake structure and function.

Due to theoretical and practical limitations, the nature and predictability of shorter lake ice season date arising from its links to winter weather-climate conditions is poorly understood [17, 18]. Very few lakes have their winter ice-in dates recorded, and thus the effect of winter weather variability in determining the lake ice formation and its timing has not been well studied. Since lake ice melts in spring, most studies focus on the relationship between spring weather conditions and lake ice-out dates [e.g., 19, 12, 13]. Nevertheless, winter is the main season that provides the freeze energy to form and thicken the ice that can be melted in spring [17]. The sharp rise in the frequency of no complete ice cover (NCIC) and ice-free winters in the northern hemisphere points implies that mild winter conditions and related decrease in the winter freeze energy not only can cause the shortening of the ice cover season but also engender dramatic changes in the lake ice regime. Finally, winter climate variability in the extratropics is linked to large scale oceanic-atmospheric circulation patterns such as ENSO, whose signals in the tropical Pacific can be detected six to nine months ahead [20, 21]. Given that this can offer prospects for seasonal or longer predictability of the annual lake ice season at a regional scale, there is a need to rethink the importance of winter weather climate variability on the lake ice phenology.

In the published literature, overall effects of shorter or no ice cover season on the lake ecosystem structure, stability and and function has also received limited attention [5, 22]. This stems from the long-held misconception that the presence of an ice cover brings all biotic and abiotic activities in lakes to a standstill [5]. However, the under-ice lake environment maintains substantial biological activity [6]. Moreover, there are case-studies [e.g., 23] that have examined the impact of shifts in lake ice phenology on the physical, chemical, and biological constituent(s) of lakes. Finally, short or no lake ice cover seasons have socioeconomic implications [2, 24, 25].

This study focuses on the nature and predictability of unusually short ice season and related human and environmental systems. In what follows, we use (a) findings from recent studies and (b) a case study (Lake Auburn), to elaborate on the relationship between winter air temperature and lake ice season in the northern regions including demonstrating the presence of winter air temperature thresholds whose exceedance/non-exceedance produces early/late ice-out dates. We also discuss the relationship between winter climate conditions and synoptic oceanic-atmospheric circulation pattern such as ENSO can be used to predict the lake ice season at local and regional scales. Following this, a review of lake ecosystem response to shorter/ no ice cover period in freezing lakes is presented. This includes developing a tentative social-ecological framework that maps the multiple pathways and feedback by which perturbations stemming from short ice cover period may cascade across the lake-watershed system.

2. Relationship between winter weather climate variability and lake ice-out dates in the extratropics

Variability of ice out dates: For the past few decades, the lake ice season in the northern extratropics is recording unusually early ice-out dates including no complete ice cover and ice-free winter [26, 7, 9]. Moreover, the pervasiveness of unusually early ice out dates is attributed to the combined effect of secular trends and interannual annual to interdecadal scale variability in ice-out dates [7, 27, 10]. From the late nineteenth century, Magnuson et al. [11] and other studies [12, 13, 7, 9] have detected significant trends towards earlier ice-out dates for lakes in the northern hemisphere with the exception of the very northern lakes. However, the trends in the ice phenology of most lakes are also marked by significant decadal and inter-annual variability which enhance or reverse the trend in the lake ice out dates [28, 27, 7, 8, 29, 10]. For instance, the ice-out dates at Lake Auburn, Maine (USA) from 1870-2010 displays a significant ($p < 0.05$) long-term trend towards earlier ice-out date, wherein the mean ice-out date shifts from April 27^{th} for the 1870-1900 period to April 17^{th} for the 1980-2008 period (see Figure 2). However, during the 1870-1900 period, there were still three years when the ice-out date was earlier than April 17^{th}, while there were five years when the ice-out date was later than April 27^{th} during the 1980-2010 period. In the extratropics, the chain of events that modulate the inter-annual variability of lake ice phenology often involve synoptic oceanic-atmospheric circulation (teleconnections) patterns, regional weather regimes, and local meteorological conditions that accelerate or impede lake ice growth or melt [28, 30, 27, 29, 18].

Winter air temperatures and Ice out dates:For lakes, ice cover formation, growth, and decay are outcomes of the thermal energy transfer between lake and overlying atmosphere, integrated over time and space (for large lakes) [31]. The heat energy exchange between lake and atmosphere is primarily determined by prevailing meteorological conditions particularly air temperature, as they indicate the energy surplus or deficit in the atmosphere [32, 31]. In general, ice forms and grows on the lake surface under sub-freezing daily air temperatures and in the northern extra-tropics, winter months are often characterized by daily air temperatures below 0°C [18]. Ice melts follows a period of above-freezing daily air temperatures, predominantly during the spring months in the northern extratropics. Consequently, both winter and spring seasons temperature play a critical role in determining the length and phenology of the ice season. In order to illustrate the effect of daily winter air temperatures on the evolution of ice for lakes in the northern extratropics, we model the lake ice evolution at Lake Auburn for the 2005-6 and 2006-07 ice season using a 1-D freshwater lake thermodynamic model FLake [33].

At Lake Auburn, the ice-in dates for the 2005/06 and 2006/07 ice cover season were December 18^{th} and 10^{th} respectively (Figures 3a & b). After the ice-in date, the ice cover begins to thicken rapidly. During the two ice cover seasons, significant thickening of lake ice occurred during the winter (December to February) period (Figures 3a & b). Moreover, the rate of ice growth corresponded to the daily freezing degree days —the extent (in degrees) to which daily air temperatures fell below freezing (Figures 3e &f). At the end of February, the ice cover thickness in 2007 was twice as much to that of 2006 (Figure 3a & b). This was because the total sum of the daily winter freezing degree days (Accumulated Freezing Degree Days-AFDD) in 2006/07 was about 1.5 times higher than that of 2005/06 (Figure 3c & d). At the beginning of March, however, the ice cover stops growing and even starts to thin (melt) given that the daily average temperature start rise above the freezing point (Figures 3a & b). In both seasons, the rate at which the ice melted in spring (March-June) mirrored the daily melting degree days—the extent (in degrees) to which daily air temperatures rises above freezing (Figures 3e & f). The ice-out date in 2006/07 was about 18 days later than in 2005/06 ice cover season (Figures 3a & b).

The timing of the spring lake ice-out dates depends on the thickness of winter ice and the heat energy during the melt (spring) period [34, 32]. Generally, thinner winter ice and/or warmer spring air temperatures are associated with earlier spring ice-out dates and thicker ice and/or cooler spring air temperatures are related to later spring ice out dates. Given that winter is the main period that provides the bulk of the freeze energy to form and grow ice, seasonal winter air temperatures can modulate the variability of spring ice out date by controlling the ice thickness [34, 28]. Consequently, for many lakes in the extratropics, seasonal winter air temperatures (and derived degree day variables) are significantly correlated to the spring lake ice-out dates [28, 17]. Franssen and Scherrer [35] showed for multiple lakes in Switzerland that there are winter AFDD thresholds whose exceedance/non exceedance determines whether ice forms on lakes. North American studies [10, 18] have also shown for multiple lakes in northern North America that the response of spring ice-out dates to seasonal winter air temperatures can be nonlinear, and that there are seasonal winter degree-day indices whose exceedance or non-exceedance produces dramatic changes in the spring lake ice-out dates. Figure 4 depicts the joint winter AFDDs and AMDDs that correspond to the earliest and latest 15 ice-out dates at Lake Auburn from 1950 to 2010.

Synoptic Teleconnection patterns and Ice out dates: For many lakes in the northern extratropics, the spring ice out date shows coherence with synoptic teleconnection patterns. Large-scale teleconnection patterns refer to semi-periodic and persistent atmospheric and oceanic anomalies that extends over a large geographical area [36]. In northern Europe, United Kingdom, and Russia, studies have found the timing of the spring ice-out date has a strong relationship with the phases of the Northern Atlantic Oscillation (NAO) pattern [37, 38, 29]. For lakes in northern USA and Canada, variability of spring ice out dates has been related to one or more of the following synoptic teleconnection patterns: NAO [30, 8, 29, 10], ENSO [30, 8, 27, 18], Pacific Decadal Oscillation [30, 27], Pacific North America [30], and Tropical Northern Hemisphere [10]. Large-scale teleconnection patterns modulate the variability of spring lake ice-out date by promoting warm and cold and/or wet and dry spells that delay or accelerate lake ice formation or melt [30, 27, 29, 10, 18]. Moreover, in regions where multiple teleconnection patterns exist, the effect of one pattern on spring ice out dates might be moderated by the effect of another pattern. For example, Bai et al. [8] found that the effect of ENSO on Great lakes ice extent can be moderated or enhanced by NAO. Livingstone [28] found that relationship between NAO pattern and spring ice out dates at Lake Mendota have weakened since the first half of the twentieth century.

ENSO is the largest source of global winter climate variability, and phase shifts in ENSO arise due to its sensitivity to particular tropical Pacific sea surface temperature anomalies [21]. The slow evolution and persistence of ENSO events affords seasonal predictability [21, 20]. Studies show ENSO-related wintertime climate forecast skill in the northern extratropics modulates atmospheric circulation patterns [39]. Consequently, few North American studies have characterized the relationship between spring ice out dates, seasonal winter air temperatures, and ENSO patterns to predict lake ice season [40, 8, 10, 18]. For example, Bai et al. [8] showed that for Great Lakes, mild winters and reduced ice cover extent occur during El Niño (warm phase of ENSO) and positive NAO phases. Beyene and Jain [10] found that for eight selected lakes in Maine, El Niño events increases the likelihood of mild winters that are associated with early spring ice-out dates by 50-80% relative to the climatology (1950-2010). Beyene and Jain [18] showed that for seven out of the eight selected lakes in different North American regions, the occurrence probability of mild winters that produce early spring ice-out dates increases by 1.5-2.8 times to that of the climatology during strong eastern El Niño patterns (1951-2010).

3. Delineation of lake-watershed processes within the context of lake ice

We reviewed over 40 peer-reviewed case studies that examined the response of one or more lake-watershed parameter(s) to the early end of the ice cover period (Table **??**). In what follows, we summarize the potential impact of shorter/no ice cover season on the physical, chemical, biological and social attributes of lakes in the northern extratropics. Figure 5 shows the response and feedback of key lake ecological and social processes.

Seasonal Thermal Structure and Mixing Regime: When the surface of lakes is covered in ice, only a small fraction of the atmospheric heat input reaches the lake water column. This is because ice reflects back 30-90% of the solar insolation [31]. Early ice out increases atmospheric heat input into lakes. For lakes in the northern cold regions, this can lead to warmer spring and summer lake water temperatures [e.g., 41, 42, 43], earlier onset of spring turnover and summer stratification period [e.g., 44, 45, 46], and upsurge in spring/summer sensible and latent heat flux [47]. For some lakes, the absence of lake ice during winter triggers dramatic changes in the lake's mixing regime such as a shift from cold monomictic to dimictic or from dimictic to warm monomictic [e.g., 48, 49]. However, the persistence and degree to which shorter or no ice duration affects the thermal structure of northern cold region lakes depends on lake specific factors such as water clarity, morphometry, and water residence time, which determine the distribution of extra added heat in lake volume [41].

Nutrient Cycling: During long ice cover periods, benthic respiration and decomposition of organic matter near sediment [50, 51] causes depletion of oxygen. Oxygen depletion is pronounced in lakes with low hypolimnion water volume and high organic matter. Oxygen depletion creates an anoxic (reducing) environment at lake water-sediment interface, which promotes the release of reactive manganese, iron, and phosphorous [52, 53, 54]. Conversely, a shorter or no ice cover season may decrease the likelihood of anoxic conditions from developing at lake sediments during the winter season. However, the early end to the lake ice season in lakes often leads to the early onset of spring-summer lake stratification period, with limited mixing between epilimnion (upper) and hypolimnion waters [43, 46]. In shallow lakes or ones with a strong thermocline at a lower depth, the lengthening of the stratification season enhances the development of anoxic conditions at the sediment-water interface, which in turn favors the release of reactive nutrients from sediments to the overlying water column [55].

Aquatic species and trophic interaction: During complete ice cover period in lakes, the surface snow-ice cover acts as a lid, creating dark, less turbid and cold under-ice lake environment [5]. These conditions generally favor heterotrophic processes and lower plankton biomass as the low light setting restricts autotrophic plankton productivity, and the non-turbulent conditions promote sinking of non-motile algae [6]. Thus, early ice-out period may lead to increases in the spring and summer algal biomass [23, 37, 45], change in the seasonal composition and succession of plankton species [56, 57, 53] for various cold region lakes. Significant mismatches in the response of predator and prey plankton species caused by shorter ice cover season can also engender the re-organization of the lake food web [58]. However, the extent to which shorter or no ice duration alters the plankton abundance, community and trophic relationships in lakes depend on factors such as snow-ice conditions, nutrient availability and spring/summer climate [59]. The cold, dark, and oxygen-limited lake environment during ice cover season also provides an optimum environment for native cold-water fish species [60]. Therefore, the early end to the lake ice season commingling with warmer lake water temperatures diminish the survival advantage of these native fish species and promote the spread of invasive warm water fish species [61, 62]. It also reduces the likelihood of winter fish kills, as there is less potential for anoxic conditions to develop at the lake bottom during short or no ice cover period [55]. On the other hand, early ice-out dates may correspond to the lengthening of summer stratification period in lakes, and in shallow lakes or lakes with strong thermocline at lower depth, this promotes the occurrence of anoxic conditions and fish kills in the hypolimnion waters during summer/fall season [14].

Economic and Cultural Values: Over half of a billion people live in northern cold regions, where lakes freeze periodically [9]. For humans, lake ice has always inspired appreciation of nature's power, value, and beauty as evidenced by the long-term ice phenology records kept for hundreds of years [11]. Consequently, lake ice has been related to the sense of identity and emotional, social, and spiritual wellbeing [2]. For example, for over five centuries, Shinto priests used Lake Suwa ice phenology to start their purification processions and predict the rice harvest [2]. In Canada, USA, and Europe, frozen lakes are long been used as venues for various festivals and tournaments such as ice fishing derbies and skating competitions [31, 49]. The shortening of annual lake ice season may jeopardize spiritual practices and cultural traditions. For example, the purification processions at Lake Suwa were performed only 69 times in the past 100 years because the lake surface did not freeze in winter [2].

Shorter or no lake ice cover season can have local and regional economic implications. For land locked locations, it can contribute to increased economic hardship and scarcity of provisions, as lake ice offers an inexpensive winter roadway to rural and distant communities and industrial development and mining sites [49, 63]. In Manitoba (Canada), mild winter conditions in 2010 prompted the closure of a 2200km winter road (located on frozen ground, rivers, and lakes) and hindered the transport of food, gas and construction materials to more than 30,000 first nations people [24], thus resulting in an emergency declaration [24]. Shorter or no annual lake ice season may cause the cancellation of wintertime recreational events and loss of revenues from the popular outdoor winter recreational activities–ice fishing, skating, and snowmobiling [49, 2, 64]. In addition, for many northern indigenous communities, shorter ice season and thinner ice in northern lakes may disrupt the timing, occurrence and harvests of various subsistence activities (e.g., hunting, gathering, fishing) as ice covered lakes provides access to traditional hunting, fishing, and trapping grounds [65, 25, 66]. Finally, we noted earlier that shorter or no ice season might lead to increased algal biomass and loss of cold-water fishes in cold region lakes. These conditions may put off recreational activities during the open water season, increase water treatment costs, and reduce lake-shore property prices [49]. However, it is important to note that the economic implications of shorter ice cover season are not all negative and are site specific. For instance, [67] reported that for the Great Lakes, smaller ice cover extents and longer ice-free period lead to longer shipping periods and lowering of ice breaking costs.

Local climate: During the open water period, lakes moderate local climate conditions by giving up their thermal energy (via sensible and latent heat flux) in late fall and winter to warm local atmospheric conditions and absorbing (via sensible heat flux) the heat energy in the atmosphere in late spring and summer to cool atmospheric conditions. The presence of complete ice cover severely limits the thermal and moisture exchange between the relatively3 warm lake waters under ice and overlying frigid air [5, 31]. Gerbush et al. [68] found that for Lake Erie, the latent heat flux for an ice cover with 90% ice concentration was approximately 13% of that of the open water period. During late fall and winter, later ice-in date or lower ice cover extent in medium-to-large lakes can dramatically raise the moisture and heat (sensible and latent) lost to the atmosphere. Such conditions promote the development of severe downwind fog and precipitation (e.g., lake snow effect) [69, 70]. For instance, due to lesser than average ice-cover extent over Lake Ontario during the winter of 2007, the town of Redfield, New York (USA) received about 141 inches of lake effect snowfall over seven days. In spring and early summer, early ice-out increases solar insolation and the heat energy stored in lakes. This enhances the seasonal and annual moisture and latent heat fluxes from lakes. For medium to large lakes, it may also prolong the period lake and atmosphere flux exchanges and delay the winter ice-in date.

4. Concluding Remarks

Over the past century, the length of the ice season and its phenology of northern extratropical lakes has undergone significant changes towards shorter or no ice season. Current and projected warming of air temperatures and interannual and decadal climate variability are likely to exacerbate this trend. The consequences of changes in lakes with seasonal ice cover are far reaching and range from water supplies, ecosystem structure and health, cultural uses, to local and regional tourism and economy. This review presents a general framework by which the nature and predictability of short/no ice cover seasons and its impacts on linked socio-ecological systems may be examined and understood at local and regional scales. To improve on this framework, we recommend future works in the following research areas:

- *Winter Limnology*: Advancing our understanding of lake ice processes requires improvement to the current monitoring and investigative approaches and topics; novel lake sampling instruments and procedures that work when lakes are covered in ice are needed. In situ data collection must also be supplemented by adopting remote sensing monitoring approaches [49]. In addition, to achieve improved prediction of lake ice effects on the lake ecosystem structure and functions, lake ice models should be coupled with hydrological, limnological, climatic, and social systems models.

Within winter limnology studies, the influence of lake ice on the human population is the least studied subject. While many studied have casually noted the importance of lake ice on the lifestyle of local indigenous population, the authors are aware of only one study [2] where the spiritual, cultural, economic and emotional implication of lake ice on the social system are extensively studied. However, there are many indigenous communities particularly in the high latitudes whose economy, nutritional diet, lifestyle, and transport network might be massively disrupted by shortening of the lake ice season. More social implication studies therefore will be needed if adaptation and mitigation options are to be developed and effective strategies are to be adopted.

- *Lake ice season prediction/forecast*: To date, ENSO is the only phenomenon with skillful seasonal climate forecast [20]. Studies also show that ENSO exhibits a strong influence on the atmospheric circulation patterns [39], thus affording foreknowledge of lake ice phenomena. Experimental studies to characterize the role of winter meteorological variable(s) on the lake ice season would aid management efforts. Future climate research focused on ENSO-winter climate teleconnections are therefore needed where approaches and frameworks that assess ENSO-induced climate shifts will render lake social-ecological systems vulnerable.

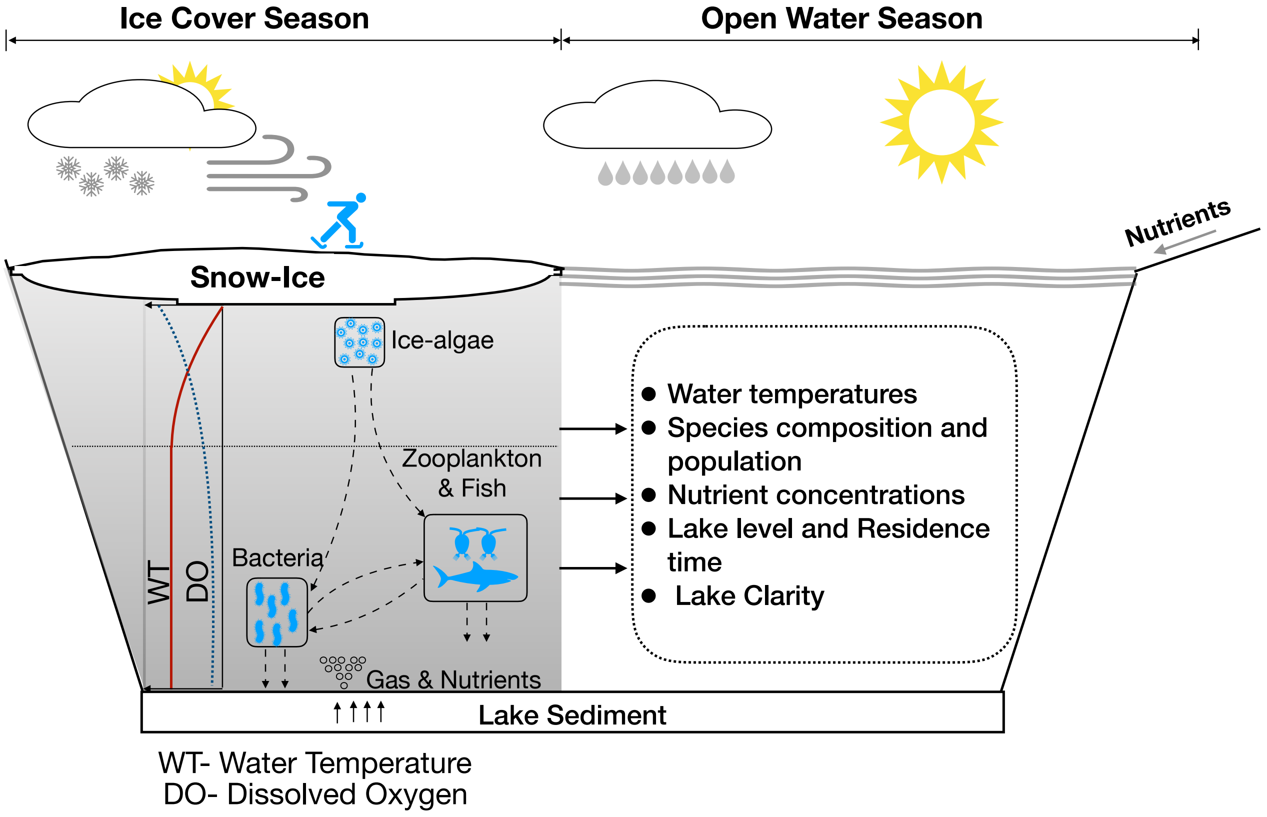

Figure 1: Conceptual diagram of expected winter activities in northern lakes.

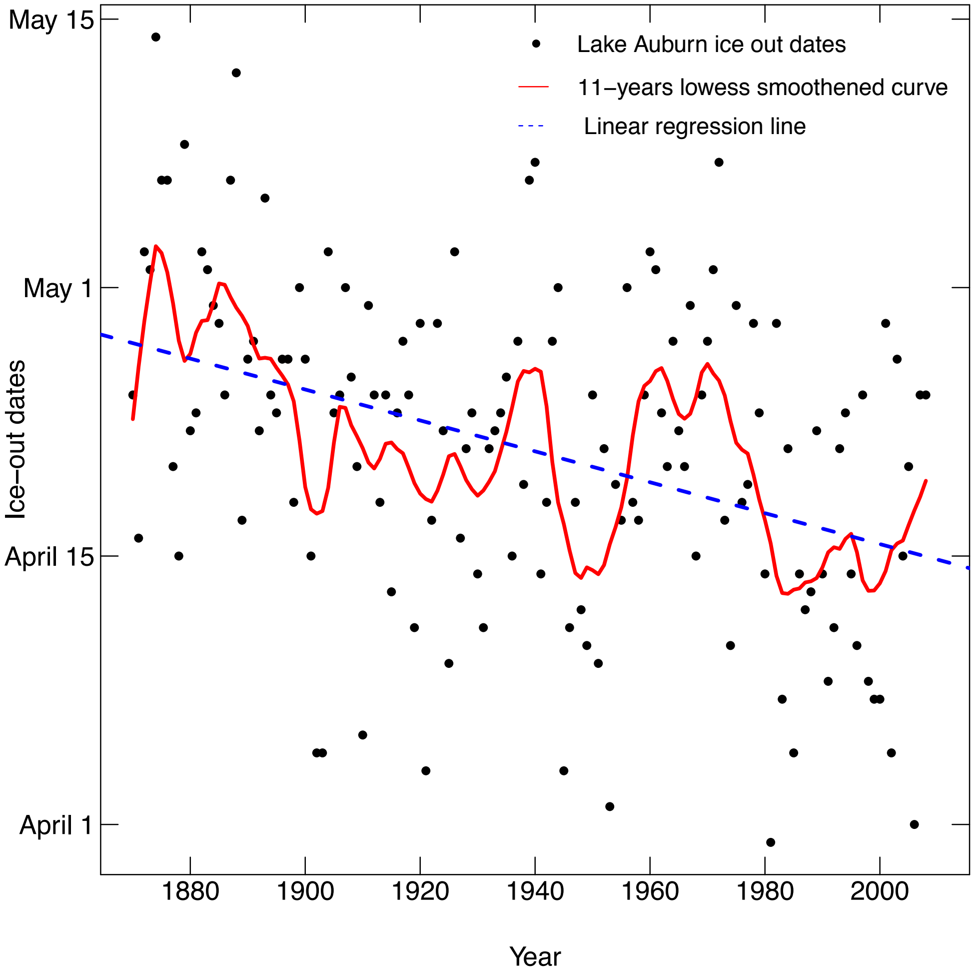

Figure 2: Trends and variability in the spring ice-out dates at Lake Auburn from 1850-2010.

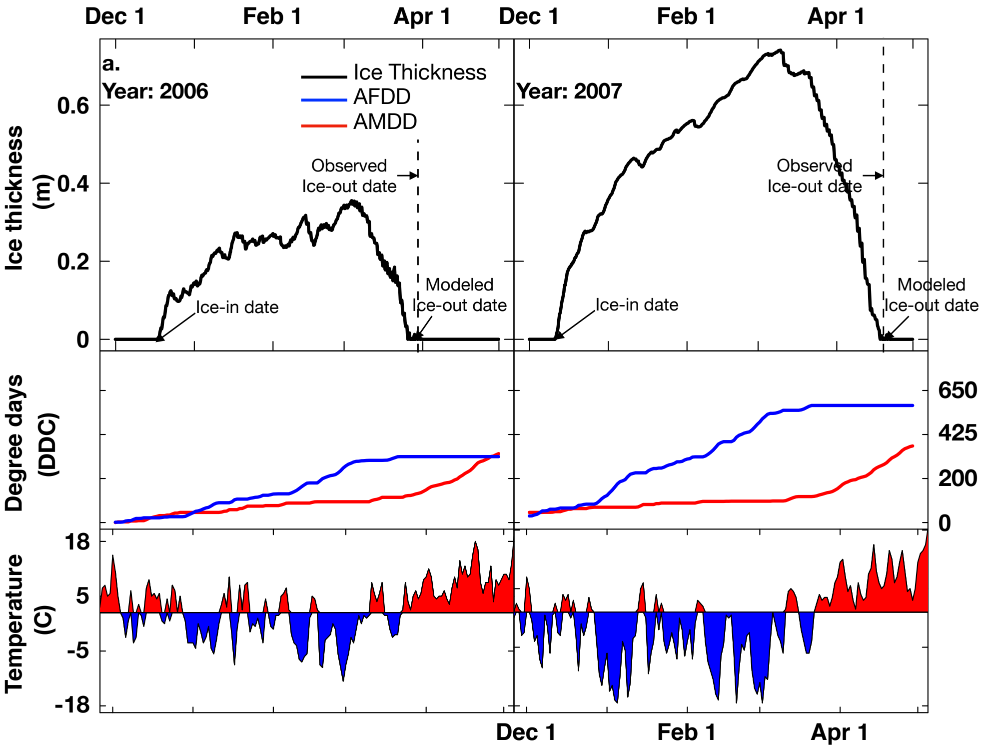

Figure 3: Contrasting the ice phenology and prevailing temperature conditions at Lake Auburn for 2005/06 and 2006/07. (a) and (b) Simulated lake ice evolution at Lake Auburn for 2006 and 2007 respectively using FLAKE. (c) and (d) Winter and spring accumulated freezing and melting degree days for 2005/06 and 2006/07 at Lake Auburn. (e) and (f) daily winter and spring temperature for 2005/06 and 2006/07 at Lake Auburn.

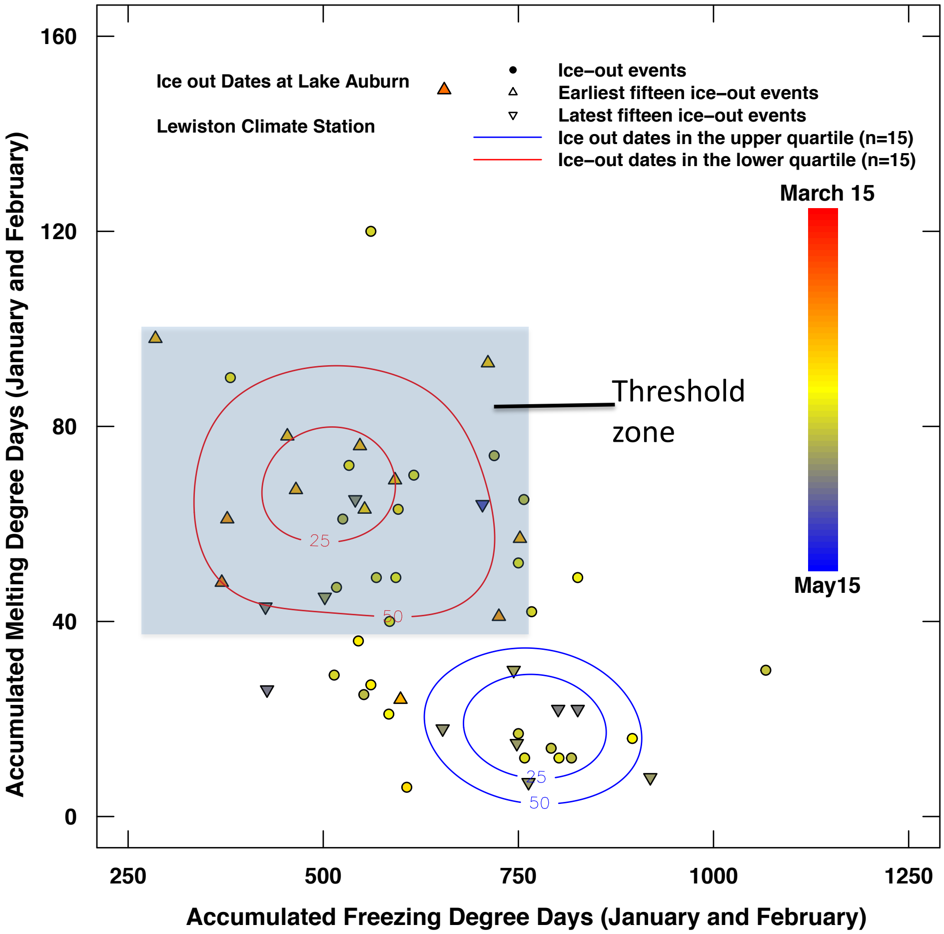

Figure 4: Winter thermal thresholds for the earliest and latest spring ice-out dates at Lake Auburn. The red and blue contours represent the joint probability density of winter AFDD and AMDD for the earliest and latest 15 ice out dates from 1950 to 2010 respectively. See [10] for method.

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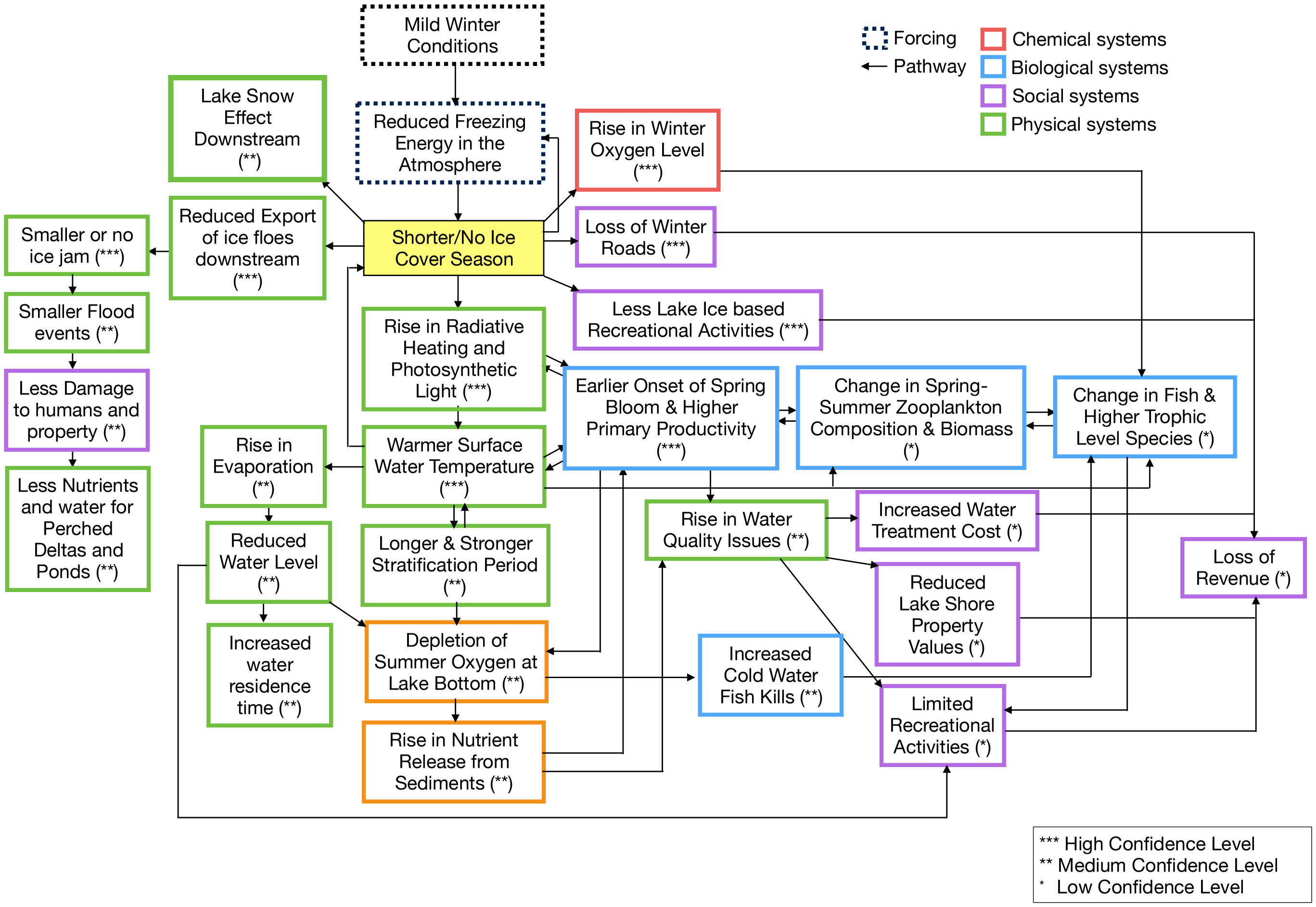

Source: Published Literatures

Figure 5: Conceptual schema of the response of lake watershed processes to shorter or no ice cover season.

References

[1] C. Verpoorter, T. Kutser, D. A. Seekell, L. J. Tranvik, A global inventory of lakes based on high-resolution satellite imagery, Geophysical Research Letters 41 (2014) 6396–6402.

[2] L. B. Knoll, S. Sharma, B. A. Denfeld, G. Flaim, Y. Hori, J. J. Magnuson, D. Straile, G. A. Weyhenmeyer, Consequences of lake and river ice loss on cultural ecosystem services, Limnology and Oceanography Letters 4 (2019) 119–131.

[3] K. Van Assche, J. Van Biesebroeck, J. Holm, Governing the ice. ice fishing villages on lake mille lacs and the creation of environmental governance institutions, Journal of Environmental Planning and Management 57 (2014) 1122–1144.

[4] A. Assur, Airfields on floating ice sheets: for routine and emergency operations, na, 1956.

[5] K. Salonen, M. Leppäranta, M. Viljanen, R. Gulati, Perspectives in winter limnology: closing the annual cycle of freezing lakes, Aquatic ecology 43 (2009) 609–616.

[6] S. E. Hampton, A. W. Galloway, S. M. Powers, T. Ozersky, K. H. Woo, R. D. Batt, S. G. Labou, C. M. O'Reilly, S. Sharma, N. R. Lottig, et al., Ecology under lake ice, Ecology Letters 20 (2017) 98–111.

[7] B. J. Benson, J. J. Magnuson, O. P. Jensen, V. M. Card, G. Hodgkins, J. Korhonen, D. M. Livingstone, K. M. Stewart, G. A. Weyhenmeyer, N. G. Granin, Extreme events, trends, and variability in northern hemisphere lake-ice phenology (1855–2005), Climatic Change 112 (2012) 299–323.

[8] X. Bai, J. Wang, C. Sellinger, A. Clites, R. Assel, Interannual variability of great lakes ice cover and its relationship to nao and enso, Journal of Geophysical Research: Oceans 117 (2012).

[9] S. Sharma, K. Blagrave, J. J. Magnuson, C. M. O'Reilly, S. Oliver, R. D. Batt, M. R. Magee, D. Straile, G. A. Weyhenmeyer, L. Winslow, et al., Widespread loss of lake ice around the northern hemisphere in a warming world, Nature Climate Change 9 (2019) 227.

[10] M. T. Beyene, S. Jain, Wintertime weather-climate variability and its links to early spring ice-out in Maine lakes, Limnology and Oceanography 60 (2015) 1890–1905.

[11] J. J. Magnuson, D. M. Robertson, B. J. Benson, R. H. Wynne, D. M. Livingstone, T. Arai, R. A. Assel, R. G. Barry, V. Card, E. Kuusisto, et al., Historical trends in lake and river ice cover in the northern hemisphere, Science 289 (2000) 1743–1746.

[12] G. A. Hodgkins, I. C. James, T. G. Huntington, Historical changes in lake ice-out dates as indicators of climate change in New England, 1850–2000, International Journal of Climatology 22 (2002) 1819–1827.

[13] C. R. Duguay, T. D. Prowse, B. R. Bonsal, R. D. Brown, M. P. Lacroix, P. Ménard, Recent trends in canadian lake ice cover, Hydrological Processes: An International Journal 20 (2006) 781–801.

[14] S. Williams, Maine Lakes Report, Technical Report, Maine Volunteer Lake Program, http://www.mainevlmp.org/wp-content/uploads/2013/07/2012-VLMP- Annual-Report-Color.pdf, 2012.

[15] T. Noges, L. Tuvikene, P. Noges, Contemporary trends of temperature, nutrient loading, and water quality in large Lakes Peipsi and Vortsjärv, Estonia, Aquatic Ecosystem Health & Management 13 (2010) 143–153.

[16] G. A. Weyhenmeyer, A.-K. Westöö, E. Willén, Increasingly ice-free winters and their effects on water quality in sweden's largest lakes, in: European Large Lakes Ecosystem changes and their ecological and socioeconomic impacts, Springer, 2007, pp. 111–118.

[17] M. T. Beyene, S. Jain, R. C. Gupta, Linear-circular statistical modeling of lake ice-out dates, Water Resources Research 54 (2018) 7841–7858.

[18] M. T. Beyene, S. Jain, Freezing degree-day thresholds and lake ice-out dates: Understanding the role of El Niño conditions, International Journal of Climatology 38 (2018) 4335–4344.

[19] M. Stankiewicz, Breakup can be foretold, Pulp Pap. Mag. Can 48 (1947) 118–120.

[20] B. Hoskins, The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science, Quarterly Journal of the Royal Meteorological Society 139 (2013) 573–584.

[21] A. Capotondi, A. T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B. Dewitte, B. Giese, E. Guilyardi, et al., Understanding enso diversity, Bulletin of the American Meteorological Society 96 (2015) 921–938.

[22] S. M. Powers, S. E. Hampton, Winter limnology as a new frontier, Limnology and Oceanography Bulletin 25 (2016) 103–108.

[23] R. Adrian, N. Walz, T. Hintze, S. Hoeg, R. Rusche, Effects of ice duration on plankton succession during spring in a shallow polymictic lake, Freshwater Biology 41 (1999) 621–634.

[24] K. Carlson, End of the roads, 2010.

[25] K. J. Moerlein, C. Carothers, Total environment of change: impacts of climate change and social transitions on subsistence fisheries in northwest alaska, Ecology and Society 17 (2012).

[26] G. A. Weyhenmeyer, D. M. Livingstone, M. Meili, O. Jensen, B. Benson, J. J. Magnuson, Large geographical differences in the sensitivity of ice-covered lakes and rivers in the northern hemisphere to temperature changes, Global Change Biology 17 (2011) 822–831.

[27] V. Mishra, K. A. Cherkauer, L. C. Bowling, M. Huber, Lake ice phenology of small lakes: Impacts of climate variability in the great lakes region, Global and Planetary Change 76 (2011) 166–185.

[28] D. M. Livingstone, Ice break-up on southern lake baikal and its relationship to local and regional air temperatures in siberia and to the north atlantic oscillation, Limnology and Oceanography 44 (1999) 1486–1497.

[29] G. Sánchez-López, A. Hernández, S. Pla-Rabes, M. Toro, I. Granados, J. Sigró, R. Trigo, M. Rubio-Inglés, L. Camarero, B. Valero-Garcés, et al., The effects of the nao on the ice phenology of spanish alpine lakes, Climatic change 130 (2015) 101–113.

[30] B. R. Bonsal, T. D. Prowse, C. R. Duguay, M. P. Lacroix, Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over canada, Journal of Hydrology 330 (2006) 340–353.

[31] M. Leppäranta, Freezing of lakes and the evolution of their ice cover, Springer Science & Business Media, 2014.

[32] G. D. Ashton, River and lake ice thickening, thinning, and snow ice formation, Cold Regions Science and Technology 68 (2011) 3–19.

[33] D. V. Mironov, Parameterization of lakes in numerical weather prediction: Description of a lake model, DWD, 2008.

[34] G. P. Williams, Correlating freeze-up and break-up with weather conditions, Canadian Geotechnical Journal 2 (1965) 313–326.

[35] H. H. Franssen, S. Scherrer, Freezing of lakes on the swiss plateau in the period 1901–2006, International Journal of Climatology: A Journal of the Royal Meteorological Society 28 (2008) 421–433.

[36] A. G. Barnston, R. E. Livezey, Classification, seasonality and persistence of low-frequency atmospheric circulation patterns, Monthly weather review 115 (1987) 1083–1126.

[37] G. A. Weyhenmeyer, T. Blenckner, K. Pettersson, Changes of the plankton spring outburst related to the north atlantic oscillation, Limnology and Oceanography 44 (1999) 1788–1792.

[38] D. Gerten, R. Adrian, Effects of climate warming, North Atlantic Oscillation, and El Niño-Southern Oscillation on thermal conditions and plankton dynamics in Northern Hemispheric lakes, The Scientific World Journal 2 (2002) 586–606.

[39] K. E. Trenberth, G. W. Branstator, D. Karoly, A. Kumar, N.-C. Lau, C. Ropelewski, Progress during toga in understanding and modeling global teleconnections associated with tropical sea surface temperatures, Journal of Geophysical Research: Oceans 103 (1998) 14291–14324.

[40] R. A. Assel, The 1997 enso event and implication for north american laurentian great lakes winter severity and ice cover, Geophysical research letters 25 (1998) 1031–1033.

[41] D. Gerten, R. Adrian, Differences in the persistency of the north atlantic oscillation signal among lakes, Limnology and Oceanography 46 (2001) 448–455.

[42] J. A. Austin, S. M. Colman, Lake superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback, Geophysical Research Letters 34 (2007).

[43] C. M. O'Reilly, S. Sharma, D. K. Gray, S. E. Hampton, J. S. Read, R. J. Rowley, P. Schneider, J. D. Lenters, P. B. McIntyre, B. M. Kraemer, et al., Rapid and highly variable warming of lake surface waters around the globe, Geophysical Research Letters 42 (2015) 10–773.

[44] A. D. Jassby, T. M. Powell, C. R. Goldman, Interannual fluctuations in primary production: Direct physical effects and the trohic cascade at Castle Lake, California, Limnology and Oceanography 35 (1990) 1021–1038.

[45] D. L. Preston, N. Caine, D. M. McKnight, M. W. Williams, K. Hell, M. P. Miller, S. J. Hart, P. T. J. Johnson, Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure, Geophysical Research Letters 43 (2016) 5353–536.

[46] Y. Zhong, M. Notaro, S. J. Vavrus, M. J. Foster, Recent accelerated warming of the laurentian great lakes: Physical drivers, Limnology and Oceanography 61 (2016) 1762–1786.

[47] W. R. Rouse, C. M. Oswald, J. Binyamin, P. D. Blanken, W. M. Schertzer, C. Spence, Interannual and seasonal variability of the surface energy balance and temperature of central great slave lake, Journal of Hydrometeorology 4 (2003) 720–730.

[48] L. Arvola, G. George, D. M. Livingstone, M. Järvinen, T. Blenckner, M. T. Dokulil, E. Jennings, C. N. Aonghusa, P. Nõges, T. Nõges, et al., The impact of the changing climate on the thermal characteristics of lakes, in: The impact of climate change on European lakes, Springer, 2009, pp. 85–101.

[49] T. Prowse, K. Alfredsen, S. Beltaos, B. R. Bonsal, W. B. Bowden, C. R. Duguay, A. Korhola, J. McNamara, W. F. Vincent, V. Vuglinsky, et al.,

Effects of changes in arctic lake and river ice, AMBIO: A Journal of the Human Environment (2011) 63–74.

[50] M. R. Penn, M. T. Auer, S. M. Doerr, C. T. Driscoll, C. M. Brooks, S. W. Effler, Seasonality in phosphorus release rates from the sediments of a hypereutrophic lake under a matrix of pH and redox conditions, Canadian Journal of Fisheries and Aquatic Sciences 57 (2000) 1033–1041.

[51] A. Kleeberg, Phosphorus sedimentation in seasonal anoxic lake scharmützel, ne germany, Hydrobiologia 472 (2002) 53–65.

[52] M. Søndergaard, J. P. Jensen, E. Jeppesen, Role of sediment and internal loading of phosphorus in shallow lakes, Hydrobiologia 506 (2003) 135–145.

[53] K. Blank, J. Haberman, M. Haldna, R. Laugaste, Effect of winter conditions on spring nutrient concentrations and plankton in a large shallow lake peipsi (estonia/russia), Aquatic Ecology 43 (2009) 745–753.

[54] D. Joung, M. Leduc, B. Ramcharitar, Y. Xu, P. D. Isles, J. D. Stockwell, G. K. Druschel, T. Manley, A. W. Schroth, Winter weather and lake-watershed physical configuration drive phosphorus, iron, and manganese dynamics in water and sediment of ice-covered lakes, Limnology and Oceanography 62 (2017) 1620–1635.

[55] X. Fang, H. G. Stefan, Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous us under past and future climate scenarios, Limnology and Oceanography 54 (2009) 2359–2370.

[56] D. Gerten, R. Adrian, Climate-driven changes in spring plankton dynamics and the sensitivity of shallow polymictic lakes to the north atlantic oscillation, Limnology and Oceanography 45 (2000) 1058–1066.

[57] M. Gyllström, L.-A. Hansson, E. Jeppesen, F. G. Criado, E. Gross, K. Irvine, T. Kairesalo, R. Kornijów, M. R. Miracle, M. Nykänen, et al., The role of climate in shaping zooplankton communities of shallow lakes, Limnology and Oceanography 50 (2005) 2008–2021.

[58] M. Winder, D. E. Schindler, Climate change uncouples trophic interactions in an aquatic ecosystem, Ecology 85 (2004) 2100–2106.

[59] R. Adrian, S. Wilhelm, D. Gerten, Life-history traits of lake plankton species may govern their phenological response to climate warming, Global Change Biology 12 (2006) 652–661.

[60] I. P. Helland, A. G. Finstad, T. Forseth, T. Hesthagen, O. Ugedal, Ice-cover effects on competitive interactions between two fish species, Journal of Animal Ecology 80 (2011) 539–547.

[61] S. E. Hampton, M. V. Moore, T. Ozersky, E. H. Stanley, C. M. Polashenski, A. W. Galloway, Heating up a cold subject: prospects for under-ice plankton research in lakes, Journal of Plankton Research 37 (2015) 277–284.

[62] T. M. Farmer, E. A. Marschall, K. Dabrowski, S. A. Ludsin, Short winters threaten temperate fish populations, Nature communications 6 (2015) 7724.

[63] G. K. Hovelsrud, B. Poppel, B. Van Oort, J. D. Reist, Arctic societies, cultures, and peoples in a changing cryosphere, Ambio 40 (2011) 100–110.

[64] K. Orru, K. Kangur, P. Kangur, K. Ginter, A. Kangur, Recreational ice fishing on the large lake peipsi: socioeconomic importance, variability of ice-cover period, and possible implications for fish stocks., Estonian Journal of Ecology 63 (2014).

[65] C. Furgal, T. Prowse, Northern canada, From impacts to adaptation: Canada in a changing climate 2007 (2008) 57–118.

[66] H. Cold, T. Brinkman, C. Brown, T. Hollingsworth, D. Brown, K. Heeringa, Assessing vulnerability of subsistence travel to effects of environmental change in interior alaska, Ecology and Society 25 (2020).

[67] G. W. Kling, K. Hayhoe, L. B. Johnson, D. J. Magnuson, S. Polasky, S. K. Robinson, B. J. Shuter, M. M. Wander, D. J. Wuebbles, D. R. Zak, Confronting climate change in the great lakes region: impacts on our communities and ecosystems (2003).

[68] M. R. Gerbush, D. A. Kristovich, N. F. Laird, Mesoscale boundary layer and heat flux variations over pack ice–covered lake erie, Journal of Applied Meteorology and Climatology 47 (2008) 668–682.

[69] A. W. Burnett, M. E. Kirby, H. T. Mullins, W. P. Patterson, Increasing great lake–effect snowfall during the twentieth century: A regional response to global warming?, Journal of Climate 16 (2003) 3535–3542.

[70] J. M. Cordeira, N. F. Laird, The influence of ice cover on two lake-effect snow events over lake erie, Monthly Weather Review 136 (2008) 2747–2763.