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Special Section:

Ŵinter limnology in a changing world

Key Points:

- Ripe opportunity to merge disciplines and harmonize data streams to further understand lake ice dynamics in changing winters
- Develop integrated plans for future data collection by moving from ice cover and phenology to multifaceted descriptions of ice conditions
- Operationalize development of skill sets to work in multidisciplinary teams by constructing a workforce and developing a common language

Correspondence to: S. Sharma,

sharma11@yorku.ca

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Sapna Sharma, Michael F. Meyer, Joshua Culpepper, and Xiao Yang are joint first authors.

Author Contributions:

Conceptualization: Sapna Sharma, Michael F. Meyer, Joshua Culpepper, Xiao Yang, Stella A. Berger, Steven C. Fradkin, Adrianne P. Smits, Emily C. Whitaker, Foad Yousef, Shuai Zhang **Project administration:** Sapna Sharma, Michael F. Meyer, Joshua Culpepper, Xiao Yang **Supervision:** Sapna Sharma, Michael F. Meyer, Joshua Culpepper, Xiao Yang **Visualization:** Sapna Sharma, Michael F. Meyer, Xiao Yang, Stella A. Berger, Steven C. Fradkin, Kathi Jo Jankowski (continued)

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Integrating Perspectives to Understand Lake Ice Dynamics in a Changing World

Sapna Sharma¹, Michael F. Meyer², Joshua Culpepper^{3,4}, Kiao Yang⁵, Stephanie Hampton², Stella A. Berger⁶, Matthew R. Brousil⁷, Steven C. Fradkin⁸, Scott N. Higgins⁹, Kathi Jo Jankowski¹⁰, Georgiy Kirillin¹¹, Adrianne P. Smits¹², Emily C. Whitaker¹³, Foad Yousef¹⁴, and Shuai Zhang⁵

¹Department of Biology, York University, Toronto, Ontario, Canada, ²School of the Environment, Washington State University, Pullman, WA, USA, ³Division of Hydrologic Sciences, Desert Research Institute, Reno, NV, USA, ⁴Graduate Program of Hydrologic Sciences, University of Nevada, Reno, NV, USA, ⁵Department of Geological Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA, ⁶Department of Experimental Limnology, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Stechlin, Germany, ⁷Center for Environmental Research, Education and Outreach, Washington State University, Pullman, WA, USA, ⁸Olympic National Park, National Park Service, Port Angeles, WA, USA, ⁹IISD Experimental Lakes Area Inc., Winnipeg, Manitoba, Canada, ¹⁰Upper Midwest Environmental Sciences Center, U.S. Geological Survey, La Crosse, WI, USA, ¹¹Department of Ecohydrology, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany, ¹²Environmental Science and Policy, University of California, Davis, CA, USA, ¹³Center for Limnology, University of Wisconsin-Madison, Madison, WI, USA, ¹⁴Department of Biology, Westminster College, Salt Lake City, UT, USA

Abstract Ice cover plays a critical role in physical, biogeochemical, and ecological processes in lakes. Despite its importance, winter limnology remains relatively understudied. Here, we provide a primer on the predominant drivers of freshwater lake ice cover and the current methodologies used to study lake ice, including in situ and remote sensing observations, physical based models, and experiments. We highlight opportunities for future research by integrating these four disciplines to address key knowledge gaps in our understanding of lake ice dynamics in changing winters. Advances in technology, data integration, and interdisciplinary collaboration will allow the field to move toward developing global forecasts of lake ice cover for small to large lakes across broad spatial and temporal scales, quantifying ice quality and ice thickness, moving from binary to continuous ice records, and determining how winter ice conditions and quality impact ecosystem processes in lakes over winter. Ultimately, integrating disciplines will improve our ability to understand the impacts of changing winters on lake ice.

Plain Language Summary Lakes are experiencing accelerated rates of warming, including shorter seasonal duration of ice cover, later ice-on, earlier ice-off, and in some years no ice cover at all. Lake ice has been historically studied independently by four subdisciplines: observations by in situ and remote sensing scientists, controlled mesocosm experiments by limnologists, and process-based models by physical modelers. Here, we highlight opportunities for collaboration between disciplines and provide guidelines to successfully integrate the disciplines to tackle the most urgent questions surrounding lake ice loss in warming climates.

1. Introduction

Long-term observations of ice cover indicate shorter ice cover duration for lakes around the Northern Hemisphere, with strong linkages to climate change (Benson et al., 2012; Magnuson et al., 2000; Sharma et al., 2019). These long-term climate effects sparked an increased interest in winter limnology (Hampton, Galloway, et al., 2017; Salonen et al., 2009), its broader importance to limnological processes and food webs (Jeppesen et al., 2003; Powers et al., 2017), and implications to the ecological goods and services that lakes provide (Brander, 2007; Mullan et al., 2017). The majority of working knowledge in freshwater winter limnology comes from in situ data collection; however, technological advances and remote sensing data sets provide the means to push the boundaries of this discipline. Merging knowledge and increasing collaboration across disciplines offers the potential to improve our ability to predict future changes in freshwater ice phenology and to better understand broader implications to limnology and ecosystem services.



Writing - original draft: Sapna Sharma, Michael F. Meyer, Joshua Culpepper, Xiao Yang, Stephanie Hampton

Writing – review & editing: Sapna Sharma, Michael F. Meyer, Joshua Culpepper, Xiao Yang, Stephanie Hampton, Stella A. Berger, Matthew R. Brousil, Steven C. Fradkin, Scott N. Higgins, Kathi Jo Jankowski, Georgiy Kirillin, Adrianne P. Smits, Emily C. Whitaker, Foad Yousef, Shuai Zhang We aim to encourage collaboration between disciplines in order to accelerate research on freshwater ice phenology, ice quality, and winter limnology. Understanding how ice duration and quality is changing throughout the world is foundational to answering questions about how lake processes and humans that rely on lakes will be affected. We define ice quality as the thickness and relative proportion of white and black ice. Black ice forms from the bottom of the ice downward as surface lake water freezes. White ice is formed from the ice surface up, when water is introduced into the snow matrix and the resultant slush refreezes. Introduced water can come from rain on snow events, midseason snow melting, or the intrusion of lake water as the weight of the snow layer depresses the ice surface below water level (Brown & Duguay, 2010). Ice quality impacts light penetration into the water column (Hampton et al., 2015), ion inclusion into ice (Adams & Lasenby, 1985; Catalan, 1989), albedo, and the melting and formation of ice (Brown & Duguay, 2010). In this perspective, we highlight key opportunities for future research and identify synergies for in situ and experimental limnologists, remote sensing scientists, and physical modelers. We discuss the current state of knowledge, recent technological advances, and barriers to data integration. We then focus on the key ways to move forward: increasing interoperability between data types, standardizing terminology, moving from binary to continuous data, and increasing the collection of additional ice quality data that, together, will allow for increased data sharing and collaboration between disciplines and greatly improve our collective capacity to understand and quantify the implications of climate change on lake ecosystems and the goods and services they provide.

This paper demonstrates the essentials of ice phenology and merging research efforts; however, we also recognize the importance of under-ice phenomena on biogeochemical processes and freshwater lake ecology. Earlier work has shown how changing ice cover regimes have increased wind speeds on Lake Superior as a result of water warming more rapidly than the atmosphere above the lake (Desai et al., 2009; Rouse, 2009) as well as an earlier onset of summer stratification (Austin & Colman, 2007). Furthermore, the early or delayed onset of thermal stratification, influenced by ice cover duration, controls the turbulent fluxes of heat and water vapor, affecting energy and gas exchange (Moukomla & Blanken, 2016). Changing ice cover duration further complicates our understanding of chemical interactions. Ice cover directly affects CO_2 and CH_4 accumulation and emissions; therefore, neglecting under-ice accumulation and emission at ice melt biases annual C budgets (Denfeld et al., 2018). Other studies and syntheses have made a significant effort to catalog these and other under-ice processes and provide methods to fill knowledge gaps, recognizing the urgent necessity to understand changing ice dynamics on limnological processes (Denfeld et al., 2018; Hampton et al., 2015; Hampton, Galloway, et al., 2017; Powers et al., 2017).

2. Working Knowledge of the Freshwater Ice Cycle

Lakes around the Northern Hemisphere show progressively earlier ice-off dates, later ice-on dates, and shorter ice duration (Benson et al., 2012; Magnuson et al., 2000; Schmidt et al., 2019). In some years, some typically ice-covered lakes may fail to freeze at all (Sharma et al., 2016, 2019). Nonlinearities and phase switches of large-scale climate oscillations, such as El Niño–Southern Oscillation (ENSO), North American Oscillation (NAO), and Pacific Decadal Oscillation (PDO), add complexity to trends with even faster rates of lake warming following 1976, 1988, and 1998 (Cleave et al., 2014; Lopez et al., 2019; Robertson et al., 1992). These large- and small-scale interactions hinder our ability to accurately forecast ice phenology (Bai et al., 2012). It is clear, however, that a set of common drivers play a significant role in the timing, duration, and quality of lake ice.

Air temperature is the most important explanatory variable for long-term trends of ice phenology and the probability of ice formation (Magnuson et al., 2000; Sharma et al., 2019). Ice-off and ice-on dates generally correlate with the 0°C isotherm (Arp et al., 2013; Duguay et al., 2006; Shuter et al., 2013); in Alaskan lakes, temperature and lake area together can explain over 80% of the variation in ice-off dates (Arp et al., 2013). Warmer air temperatures in the weeks to months preceding ice-off (Ghanbari et al., 2009; Lopez et al., 2019; Palecki & Barry, 1986; Sharma et al., 2013; Weyhenmeyer et al., 2004, 2011) and ice-on (Hewitt et al., 2018; Surdu et al., 2015) explain the most variation in ice phenology. Further, accumulated freezing degree days can predictably explain ice thickness and ice-off date, although the relationship with ice-on is more complex (Karetnikov et al., 2017).



Solar radiation is a primary driver of ice decay throughout vertical layers of the ice. As such, the penetration of shortwave radiation to the ice surface and within the ice is strongly influenced by the transparency of the ice and albedo of the overlying snow layer (Jakkila et al., 2009; Kirillin et al., 2012; Leppäranta, 2010). Seasonal changes in the absorption of solar radiation preceding the time of ice breakup in the spring accelerates the process of ice melt (Bernhardt et al., 2012; Brown & Duguay, 2010; Jeffries et al., 2013). The high sensitivity of the heat budget to the solar radiation is a characteristic feature of alpine lakes. In the Tatra mountains, solar radiation explained 48% of the variation in ice freeze-up dates (Novikmec et al., 2013). In the Tibetan Plateau, years with low radiation fluxes have increased ice cover duration (Liu et al., 2016). On decadal time scales, the decreasing solar radiation trend over the Tibetan Plateau (Yang et al., 2012) prevents lake warming and shortening of the ice cover duration despite the significant air temperature increase (Kirillin et al., 2017).

Snow cover affects the evolution of ice formation and decay in complex ways. Snow acts as an insulator, reducing heat loss and the rate of black ice thickening. However, snow can contribute to overall ice thickness due to its role in the formation of white ice (Jeffries et al., 2005). These effects have profound ramifications for the under-ice physical/chemical environment (Kirillin et al., 2012; Yang et al., 2017) and its biota (Yang et al., 2017). In a number of regions, the high albedo of thick snowpack leads to later snowmelt and delayed ice melt, resulting in later ice-off (Brown & Duguay, 2010; Jensen et al., 2007; Kouraev et al., 2007; Preston et al., 2016; Sadro et al., 2018). However, cold winters with low snowpack produce thicker ice that can also lead to later ice-off (Kouraev et al., 2007). The timing of ice-off and the relative influence of snowpack and ice thickness is determined by the duration of snowpack. Snowpack melting is influenced by both air temperature and solar radiation absorption (Bernhardt et al., 2012), with the latter as the dominant melting influence (Brown & Duguay, 2010). Snowpack albedo regulates the absorption of solar radiation for melting. However, albedo decreases as water content increases from rain-on-snow events (Bernhardt et al., 2012) and the advance of the spring melt season. The resulting increased absorption of solar radiation leads to more melting and a further albedo decline (Brown & Duguay, 2010).

Wind increases heat exchange from the lake to the atmosphere, cooling surface waters, and supporting both earlier ice formation and increased ice growth rates (Bernhardt et al., 2012; Brown & Duguay, 2010). However, wind-induced turbulence at the air-water interface can prevent or delay the first layer of skim ice. After skim ice forms, wind influences the distribution of snow cover on lake surfaces (Brown & Duguay, 2010). In the spring, high winds can mechanically break large areas of ice in a lake and accelerate melting by upwelling warmer waters (Assel, 1990; Brown & Duguay, 2010; Cai et al., 2019).

Large-scale climate oscillations correlated with air temperature and precipitation, including ENSO and NAO, explain significant variation in ice phenology (Bai et al., 2012; Ghanbari et al., 2009; Livingstone, 2000; Schmidt et al., 2019; Sharma et al., 2013; Sharma & Magnuson, 2014). Periodicities of NAO and ENSO (i.e., the length of the cycle) have decreased since the midtwentieth century in response to increasing greenhouse gas emissions and may contribute to faster rates of lake warming (Sharma et al., 2016).

Lake and landscape characteristics mediate the effects of climate on ice phenology in several important ways. Thermocline depth, an important determinant of heat storage, increases nonlinearly with lake size (Hanna, 1990) and in small lakes (<500 ha) is also influenced by water clarity (Fee et al., 1996). Thus, larger lakes with deeper thermoclines take longer to cool in the fall, require persistent temperatures below 0°C, and low wind speeds prior to freezing (Brown & Duguay, 2010; Jeffries et al., 2013; Kirillin et al., 2012; Nõges & Nõges, 2014). Lake depth is an important factor affecting lake ice phenology, evaporative losses, and bed temperatures (Arp et al., 2015, 2016; Warne et al., 2020). For example, deeper lakes are more likely to experience intermittent ice cover (Sharma et al., 2019), and very shallow lakes are more likely to freeze solid in the winter at high latitudes (Arp et al., 2016). A variety of lake and landscape features also influence wind speeds at the lake surfaces. For example, more circular lakes tend to have longer fetches which increases their sensitivity to increased wind action and breaking of the initial skim of ice that forms on a lake (Jeffries et al., 2013; Magee & Wu, 2017; Williams et al., 2004). Lakes in steep, north facing basins in the Northern Hemisphere retain ice cover longer because their topography blocks incoming solar radiation needed to melt ice (Novikmec et al., 2013). Lakes with high hydrologic connectivity and very short residence times (e.g., hours to days) are subject to mechanical and hydrological drivers that impact riverine ice processes (Beltaos & Prowse, 2009).



Anthropogenic Factors - Local factors, including urbanization, deforestation, and human engineering, such as the construction of power plants and flood control gates, may, but not always, influence trends in ice phenology. In Toronto, Canada, the population has grown from 31,000 individuals in 1822 when the local ice record was started in the Toronto Harbor in Lake Ontario, to approximately 6.2 million individuals in 2020. Between 1822 and 1920, ice-on was delayed by 37 days per century, and now the harbor no longer freezes (Magnuson et al., 2000). For the case of Toronto Harbor, the influence of urbanization far outweighs the role of climate change (Magnuson et al., 2000). Power plants may also contribute to faster rates of warming or, in extreme cases, no ice cover at all. For example, following the construction of a nuclear power plant in the 1950s, the Angara River no longer freezes. In Madison, Wisconsin, two adjacent morphologically similar lakes warm at very different rates. Lake Mendota breaks up 6.7 days earlier per century, whereas Lake Monona, the site of an electric power generation plant, is breaking up 12 days earlier per century (Sharma et al., 2013). However, in Lake Suwa, Japan, the rates of warming are predominately explained by climate warming rather than local factors, such as deforestation in the region, an urban heat island, and hot springs that do not provide substantial heat input to the lake (Sharma et al., 2016).

3. How Do We Research Lake Ice Dynamics?

Below we introduce four approaches currently used to understand lake ice dynamics, namely, in situ observations, remote sensing, process-based models, and experimental winter limnology. We synthesize the knowledge gained using these approaches and provide recommendations on moving the fields forward.

3.1. In Situ Observations

Ice phenology records are among the most detailed and temporally extensive climate records extending back decades to centuries (Magnuson et al., 2000). For example, the U.S. National Snow and Ice Data Center hosts the Global Lake and River Ice Phenology Database that provides in situ ice phenology records for over 700 lakes beginning as early as 1443 (Benson et al., 2000). Unfortunately, there are large areas of the world where in situ measurements are lacking or discontinued (Weber et al., 2016), such as in Canada where centralized records of lake ice across the country have essentially ceased since the 1990s. Thus, new and collaborative approaches are needed to fill data gaps.

Citizen scientists have long gathered invaluable long-term lake ice phenology records, in some cases dating back to the mid-1400s (Magnuson et al., 2000; Sharma et al., 2016). Such records are instrumental to understanding local and global variations in climate and for validating lake ice estimates from remote sensing and process-based models. Citizen science programs often provide instructions on reporting ice phenology but such methods can vary across programs. For example, the Mission of Lake Stewards of Maine (LSM) in the United States asks volunteers to record both the initial and final dates of lake ice-on and ice-off. Individual definitions of lake ice phenology timing may vary across not only programs but also different observers and must be considered when utilizing such lake ice data (Hodgkins et al., 2002).

In situ instrumentation can help fill data gaps for snow and ice phenology, ice growth and decay rates, and under-ice conditions. For example, temperature moorings and meteorological instrumentation provide critical input and validation data for hydrodynamic models. Within-ice temperature sensors can provide additional data for testing and validating ice growth and decay models (Reed et al., 2019; Whitaker et al., 2016). Other instruments such as ground-penetrating radar (GPR) and under-ice sonar are useful for direct measurements of snow and ice thickness (Brown & Duguay, 2011; Gunn et al., 2015). A variety of standard limnological instrumentation, often restricted for use during ice-free conditions, can also be deployed to assess physical, chemical, and biological properties.

3.2. Remote Sensing

3.2.1. Satellite Remote Sensing

Satellite remote sensing provides the capacity for observation of ice phenology across large spatial scales at regular temporal intervals. Most satellite-borne sensors can observe ice conditions over lakes because of the different signal returns from ice and open water. Depending on the wavelength of signal used, remote sensing of lake ice can be divided into two categories: optical signals (Table 1; e.g., Landsat, Sentinel-2, MODIS [Moderate Resolution Imaging Spectroradiometer], VIIRS [Visible Infrared Imaging Radiometer Suite]) and microwave signals (e.g., AMSR-E [Advanced Microwave Scanning Radiometer for EOS], ERS-1/2 [European



Table 1

Summary of Remote Sensing Instruments That Have Been Used to Study Lake Ice						
Satellite/ sensor name	Sensor type	Mission start year	Mission end year	Highest spatial resolution	Highest temporal resolution	Ice detection algorithms/band combinations
MODIS	0	2000	Present	250 m	Twice a day	Brown and Duguay (2012); Chaouch et al. (2014); Zhang and Pavelsky (2019)
VIIRS	0	2013	Present	250 m	Daily	Liu et al. (2016)
AVHRR	0	1978	Present	1 km	Daily	Latifovic and Pouliot (2007); Weber et al. (2016)
Landsat	0	1972	Present	30 m	16 days	Barbieux et al. (2018); Cook and Bradley (2010)
SMMR	Р	1978	1987	25 km	Daily	Cai et al. (2017); Che et al. (2009)
SSMI	Р	1987	2016	25 km	Daily	Cai et al. (2017); Che et al. (2009)
AMSR-E	Р	2002	2011	5 km	Daily	Kang et al. (2012)
RADARSAT 1/	А	1995	Present	100 m	Varying	Cook and Bradley (2010); Geldsetzer (2010)
2						
Sentinel-1A/B	А	2014	Present	5*20 m	6 days	Claude R. Duguay and Wang (2019)
Sentinel-2A/B	0	2015	Present	10 m	5 days	Pointner et al. (2019)

Note. O = optical, A = active microwave, P = passive microwave.

Remote Sensing satellites], Sentinel-1, ENVISAT [Environmental Satellite]). Optical sensors use reflectance values collected by the instrument at various frequencies that cover visual, near-infrared, and the shortwave infrared portion of electromagnetic waves. Microwave sensors passively (gather emitted microwave signals) or actively (emit and gather rebounded signals) monitor surface processes using microwaves of different frequencies (from 1 cm to 1 m wavelength).

Optical and microwave remote sensing use different signals at different wavelengths that reflect different properties of surface features. Optical remote sensing extends existing lake ice records, establishes monitoring for ungauged lakes (Latifovic & Pouliot, 2007), and allows estimation of lake ice phenology (Arp et al., 2013; Kropáček et al., 2013; Weber et al., 2016). However, optical sensors can be obscured by cloud cover and can only observe the surface when it is well lit, limiting its application for cloudy and winter high latitude regions. Microwave remote sensing has the ability to "see through" clouds and dust in the atmosphere. It also can be used to infer ice types and thickness. These advantages allow microwave remote sensing to map lake ice phenology (Cai et al., 2017), differentiate floating and bottom-fast lake ice (Engram et al., 2018), and classify ice types (Geldsetzer, 2010). Below we provide additional information on each type of remote sensing with examples of existing research, and discuss its advantages and limitations.

3.2.2. Optical Remote Sensing

The optical sensors commonly used to study lake ice phenology have a short revisit time (e.g., MODIS, VIIRS, and AVHRR [Advanced Very High Resolution Radiometer] all have daily images over a given location), which is essential to monitor dynamics during ice-on and ice-off. Thermal infrared bands have also been used to assist ice phenology estimation based on the derived lake surface water temperatures (Weber et al., 2016). However, shorter revisit time often means coarser spatial resolution (typical pixel size \geq 250 m), preventing these satellites from observing lake ice on smaller lakes. A recent study from Zhang and Pavelsky (2019) demonstrated that phenology can be extracted from MODIS for lakes with sizes smaller than one pixel, suggesting the potential capacity to monitor smaller lakes with daily temporal sampling. The potential of studying lake ice using optical remote sensing remains largely unexplored for medium-resolution images, such as those from the Landsat series and the Sentinel-2A/B. While these types of satellites often have longer revisit times (16 days for Landsat and 5 days when use both satellites of Sentinel-2), their finer spatial resolution allows them to characterize small lakes. The record period is also longer (the first Landsat satellite was launched in 1972), making them suitable for detecting trends and changes in lake ice. The temporal resolution can be further reduced with the proper fusion technique to harmonize data across different optical satellites. More recently, commercial companies have offered additional options. Planet launched a constellation of CubeSats (small size and cheaper cost compared to conventional satellites), showing potential to monitor large scale lake dynamics with high temporal (daily) and spatial (meter-scale resolution) imaging ability (Cooley et al., 2019).

3.2.3. Microwave Remote Sensing

Existing research uses the temporal evolution of brightness temperature calculated from background microwave signals to quantify lake ice phenology. As passive microwave data sets often have daily observations, it



is well suited to studying ice phenology (e.g., Cai et al., 2017). For example, brightness temperature from low frequency passive microwave signals has been demonstrated to correlate with lake ice thickness for two lakes (Hall et al., 1981; Kang et al., 2010, 2012). Despite the shown correlation between brightness temperature and ice thickness, remote sensing of ice thickness remains challenging. More accurate thickness measurements were made instead using GPRs mentioned in the previous section. As naturally emitting microwave signals are weak, averaging across a large area is often necessary to increase the signal-to-noise ratio. While the rather coarse resolution (~3–75 km) associated with averaging limits the use of passive microwave sensors to the largest water bodies (Zhang & Gao, 2016), such data usually can have fine temporal resolutions (~daily).

Active microwave instruments such as synthetic aperture radar (SAR) have also been used to monitor lake ice phenology (Murfitt & Duguay, 2020) and have the added ability to detect formation of bottom-fast lake ice (Arp et al., 2012; Duguay & Lafleur, 2003). The detection of lake ice was based mostly on the higher back-scatter of ice relative to that of open water. The relatively high spatial resolution (1–30 m) of SAR allows observation of smaller lakes (Duguay & Wang, 2019). However, conditions that affect the roughness of the surface will alter the backscatter, complicating the development of automated algorithms for ice phenology that could be applied over large spatial scales. For example, it may be difficult for SAR to distinguish between ice and open water when the ice is wet and smooth (e.g. after rain on snow/ice events; Lundhaug, 2002; Wakabayashi et al., 1993) or when windy conditions create increased roughness over the open water (Sobiech & Dierking, 2013).

3.2.4. Unmanned Aerial Vehicles

While still in its infancy, remote sensing using unmanned aerial vehicles (UAVs) (e.g., drones) has some advantages over their traditional remote sensing counterparts. First, drones offer imagery with orders of magnitude higher spatial resolution (~ 1 cm). Second, they are less limited by cloud coverage, a common issue for passive optical sensors. Third, and specifically related to limnological and ice phenology research, drones can be used for water sampling during the ice-off period when lake ice is thin and not stable for direct sampling (Lally et al., 2019). Last but not least, the flexibility of flying UAVs allows repeat measurements that captures dynamic processes occurring during the beginning and the end of the ice seasons.

UAVs can also be equipped with a diverse array of sensors. RGB sensors and multispectral sensors offer an opportunity to study ice phenology and extent in both lakes and rivers (Alfredsen et al., 2018). Researchers at arctic regions have used UAVs to study methane emissions from arctic lakes (Lindgren et al., 2019) during early winter lake ice. UAV-mounted LiDAR (Light Detection and Ranging) can be used to measure snow depth from differencing coregistered lidar maps (one on bare terrain and one when snow covered), similar to those acquired from airborne and on-the-ground instruments (Deems et al., 2013) in terrestrial environments. While previous generations of UAVs have experienced limited flight time (maximum of 30–40 min), recent developments in this field have increased the flight duration, supporting longer field sampling campaigns over larger bodies of water. It is worth noting that the use of UAVs for research often requires pilot certifications, flights in some regions (e.g., near airports, cities, and some national parks) are restricted, and image processing can require significant technological expertise and time.

3.3. Process-Based Models

An increasing number of physical lake models incorporate ice development (Brown & Duguay, 2010; MacKay et al., 2009, 2017; Stepanenko et al., 2016) and a growing body of literature (Kirillin et al., 2012; Leppäranta, 2010) quantifies the physical processes that drive ice growth and decay. Such models provide reasonable and improving representations of ice phenology for lakes where they were calibrated, generally reporting ice-on or ice-off within several days of observations. However, significant challenges remain in relation to forecasting. The accurate prediction of input variables that drive ice growth and decay processes (e.g., cloud cover; wind speed; and snow compaction, depth, and density) remains limited, leading to errors in ice-on or ice-off dates on the order of weeks (Bernhardt et al., 2012; Bueche et al., 2017; MacKay et al., 2017; Magee & Wu, 2017; Shatwell et al., 2019; Su et al., 2019). Further, calibration for individual lakes is time consuming and presents challenges for scaling to multiple lakes across regional or higher spatial scales. Despite large uncertainties, modeling remains an important tool in large-scale applications. The recent development of remote sensing and autonomous in situ observations provide ice modeling with an opportunity for validation and improvement of modeling algorithms.





Figure 1. Spectrum of tools used to study lake ice dynamics and winter limnology in general. In situ measurements collected by (a) coring holes in the ice, (b) ground-penetrating radar, (c) shoreline observations by stationary wild-life cameras or human observations, and (d) drones create foundational data for understanding lake ice phenology within and across systems. High-frequency climate sensors (e) (e.g., flux towers), (f) spaceborne remote sensing instruments, (g) in situ experiments, and (h) process-based models can offer more nuanced perspectives of lake ice phenology, enabling researchers to expand observations and create a more holistic understanding of winter limnology.

Process-based models are well poised to address developing complexities in lake ice modeling toward a holistic lake ice model because of the foundations laid by previous, simplified ice dynamics models. Simulating heat transfer at the ice-water and ice-atmosphere interfaces presents a particular challenge for modeling lake ice cover. In freshwater lakes, the under-ice boundary layer is stably stratified with temperature and density increasing from the freezing point at the ice base downward. As such, under-ice stratification suppresses upward heat transfer into the ice layer. However, under-ice currents and internal waves, which historically have been considered negligible, can increase heating up to an order of magnitude, accelerating ice melt (Aslamov et al., 2014; Kirillin et al., 2018, 2020). In turn, stratification conditions in the lower atmosphere vary widely by season but are typically stable during the melting period. Similar to the fluxes at the ice base, snow depth and density on top of ice can alter heat fluxes between the ice surface and atmosphere (Zhang & Jeffries, 2000), which, if unaccounted for, can lead to potential sources of large errors. While snow effects on the vertical heat transport represent the major challenge for modeling of ice growth, the breakup period is characterized by complex transformations of the ice cover, including strong variations in the ice structure, porosity, and surface albedo, which are difficult to implement in process-based models. Aside from physical drivers, accurate model predictions of ice growth and decay can depend on the structural and physical properties of the ice itself (Leppäranta et al., 2019). Particularly during ice breakup, model inaccuracies can arise from lake- and season-specific spatial and temporal heterogeneities in the ice structure as the melt tends to occur from the edge to the center. Correct simulation of the partial ice coverage, especially in large lakes, requires multidimensional modeling approaches, including ice mechanical properties and drift (Leppäranta & Wang, 2008). In addition to heat transfer at the surface, heat exchange between sediments and the water column can influence ice cover, especially in snow-covered and high-latitude lakes where the level of under-ice solar radiation is low. Several approaches exist to model the water-sediment heat flux (Hamilton et al., 2018; Golosov & Kirillin, 2010; Tsay Ting-Kuei et al., 1992), demonstrating the importance of sediment heat storage for ice cover duration and under-ice water temperatures. Further, advances in model complexity such as the coupling of 3-D hydrodynamic lake models with ecosystem models have the potential to greatly advance our understanding of the role of ice cover in lake ecosystem dynamics (Oveisy et al., 2014; White et al., 2012).



Physical models have shown promise in modeling lake ice dynamics in specific systems; however, applying physical models across landscapes presents several challenges. The data required to drive these models are often unavailable for a large number of lakes or at the appropriate spatial scales. Additionally, landscape features that drive spatial variation of important model inputs (e.g., insolation, temperature, snow, wind speed) are challenging to estimate without direct local measurements. Data derived from weather and climate models or remote sensing may be insufficient to account for spatial differences at local scales. For example, local variations in snow accumulation driven by landscape features can be an important driver for ice decay and the date of ice out (Arp et al., 2013; Novikmec et al., 2013; Preston et al., 2016). Additionally, physical models are often developed for specific lake types (e.g., deep dimictic lakes, polymictic lakes, large or small lakes) or specific regions, limiting their widespread application across regions, let alone continental or global scales.

Due to challenges in widespread application of physical lake models, semiempirical statistical models have created opportunities to evaluate regional to global trends in ice phenology and their drivers (Sharma et al., 2019). These models often identify factors not referenced in physical lake models. Elevation and latitude, for example, covary with air temperature, solar insolation, and other factors (e.g., snow thickness, ice quality, topographic features), all of which influence ice phenology. Although the application of physical models to lakes at global scales is currently limited (Woolway & Merchant, 2019), using physically informed statistical approaches may be another tractable solution for improving prediction efforts (Read et al., 2019), thereby enabling more robust syntheses of large-scale trends in lake ice dynamics.

3.4. Experimental Winter Limnology

The combination of observations, modeling, and experiments is critical to obtain a mechanistic understanding of complex ecosystem responses to multiple stressors (e.g., Grice & Reeve, 1982; Stewart et al., 2013; Stibor et al., 2019), including responses to climate induced alterations of ice dynamics in lakes (Figure 1). For example, observed long-term changes in lake ice cover have been associated with shifts in timing of under-ice phytoplankton blooms and the onset of summer stratification (Katz et al., 2015). Unlike remote sensing and in situ observations, mesocosm experiments enable researchers to manipulate lake conditions and identify mechanisms for physical, chemical, and biological responses of variable ice dynamics. Such experiments thus have the potential to provide the ultimate test of ecological theory and offer parameter acquisition for physical models that are often unavailable for a large number of lakes or at the appropriate spatial scales. Continuous and precise high-resolution temperature measurements in experimental setups enable understanding heat transfer at the ice-water and ice-atmosphere interfaces, and thus stratification pattern during winter as well as ice melt affected by under-ice currents and internal waves (Aslamov et al., 2014; Kirillin et al., 2018). Whole ecosystem experiments under controlled conditions allow variables to be isolated or combined, thereby providing increased confidence in the causal links between organismal response and particular global change stressors such as warming and consequently changes in ice and snow coverage of lakes, rivers, and ocean bays (Berger et al., 2014).

Experimental winter limnology is new and challenging, but necessary to understand the effects of variable ice and winter conditions on lake plankton and benthic ecosystems, especially in times of climate change and global warming (Bertilsson et al., 2013). Ice coverage with or without snow impacts autotrophic organisms, as only 10 cm snow can reduce light penetration to levels insufficient for photosynthesis (Salmi & Salonen, 2016). Some of the pioneering overwintering experimental mesocosm studies span even several years to examine cross-seasonal connections of different winter conditions (Liboriussen et al., 2005) and may include simultaneous long-term experiments in several geographic regions (http://www.maraujolab. com/iberianponds/).

While in situ mesocosm experiments are powerful in their natural context, implementation during winter poses technological challenges (Block et al., 2019) and only recently such in situ experiments have been conducted (Hrycik & Stockwell, 2019). Advances in technology and new infrastructural developments such as ice-resistant mesocosm systems have created opportunities for experimental studies on lake ice dynamics. The Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB)-LakeLab in Lake Stechlin, Germany, is one of the few in situ lake mesocosm facilities where all-season experiments, including winter ice manipulations, have been performed (Giling et al., 2017, Berger, personal communication). A free-floating, ice-resistant mesocosm prototype was recently designed and constructed following the Kiel



Offshore Mesocosms for Ocean Simulations (KOSMOS) system (Riebesell et al., 2013) within the AQUAtic MesoCOSM (AQUACOSM) project and tested during winter in the northern Baltic Sea in order to examine physical requirements in sea ice during winter. The AQUACOSM prototype bears the potential to standardize aquatic research throughout all climatic zones, elevating environmental research to high comparability, thus enabling new insights into global patterns of ecosystem functioning in situ (www.aquacosm.eu; www. mesocosm.eu).

Tank systems in climate-controlled rooms are effective for isolating variables but have the challenge of demonstrating that results are relevant to natural systems. Technological advancements of indoor tank systems allow for testing of various factors affecting ice phenology, quality, forming and decay, through manipulations of air and water temperature, wind, radiation, snow cover, precipitation, mixing depth (heat storage), mixing and turbulence (wind induced), shading (light), hydrologic connectivity, and retention time. For example, experiments under different flow and ice conditions helped reveal the mechanics of formation and evolution of ice accumulation waves in rivers (Wang et al., 2019). Variables that drive ice growth and decay processes such as insolation, snow accumulation, cloud cover, wind speed, and snow compaction could be manipulated in experimental tank setups accompanied by high resolution temperature loggings and meteorological instrumentation. Finally, experimental facilities also provide a unique platform to support the development and intercalibration of sensors, coordinated testing of autonomous probes under harsh conditions, and validate remote sensing technology (Alfredsen et al., 2018). These research activities in experimental winter and all-season limnology in combination with interdisciplinary collaboration are crucial to cross-link and harmonize the research field of aquatic ecosystem science to tackle the challenges of a climatically and environmentally changing world.

4. The Value of Integrating Research Efforts

Each of the four discipline areas (in situ and remote sensing observations, process-based modeling, and experiments) have added to our understanding of lake ice dynamics (summarized in Figure 1). Increased cross-pollination between disciplines would leverage each discipline's unique strengths to increase our understanding of winter limnology across spatial and temporal scales. Currently, in cases where there is integration between the fields, experiments are the least well represented. Including experiments within the integration between all four disciplines will create an opportunity to further our understanding of winter limnology. We have identified four main modes by which integration of research methods will enhance research capability: validation, calibration, extending existing ice records, and developing statistically based lake ice models.

In situ observations and remote sensing have been used to validate each other and validate model estimates. For example, Zhang and Pavelsky (2019) used lake ice-on and ice-off dates collected by citizen scientists in Maine to validate their MODIS-derived lake ice phenology and then calibrated their ice presence algorithm with Landsat derived ice conditions. Doing so, they captured ice presence on lakes smaller than MODIS's spatial resolution that would normally rely entirely on in situ observation for ice phenology data. Šmejkalová et al. (2016) used in situ lake ice data from 25 lakes in Finland and Sweden to validate in situ observations, but remote sensing images provide significant advantages for large lakes where the full extent of ice cover may not be observable from shore.

Integrating in situ, remote sensing, process-based models, and experimental data can also be used to hindcast and extend discontinued in situ ice records or even establish records for lakes that have not been monitored. Latifovic and Pouliot (2007) developed the AVHRR-based lake ice algorithm to extend in situ records for 36 Canadian lakes and created new ice records for 6 lakes located in Canada's far north. Using the remotely sensed lake ice data to fill the gap of the in situ records, they were able to robustly estimate the trends in lake ice breakup dates.

Integrating data from multiple sources reveals patterns in lake ice dynamics and the lake's under-ice environment. Kheyrollah Pour et al. (2017) used snow depth estimates from a meteorologically driven lake ice model to improve the accuracy of ice thickness retrieval from MODIS's land surface temperature product. Improving accuracy in the quantification of lake surface temperature and ice condition is useful for winter limnology and is crucial for local to regional weather forecasting, due to the role of ice in regulating







evaporation and energy exchange. Kourzeneva (2014) showed that assimilating lake surface temperature and ice phenology observed in situ and via remote sensing can greatly improve the accuracy of lake surface temperature prediction in a weather forecasting model. Given its capacity to assess ice phenology at larger spatial scales, remote sensing provides a unique opportunity to understand the importance of lake morphologies and landscape factors that can modify meteorological inputs (e.g., wind speed and snow thickness) to physical models.

In order to realize the full potential of integrating research methods to expand our understanding of lake ice dynamics, researchers will need to overcome some common challenges. Integrating data sets from multiple sources requires transparent data collection procedures, detailed metadata, and researcher prudence. Figure 2 offers a case study of the potential power of leveraging multiple data sources for detailing lake ice phenology. While harmonizing data from multiple levels of aggregation (Figure 2) presents certain challenges, we argue that synthesizing data from in situ, process-based models, remote sensing, and experiments empowers researchers with the data to address new questions related to ice phenology and its associated ecological consequences. In the following sections, we detail how to confront each challenge in practice through data harmonization and utilization of multiple data types.





Figure 3. Ice duration spectrum ranging from permanent ice cover to year-round ice-free conditions. Persistent seasonal ice phenology has continuous ice punctuated by an ice-free season. The intermittent ice onset/ loss phenology has a period of continuous ice bracketed by periods of intermittent freeze/thaw cycles. The intermittent ice phenology has no continuous ice, only a period of intermittent freeze/thaw cycles. The ice-free phenology has continuous year-round open water.

4.1. Harmonizing Data from Disparate Sources

Efficiently merging data sets from different sources poses a significant challenge to integrating data for all interdisciplinary research, including when integrating remote sensing, physical based models, and in situ data. Merging data sets require two things: (1) the existence of a common identifiers across the data sets or the criteria based on which to match the data sets and (2) prudence from the researcher to aggregate the data as data sets may be collected at different temporal or spatial scales. Frequently, data sets meant for wide usage require common, unique identifiers (primary and foreign keys), pairing complementary rows of different data sets. For example, the HydroLAKES data set (Messager et al., 2016) contains a unique lake identifier ("Hylak_id"), which could be used to combine HydroLAKES with other data sets, provided that each lake maintains the same "Hylak_id." A wide variety of research questions and scales exist, which can complicate how data sets combine (i.e., their interoperability). For larger scale data sets, the HydroBASINS data product (Lehner & Grill, 2013) provides unique basin-level identifiers with standardized, meaningful IDs to denote the location and the Pfafstetter basin

level (the method used to classify basins in the HydroBASINS and HydroSHEDS databases) (Pfafstetter, 1989; Verdin & Verdin, 1999). HydroBASINS and HydroLAKES are complementary and amenable to accessing basin-level and lake-level processes, yet no shared identifier currently joins the two. As a result, merging the two data sets requires prudence from researchers, such as selecting spatial criteria to define how a lake should be assigned a complementary basin (i.e., spatial joining).

Researcher prudence is especially integral when harmonizing data sets with different spatial and temporal aggregations. Within-lake temperature measurements, for example, may be continuously collected at minute or hour time steps. Effectively merging temperature data with ice observations, however, may require researchers to aggregate temperature measurements to weekly, monthly, or seasonally averaged temperatures. Likewise, differences in spatial aggregations can create issues in interoperability of data sets. Climate data, for example, is usually aggregated within a grid structure, whereas in situ lake measurements may be aggregated at either a whole lake scale or sections within the lake via point measurements. Whether researchers focus intensively within individual systems or extensively across systems, prudence must be exercised so as to accurately harmonize disparate data sets with varying aggregation schemas.

Data sets will be most interoperable if measurements are collected, described, and stored in a standardized format between lakes and research projects. While few researchers now will advocate for a onesize-fits-all approach, having overlap in collection and reporting methods ensures that equivalent comparisons are made when otherwise interoperable data sets are joined together. Recent efforts to increase ease of interoperability have contributed to the rise of FAIR (Findable, Accessible, Interoperable, and Reproducible) data and metadata practices (Wilkinson et al., 2016). While metadata are often overlooked, detailed and standardized metadata are pivotal to describe how and why data were collected. These provide future users with insight for which situations data should and should not be applied. Finally, interoperability depends on data sets having either a common file format, or at least a shared understanding of how to convert one data format (e.g., raster) into one that can be harmonized with a corresponding data set in a different format (e.g., csv). Shared resources can be developed to convert between formats as needed, for example, GitHub repositories documenting scripts and programs that can be used to interchange aggregation levels/formats.

4.2. Moving Beyond Phenology

In addition to challenges to harmonizing disparate data sets, integrating data sources can be further complicated when considering whether data were collected in a categorical or continuous context. For example, lake ice phenology data are generally recorded as binary records corresponding to representative dates of ice formation (ice-on) and ice breakup (ice-off). Analyses of trends detected from these records have proved valuable to infer global long-term climatic change (Magnuson et al., 2000). Despite the valuable insights



these binary ice-on/off data have provided, they are insufficient to fully characterize lake ice regimes and their impact on lake processes. A spectrum of ice regimes is present in lakes from high latitude to temperate systems and high elevation to low elevation systems. This spectrum ranges from permanent ice cover to permanent ice-free conditions (Figure 3). In between are regimes of persistent seasonal ice cover, seasonal ice cover with variable periods of intermittent ice bracketing the onset and loss of persistent ice, and regimes with only a period of intermittent ice formation and loss. Incorporation of intermittent ice periods into analyses will likely change estimates of under-ice ecological and biogeochemical processes, an area receiving increased attention (Grosbois et al., 2017; Powers et al., 2017). Additionally, change in the degree of ice intermittency may be an important metric of climate change impacts on lakes. Remote sensing is now capable of characterizing the entire surface area of a lake to provide a continuous measure of ice cover (e.g., percent area cover), in addition to measuring the spatial heterogeneity of ice cover. These measurements allow for the analysis of ice intermittency, duration, and spatial coverage. Ultimately, a fuller consideration of ice regimes will allow us to begin to bridge lake studies across regions and provide a more nuanced understanding of the spatial and temporal heterogeneity of lake ice phenology and its effect on lake processes.

While the continual evolution of remote sensing creates opportunity for expanding the breadth of ice phenology research questions, its incorporation necessitates clearer definitions of ice-on and ice-off if previously collected data are to be comparable with continuous metrics. In particular, in situ researchers maintaining binary records of ice cover will likely need to supply threshold criteria for considering an ice onset. Conversely, researchers constructing binary ice cover records from continuous measurements likewise will need to report threshold criteria for considering a lake as ice covered. We advocate for the development of consistent protocols and standards that both academic researchers and citizen science groups could use that would better facilitate harmonization of the valuable data that are generated by both groups. These standards could then be used to develop online workshops and quizzes to ensure consistency among definitions and observers. For example, observers could pass an online quiz to ensure that there are universal definitions of "ice-on," "ice-off," and the intermittent freeze-thaw information as we move away from the binary system. This will allow the community to standardize methods across new observers and remove any biases. Similar to birding groups (https://www.aba.org, https://www.birdwatchersdigest.com/bwdsite/solve/ quizzes.php), a website could host monthly/weekly quizzes that asks participants how frozen a lake is from a photo, from 0% to 100%. While we cannot advocate for a universal solution for how best to collect, document, and operationalize continuous ice cover data, we hope to spark a conversation on the implementation of a universal language among subdisciplines and recommend that future researchers at least both (1) consider the challenge of defining ice-on/off when designing studies and (2) document criteria for ice-on/off thresholds explicitly through metadata.

4.3. The Power and Promise of Integrating Research Efforts

Integrating physical models, in situ measurements, and remote sensing data creates potential for extensive environmental data sets to offer synthetic insights at large scales. Remote sensing, in particular, has enabled robust global analyses of aquatic systems. Explaining variation detected from remote sensing, however, often necessitates additional place-based information to explicate causes for observed changes. For example, planktonic community and water chemistry data in tandem with fluid dynamics models and remote sensing can inform intralake heterogeneity of phytoplankton production (Hedger et al., 2002). In addition to enhancing intensive within-system study, remote sensing can measure common variables across systems, allowing for comparison of individual systems at regional, continental, and global scales. Similar to how the U.S. Environmental Protection Agency's National Lake Assessment program can be used to compare physical, chemical, and biological variables of individual lakes to continental-scale distributions (Pollard et al., 2018), it is conceivable that lake ice cover data from remote sensing techniques can be used to create distributions of ice duration. Local managers and monitoring programs could then compare ice duration of individual systems to regional, continental, and global ice durations to assess whether their system is representative or an outlier relative to other systems. Further, such an assessment would allow assessments of how landscape variables influence ice dynamics and phenology. As with combining highly voluminous, disparate data sets, merging and effectively manipulating remote sensing data with in situ measurements requires specialized skill sets, which may hinder research productivity. The overall benefits, however, offer promising opportunities for researchers interested in ice dynamics at multiple spatial and temporal scales.



4.4. Creating a Workforce

While the potential for innovative data collection, integration, and analysis have increased radically in recent decades, relatively few researchers are poised to fully take advantage of these opportunities. Most researchers do not receive any formal training in data-intensive research skills and many faculty do not feel prepared to incorporate such computational and data skills training into their courses and curricula (Hampton, Jones, et al., 2017; Strasser & Hampton, 2012). "Big data" needs once centered around hardware and technologies. Recent developments in high-performance, cloud-based computing have helped to remove such barriers. Google Earth Engine (GEE; Gorelick et al., 2017) is a notable example of a cloud-based computing platform that provides free access for researchers to conduct geostatistical and geospatial analysis. A recent national survey of biologists in the U.S. identified computational training as the prominent barrier to "big data" integration (Barone et al., 2017). An additional complexity for merging of remote sensing and in situ data is that even though researchers may focus on understanding water, they often come from different disciplines. Working across fields presents barriers associated with discipline-specific jargon, concepts, and even data formats and coding practices. Potential solutions may involve the creation of not only courses, workshops, and curricula focused on data skills training, but also those that intentionally convene researchers involved in satellite and in situ research who can decode differences among fields. One can imagine specialized workshops, such as slightly morphed Data and Software Carpentry workshops (https://carpentries.org/), to increase familiarity across in situ and remote sensing.

5. Conclusions

Global understanding of freshwater ice dynamics is still in its infancy, yet accumulating evidence suggests more rapid change than previously expected (Sharma et al., 2019), lending urgency to this field of research. Technological advances, in remote sensing and beyond, create unprecedented potential to fill gaps in knowledge that would otherwise be impossible or impractical using traditional in situ limnological methods. However, the knowledge gained through in situ limnological studies is the key to unlocking that potential. Physical limnological models provide the blueprint for both fields to focus on variables that not only are considered most important by physical limnologists but also of practical use in parameterizing models. In taking this approach, ideally limnology will have the opportunity to scale up beyond predictions for individual lakes and take a broader perspective on lake ice as it changes regionally and globally. In addition to scaling up from single lakes to regionally or globally distributed lakes, this approach, grounded in mechanistic understanding, should aid the difficult effort of downscaling from global to regional and individual ecosystems. Thus, we argue that the integration of data across scales is urgently needed to speed discovery and enhance our ability to make cross-scale and process-based predictions of ice dynamics and its effects on lake ecosystems.

As ice duration changes so do freeze-thaw events and ice thickness. These factors have both ecological and safety importance. Ice duration and ice quality are important for ecological dynamics, regulating light, water circulation, and gas exchange that are key to fundamental ecosystem processes throughout the year (Bertilsson et al., 2013; Hampton et al., 2015; Hampton, Galloway, et al., 2017; Salonen et al., 2009). The ecological implications of these drivers are broad and require intentional reviews, experiments, and monitoring that are beyond the scope of this paper. We call on researchers to investigate these impacts of fluctuating ice coverage as a driver for varying nutrient composition for phytoplankton as well as bloom timing (Adrian et al., 1999; Felip & Catalan, 2000; Grosbois et al., 2017), how new prolonged winter gas exchange may change gas cycling in ecosystems (Cavaliere & Baulch, 2018; Denfeld et al., 2018; Desai et al., 2009; Powers et al., 2017), and how changing ice growth rates will vary ion exclusion models for dissolved organic matter further influencing biogeochemical interactions (Belzile et al., 2000; Belzile et al., 2001).

Beyond potential impacts on ecosystem services, rapid changes in ice have additional, more direct effects on humans, particularly for regions in which ice fishing and over-ice transportation are common (Knoll et al., 2019). As we have detailed, multiple challenges can stymie nascent collaborations that attempt to take advantage of the opportunities to integrate disparate data types. However, emerging literature demonstrates an increasing interest in integrating across remote sensing, physical-based models, experimental, and in situ limnology, with growing recognition that we cannot answer the most critical questions about ice loss using



solely one approach. Remote sensing gives us spatial coverage and allows us to gather data in places too remote or dangerous for in situ work; such an advantage is particularly important for winter limnology where lakes that are safe and convenient during the summer are frequently dangerous and inaccessible in the winter. We suspect that ultimately integration of these research approaches will be key to working across scales and also will lead to more nuanced understanding of lake response to a full suite of ice characteristics rather than only a binary condition (ice-on/off). By presenting this framework, in which physical limnology models and experimental approaches can guide the discussion now growing between remote sensing researchers and limnologists, we hope to accelerate and broaden that dialog.

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