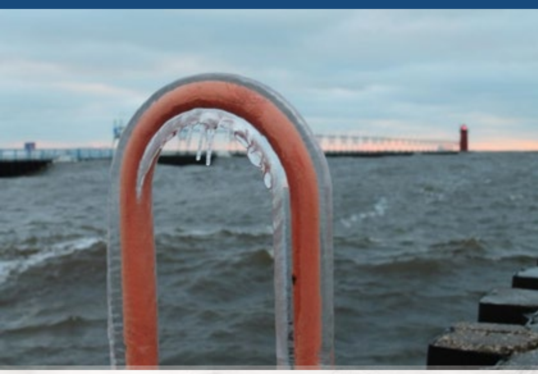
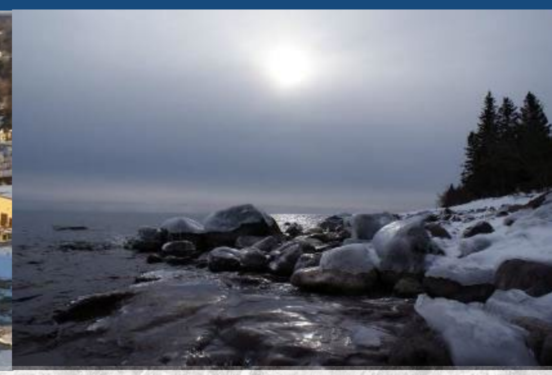
Great Lakes Winter Science Study

February 2025






Great Lakes Winter Science Study

Final Report

February 2025

Prepared for:

International Joint Commission
Science Advisory Board – Science Priorities Committee

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Disclaimer

Members of this project team participated in their professional expert capacities, but the conclusions, recommendations, findings, and opinions expressed in this report do not necessarily represent those of all members, their employers, affiliated organizations, or funders. Any use of product, company, or organization names or citation of references and resources is for information or descriptive purposes only and does not represent endorsement.

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Cover Images

Left: Ice-covered metal along shore of Lake Michigan. Credit: HippoPx

Center: Commercial shipping activities on the Great Lakes. Credit: Jeff Houser, MarineLink

Right: Winter landscape along the Lake Superior shoreline. Credit: standuppaddle

Background: Image of the Great Lakes showing ice beginning to build up around the shores of each lake and snow on the ground across virtually the entire scene. Credit: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC

Executive Summary

The International Joint Commission (IJC) Science Advisory Board (SAB) recognizes that winter is an understudied season in the Great Lakes Basin, even though some of the lakes are the fastest warming on the planet, indicating that the season is heavily impacted by climate change. Documented responses to climate change include increases in water temperature, loss of ice cover, increased runoff of bioavailable nutrients, and longer periods of seasonal thermal stratification. The lack of winter observations is due in large part to the logistical challenges of executing winter research, including the need for specialized equipment, personnel trained in the appropriate science and safety protocols, and coordination complexities. Additionally, lack of funding and a general lack of awareness about the importance of winter studies contribute to a lack of data. Management decisions about the fishery, shipping, power generation, drinking water, and weather forecasting are hampered by this lack of winter data in the Great Lakes.

In order to help address these gaps, the IJC SAB conducted a Winter Science Study from 2022 through 2024 with the following goals:

1. Survey the status of winter science, as it affects the quality of the waters of the Great Lakes and their watersheds, by:
   - Conducting a literature review, and
   - Cataloging existing datasets collected in the winter.
2. Assess existing research needs and proposed solutions by:
   - Acquiring expert opinions on needs through stakeholder interviews and expert workshops.
   - Prioritize science needs and determine infrastructure and personnel training required for winter science.
3. Provide recommendations on approaches to fulfill the needs for Great Lakes winter science.

The Winter Science Study consisted of regular project meetings with workgroup members, IJC staff, and contractors; a literature review; database compilation; interviews with subject matter experts; a series of three expert workshops; and preparation of this synthesis report. Important findings, gaps, and recommendations identified through this study are summarized here.

Findings

The study yielded several key findings about the status of winter science in the Great Lakes Basin, including the following:

- Winter science should be broadly understood as including the late fall and early spring shoulder seasons, in addition to astronomical or meteorological winter proper, because important physical and ecological transitions happen before and after winter.
- The Great Lakes experience high variability in winter conditions, but it may still be possible to determine climate-driven trends with sufficiently long datasets.

- Multiple databases that include Great Lakes winter data exist, but they can be challenging to identify and access.
- There is a need to study winter ice and under-ice ecological processes not just within the main bodies of lakes, but also in their tributaries and watersheds.
- Lack of integration across disciplinary silos may act as a barrier to developing a holistic understanding of the current and future changes in winter in the Great Lakes.
- Societal impacts from changing winter conditions in and around the lakes are large and include both positive and negative elements. Among these are increased duration of ice-free shipping; increased shoreline erosion due to decreased protection from winter storms by shore-fast ice; changing recruitment patterns in critical fishery species; on-ice transportation and safety impacts; economic effects from decreased availability of winter recreation activities, and changes in lake effect snowstorm intensity.

Gaps

Critical gaps and barriers to improved understanding of Great Lakes winter phenomena and the impacts of climate change, which could be addressed with additional research and resources, include:

- Limited under-ice observations of physical, chemical, and biological properties and processes in the lakes due to access, equipment, and instrumentation challenges.
- Uneven data coverage by lake based on size, consistency of ice cover, availability of support platforms (icebreakers, helicopters), and proximity to research institutions.
- Sparse subsurface data on changes in the lakes associated with fall and spring turnover.
- Low temporal and spatial resolution of ice properties, ice type, and ice phenology measurements limit advances in ice forecasting.
- Few measurements of over-lake fluxes of water (evaporation, condensation, precipitation, sublimation) and gasses in winter and shoulder seasons to inform water budgets, lake level forecasts, and lake effect precipitation forecasts.
- Insufficient access to icebreakers or ice-hardened vessels to support winter research.
- Lack of focus on advanced observational capabilities such as under-ice autonomous underwater vehicles to augment traditional vessel-based sampling platforms.
- Inadequate numbers of research staff and scientists who are trained in winter science methods and safety protocols, and limited winter rescue capabilities.
- Coordination challenges that exist between the United States and Canada, as well as across key federal, state/provincial, local/municipal, university, cultural, and non-governmental organizations participating in winter science activities.
- Cultural changes in winter recreation (ice skating, ice fishing, snowmobiling), community celebrations, and sense of place are significant with the loss of ice, yet the social, cultural, and economic impacts of these changes on Great Lakes communities are notably understudied.

Recommendations

Important actions and investments to address these winter science needs and priorities include:

- Within the next 18 months, the IJC Science Advisory Board should encourage the GLWQA Annex 10 (Science) to perform a binational analysis to articulate the specific winter data gaps that can be met by monitoring and that are limiting policy development and lake management decision making (e.g., Annex 2).
- Promote the development of a coordinated binational plan by 2027 to improve modeling and forecasting of ice properties for both short-term and long-term time horizons through targeted winter data validation.
- Improve winter data collection through the support of the nascent Great Lakes Winter (GLWin) network or a similar coordination group to improve winter science monitoring coordination and infrastructure (both offshore and shore-based) to lower the barriers to winter science monitoring participation.
- Encourage improved understanding of watershed linkages as well as the role of winter in the basin-wide delivery of ecosystem services by requesting that a short scoping document be developed collaboratively by 2027 among all IJC advisory boards with Great Lakes roles.
- Charge the lead coordinating agencies of the Cooperative Science and Monitoring Initiative (CSMI) with developing guidance language and programmatic approaches to include all seasons and fill the gaps between CSMI sampling years by securing access to ice-breaking, ice-hardened, and winter-capable vessels to support science activities on one lake and associated connecting waters per year, in conjunction with CSMI priorities.
- Request that federal agencies develop an architecture by 2027 for a master, open-access, winter science database that leverages artificial intelligence (AI) and other advanced data analysis approaches to consolidate or link information from existing databases and make collected winter data more consistent with F.A.I.R. principles (findable, accessible, interoperable, and reusable), while ensuring data quality standards are met.
- Formally communicate the IJC's endorsement for building winter science capacity by lowering barriers to entry and emphasizing early career training, internships, outreach, and inclusive hiring to the governments of Canada and the U.S. and federal science funding agencies, as well as major research institutions in the region, as part of the implementation plan for the Great Lakes Science Strategy.

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Acronyms

Acoustic Doppler Current Profiler	ADCP
Asian-Bering-North American	ABNA
Autonomous System for Lake Ice Monitoring	ASLIM
Autonomous Underwater Vehicle	AUV
Artificial Intelligence	AI
Cooperative Science and Monitoring Initiative	CSMI
Degrees Celsius	°C
Eastern Pacific Oscillation	EPO
El Niño–Southern Oscillation	ENSO
Findable, Accessible, Interoperable, and Reusable	F.A.I.R.
Great Lakes Water Quality Agreement	GLWQA
Ground-Penetrating Radar	GPR
International Joint Commission	IJC
Machine Learning	ML
National Aeronautics and Space Administration	NASA
NASA Unified Weather Research and Forecasting	NU-WRF
National Oceanic and Atmospheric Administration (US)	NOAA
National Science Foundation	NSF
Natural Sciences and Engineering Research Council of Canada	NSERC
North Atlantic Oscillation	NAO
Pacific–North American	PNA
Quality Assurance	QA
Quality Control	QC
Great Lakes Science Advisory Board	SAB
Specific, measurable, achievable, relevant, and time-bound	SMART
Soluble Reactive Phosphorus	SRP
Soil and Water Assessment Tool	SWAT
Total Phosphorus	TP
Tropical–Northern Hemisphere	TNH
United States Coast Guard	USCG
Variable Infiltration Capacity	VIC

1. Introduction

The International Joint Commission (IJC) Science Advisory Board (SAB) conducted a Winter Science Study seeking to document the state of winter science in the Great Lakes and develop recommendations to address research priorities that will help improve understanding of the impacts of climate change on winter and on the chemical, physical, and biological characteristics and quality of the waters of the Great Lakes. Climate change has been identified as one of the most important problems facing humanity today. The 2021 Intergovernmental Panel on Climate Change report emphasized the importance of limiting global temperature increases below 1.5 degrees Celsius (°C) within the next decade to reduce catastrophic impacts on ecosystems and society (IPCC, 2018). Responses of lakes to climate change are being documented, including increases in water temperature, loss of ice cover, alterations in the distribution of freshwater fish, and changes in thermal stratification and dissolved oxygen concentrations. Some of the largest lakes in the world are most vulnerable to losing ice cover and are warming at the fastest rates, in some cases as much as 1°C per decade.

The IJC SAB recognizes that winter is an overlooked season across the Great Lakes -St. Lawrence River watershed system, even though it is the season that is altered the most by the impacts of climate change on lake temperature and resulting impacts on ice cover and winter precipitation. This is partly due to the challenges of collecting winter observations, including the requirements for specialized equipment, highly trained personnel, and coordinated approaches. As a result, management decisions are often based on data and models that are primarily calibrated to warm season and ice-free observations. The topic of winter science in the Great Lakes-St. Lawrence River system involves multiple annexes of the Great Lakes Water Quality Agreement (GLWQA), but winter[1] is not currently incorporated into any of the annexes explicitly.

The SAB has undertaken this project to better inform the IJC about the gaps that exist in the understanding of winter in the Great Lakes and the impacts of climate change; to document research priorities and proposed solutions to improve winter science; and to provide recommendations on meeting these winter science needs and priorities. The emphasis placed on winter science in this study highlights growing interest across the IJC on the potential effects of climate change on winter across the region, and the way these effects may interact with climatic conditions throughout the year. As an example, the SAB met with the IJC Rainy-Lake of the Woods Board during the course of the study, and the Board raised concerns about the lack of winter data available for the watershed. The Lake of the Woods experienced its worst algal bloom on record during the summer of 2024, preceded by the lowest ice cover ever recorded in the winter of 2024. Greater emphasis on winter studies and data collection would support the Board in understanding possible correlations between algal blooms and ice cover to better prepare for future climate change scenarios.

[1] Spring is the only season mentioned in the 2012 GLWQA; Annex 4.

Major activities conducted under the project included the following:

- Regular meetings with the project Workgroup were held to provide progress updates on the status of the project including the progress to date, challenges, proposed solutions to challenges, and any impacts to work and schedule due to challenges encountered.
- A literature review (completed March 2023, but periodically updated with suggested literature from the workgroup and workshop participants) to uncover new knowledge published since the completion of other recent literature reviews and workshops and identify persistent knowledge gaps and barriers to winter science as it impacts the Laurentian Great Lakes.
- A survey of publicly available databases containing information relevant to winter and winter science in the Great Lakes (completed March 2023).
- Interviews with stakeholders and rights holders, agency personnel, academic researchers, and members of shipping and other industries in the Great Lakes (completed April 2023).
- Three expert workshops designed to identify winter science gaps, needs, and science priorities; identify, describe, and assess research needs related to infrastructure, training, inter-agency coordination, and meeting science priorities; and winter science priorities with existing and future capacities and to develop recommendations for sustainably meeting winter science needs. Workshop #1 was completed in May 2023, Workshop #2 was completed in September 2023, and Workshop #3 was completed in February 2024. The findings for each workshop were synthesized into separate 20–40-page written reports to summarize the workshop outputs and to assess the completion of the tasks identified for them. Further details regarding these workshops can be found in Section 2.4.

The following sections provide summaries of key findings and outcomes from the above-listed project activities.

2. Literature Review

Following the growing understanding and widespread recognition over recent decades that climate warming is impacting winter limnology, numerous winter limnology summits and working groups have been formed. Notable examples include the CIGLR-funded 2019 University of Minnesota Duluth Summit: Winter Limnology on the Great Lakes – Prospects and Research Needs (which resulted in Ozersky et al. 2021), the International Society of Limnology Winter Limnology Working Group, the Global Lake Ecological Observatory Network Winter Limnology Workgroup, and the 2019 Chapman Conference on Winter Limnology in a Changing World, from which came the publication of an 18-paper special collection on winter science published in *JGR: Biogeosciences* (Sadro & Xenopoulos, 2022; Winter Limnology in a Changing World, 2022). A nascent community of practice known as GLWin has also coordinated sampling events across the Great Lakes basin (Pu et al., 2025) and provided a forum for the exchange of information and research results. The US National Science Foundation has also supported a new Winter Limnology Network beginning in 2024 (https://winter-ice.github.io/winter-ice/ ; Hampton et al., 2024) that is not specific to the Great Lakes but does include several Great Lakes researchers.

2.1 Definition of "Winter"

Winter, as it pertains to the Great Lakes, has many criteria by which it can be defined: the period between the winter solstice and spring equinox, the period when average daily air temperatures are below freezing, the period of appreciable ice cover on the lakes, or the period of inverse stratification within the lakes (Ozersky et al., 2021). Ice in the Great Lakes region is widely regarded as a "master variable" that regulates many of the lakes' wintertime physical, biogeochemical, and biological processes (Ozersky et al., 2021). With increasing variability in weather, lake heat content, and ice formation on the Great Lakes, wintertime in this region can no longer be consistently characterized by the presence of ice. To best characterize changes occurring during winter and understand how they are impacting lake limnology on seasonal and annual scales, for this review, winter was defined by calendar dates determined by seasonal photoperiod (December 21 to March 20). This definition is not only applicable across multiple studies but also provides transferable benchmarks by which interannual shifts in winter phenomena and processes can be evaluated, as well as changes occurring in the fall (November-December) and spring (March-April) shoulder seasons.

2.2 Literature Review Methodology

Interest and participation in winter science have been steadily gaining momentum; these conferences, workshops, and previous literature reviews have put forth extensive efforts to summarize what is currently known of winter science, and have also revealed an extensive suite of knowledge gaps pertaining to winter limnology (Agbeti & Smol, 1995; Block et al., 2019; Hampton et al., 2017; Jansen et al., 2021; Ozersky et al., 2021; Powers & Hampton, 2016). While by no means a complete list of the knowledge gaps identified to date, several such examples include:

- Ice phenology and snow and ice properties, including thickness, clarity and spatial and temporal variance
- Ice vs ice-free physical limnology, thermal stratification, heat content, and mixing regimes
- Winter hydrodynamics, including vertical mixing and horizontal circulation patterns
- Impacts of winter waves on ice properties and coastal erosion
- Winter light conditions under ice and ice-free conditions
- Quantification of differences in primary productivity between winter and summer
- Wintertime respiration
- Phytoplankton composition and nutritional quality in winter
- Winter zooplankton community composition
- Energy flows through winter food webs
- The concentration, transformation, and transportation of key carbon, nutrient, and biologically important constituents in winter
- Overwintering strategies for key aquatic species
- Impacts of changing ice regimes on recruitment success of wintertime spawners
- Influence of ice on greenhouse and biogenic gas production
- Links between ice-cover dynamics, microbial ecology, and below-ice physical processes, and their implications for redox potential at the sediment-water boundary
- Wintertime oxygen depletion and winterkill events
- Implications of coupled under-ice physical and biological processes on annual lake organisms and biogeochemistry
- Quality and timing of wintertime water, nutrient, and sediment inflows from watersheds
- Impacts of lake-atmosphere-land linkages on local winter climate under shifting snow-ice regimes, including the potential for increased lake-effect snow from ice-free lakes
- Winter sampling equipment, methodologies, and analysis procedures
- Winter-related socioeconomic and cultural services such as recreation, shipping, over-ice transportation, community identity, and sense of place

The intent of the literature review conducted for the Winter Science Study was not to be an extensive synthesis of all winter limnological information collected to date. Rather, the focus of this review was to uncover new knowledge that has been published since these previous literature reviews were conducted, specifically pertaining to winter science as it impacts the Laurentian Great Lakes and identify persistent knowledge gaps that remain. As such, emphasis in this review was put on relatively recent literature (within the last three to four years) while still acknowledging the fundamental contributions to this field put forth by the foundational research and literature syntheses that have come before. This synthesis of new information can then be combined with the previously developed body of winter limnology work to identify which remaining knowledge gaps are the most pressing to address, as well as inform where and how resources could be allocated within the Great Lakes region to close these gaps.

Papers were identified using the Google Scholar search engine and various combinations of search terms and phrases including winter, limnology, winter science, biology, water quality, watershed, ice, snow, Laurentian Great Lakes, Great Lakes, shoulder seasons, and shipping. Potential papers identified through this search were reviewed for applicability to water quality in the Great Lakes and connecting waters, as defined in the GLWQA (IJC, 2012). Studies focusing on lakes or watersheds other than the Laurentian Great Lakes were included in this review if the knowledge gained from them was applicable to the Great Lakes region. Of this initial group, 151 articles were found to have relevance to this project's scope and are included in the synthesis below. Table 1 provides a summary by lake of the number of articles reviewed.

Resources were reviewed for information in the following categories pertaining to winter science: physical properties, chemistry and biogeochemical cycles, biology, modeling and forecasting, and socioeconomic and cultural services. The synthesis below summarizes key information pertaining to each category included in the review, emphasizing key informational gaps identified by the literature.

Table 1. Summary of articles reviewed by lake.

Lake Studied*	Number of Articles Reviewed
Superior	63
Michigan	52
Huron	43
Erie	56
Ontario	53
Other Lakes and Rivers	50

* Several studies included more than one lake and were counted once for each lake studied.

Figure 1 summarizes the number of studies reviewed and the lake or watershed on which they focused. Note that several studies focused on more than one lake.

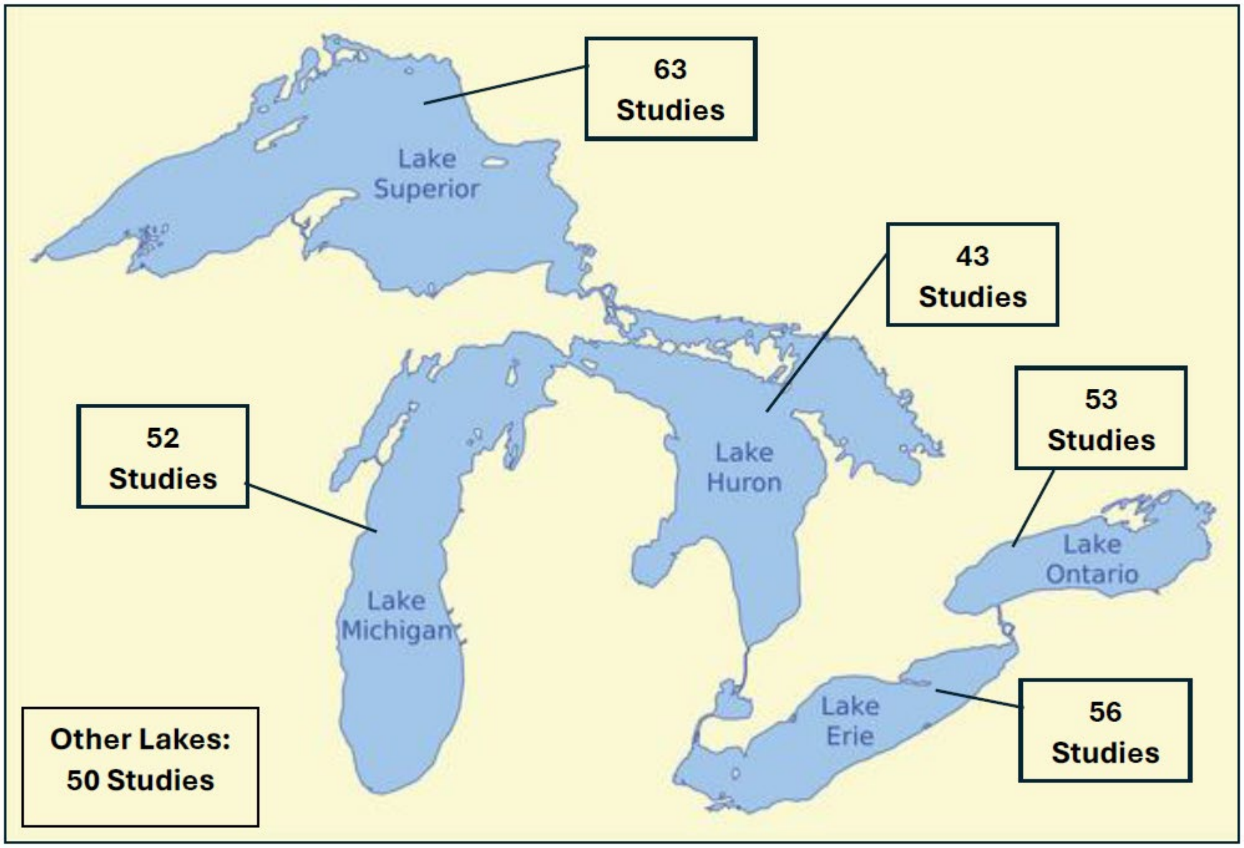


Figure 1: Number of studies included in the literature review related to each lake.

Many other papers, including several recent publications, were recommended by reviewers for inclusion after completion of this literature review (see Appendix A). While these papers are not included in the counts shown in Table 1 and Figure 1, they are cited in the following sections.

2.3 Findings

The region bordering the Great Lakes is the fastest-warming region in the United States, and average surface temperatures in Canada are warming twice as fast as the rest of the world on average (Lam & Dokoska, 2022). The greatest future temperature increases for the Great Lakes basin are anticipated to occur in the fall and winter seasons, and critical changes to the winter season are expected in this region as a result (Lam & Dokoska, 2022). Much progress has been recently made in understanding the physical, biogeochemical, and biological processes that drive aquatic ecosystems in winter. This improved understanding, however, has spurred a multitude of new questions regarding the nature of freshwater lakes in winter, particularly at the intersections of lake hydrodynamics, biogeochemistry, and biology (Jansen et al., 2021). There are many challenges associated with integrating spatially and temporally divergent datasets needed to address these knowledge gaps. While collaborations among fields historically involved in ice-related research can be leveraged to overcome these challenges (Sharma et al., 2020), increased efforts to produce data sets focused on ecological responses to changes in winter are needed (Cotner et al., 2022), including increased in-situ winter measurements across a multitude of physical, chemical, and biological parameters. Further, while modeling capabilities have advanced greatly, improvements are still needed to increase model accuracy, resolution, and forecasting abilities. Finally, the environmental patterns that govern winter limnology, hydrology, biology, chemistry, and ecology are changing rapidly throughout the Great Lakes. Advancements in in-situ lake observations, remotely sensed measurements, coupled lake and climate models, and socioeconomic evaluations are needed to better understand how these changes will affect Great Lakes water quality in the future as well as the people who rely on it. Table 2 summarizes the topics and themes identified in this literature.

Table 2: Topics and themes identified in literature review.

Topic	Topic Themes
Physical Properties (101 Studies)	Ice patterns, shoulder seasons, and ecological memory, coastal processes, temperature, hydrological cycle, light exposure.
Biogeochemistry (46 Studies)	Carbon, CO_2, and CH_4 flux, nutrients, oxygen, salt, and other solutes.
Biology (53 Studies)	Fish, phytoplankton, zooplankton, microbes, and food web connections.
Remote Sensing, Modeling, and Forecasting (45 Studies)	Teleconnections and oscillations, ice and heat, hydrological modeling, lake effect snow.
Socioeconomics and Cultural Services (28 Studies)	Ecosystem services, shipping, human wellbeing.

Each of these topics is briefly discussed below. Additionally, of the studies reviewed, only 31 provided the full set of data used in the study.

2.4 Physical Properties

Regarding physical properties, information across five general themes emerged from the recent literature: ice patterns, coastal processes, temperature, hydrological cycle, and light exposure. While much focus has been placed on understanding the impacts of a changing climate on the Great Lakes, understanding the physical dynamics of the waters of the Great Lakes in wintertime is also essential as nearshore water quality is heavily influenced by both physical and climate drivers (Song et al., 2022).

2.4.1 Ice Patterns, Shoulder Seasons, and Ecological Memory

Foundational work from Magnuson et al. (2000) looked at 39 historical datasets of freeze and ice break-up dates from rivers and streams across the northern hemisphere from 1846 to 1995. This study found that freeze dates on average were delayed 5.8 days per 100 years, ice break-up dates on average occurred 6.5 days earlier per 100 years, and interannual variability in both dates has increased since 1950. This study revealed that warming trends and resulting ice cover changes have been occurring across the northern hemisphere since 1850 and may be further influenced by more recent human-induced climate change (Magnuson et al., 2000). One Great Lakes-specific study (Assel, 2005) provided a 30-winter benchmark of average ice cover, ice-on, ice-off, and ice duration for each of the Great Lakes between 1973 and 2002. This work developed an ice cycle classification scheme for ice severity (mild, typical, and severe), and observed that most severe ice cycles occurred earlier in the data period, while half of the mild ice cycles occurred in the last 5 years of the data period. Furthermore, this study found higher average ice cover on Lakes Superior, Erie, and Huron relative to Lakes Michigan and Ontario (Assel, 2005). Also see Fujisaki-Manome et al. (2024) for a more recent mean air temperature dataset from 1897 – 2023, for Great Lakes weather stations. Cumulative ice cover datasets are maintained by the National Oceanic and Atmospheric Administration (NOAA) (Figure 2).

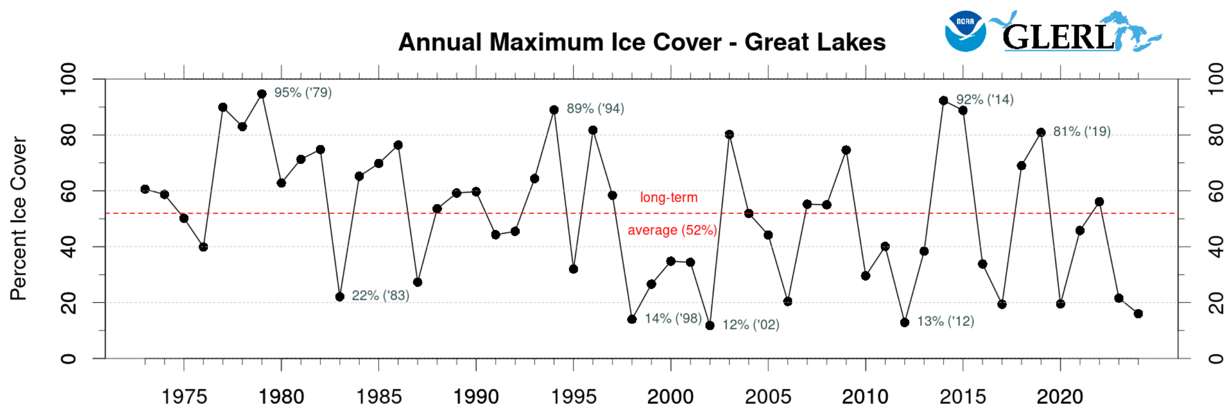


Figure 2: Great Lakes annual maximum ice cover from 1973-2024. Graph from NOAA-GLERL.

Recent literature about ice phenology, or the timing of ice formation and loss throughout the year, emphasized that lake temperature responses to alterations in ice phenology remain a significant research gap (Li et al., 2022). Note that the presence or absence of ice cover is easy to determine, but it may be less important for some purposes than other properties such as ice thickness and quality, which are much more difficult to determine. Imrit & Sharma (2021) investigated ice cover data starting as early as 1810 across 18 northern hemisphere lakes and found that ice duration across the region is generally shortening as ice-on is happening later, whereas ice-off is happening earlier (see also: Basu et al., 2024).This study also discovered that these changes in ice duration are accelerating and that ice phenological breakpoints were explained by warmer air temperatures associated with a changing climate. Similarly, Sharma et al. (2021) investigated the ice phenology records of 60 lakes throughout the northern hemisphere, concluding that over the last 100 to 200 years, ice duration was on average 17 days shorter per century resulting from ice-on that was 11 days later, and ice-off that was 7 days earlier. This work highlighted the urgent need to understand the implications of ice loss on both lake ecology and economy in regions such as the Great Lakes.

Higgins et al. (2021) studied the relationship between ice phenology and air temperature for small boreal lakes in Ontario, Canada between 1970 and 2019, concluding that ice cover duration decreased significantly by a rate of four days per decade, that the duration of ice cover became more variable over time, and that lake size affected the timing of ice formation and decay but did not influence the rate of change over time. Dugan (2021) investigated whether “lakes have ecological memory of ice-off in the subsequent summer” and concluded that lakes that experience the longest winters will likely undergo the largest changes in the spring and summer ecosystem dynamics. Hampton et al. (2017) also examined the connectivity between winter and summer ecology and seasonal differences and connections and found that winter influenced the subsequent summer for some nutrient variables and zooplankton biomass. In addition to ice phenology, direct measurements of deep-water, non-coastal ice characteristics are urgently needed throughout the Great Lakes. One such study of Lake Superior used moored, subsurface acoustic Doppler current profilers (ADCP) to assess ice drift and velocity and observed sensor vertical displacements suggesting the presence of ice keels greater than 13 meters deep in the high-ice winter of 2014 (Titze & Austin, 2016). These observations of heterogeneous ice thickness highlight the need to better understand how ice characteristics are impacted by changing climate, particularly as opportunities to collect such data are dwindling with the increasing frequency of ice-free years (Ozersky et al., 2021; Titze & Austin, 2016). Thellman et al. (2021) underscored the limited amount of river ice observations, and how this paucity of information on ice-covered river ecosystems is inhibiting the understanding of how changes in river ice cover are not only altering rivers but also their connected network of ecosystems. This article emphasized the importance of studying winter ice and under-ice ecological processes not just within the main bodies of lakes, but also in their connected rivers and watersheds, all the way to their headwaters. Overall, recent literature concerning changing ice patterns generally agrees that ice duration across the Great Lakes region has been shortening over the last century, and particularly since the early 1970s, with later ice-on and earlier ice-off dates. However, more ice observations within the Great Lakes and their river tributaries are needed to understand how these changes will impact each of the lakes, as well as the watershed ecosystems that feed them.

2.4.2 Coastal Processes: Water Levels, Waves, Erosion

Two studies on coastal processes were identified, both of which investigated how the loss of winter shore-fast ice is impacting the erosion and evolution of Great Lakes coastlines. Theuerkauf et al. (2021) conducted a yearlong drone-based study of the Lake Michigan western shoreline and concluded that anomalously high lake levels and a lack of shore-fast ice contributed to the high erosion rates within the sandy beach-dune system. This study highlighted the need to understand how the geomorphic impacts of storms may change because of ice-free winters to better inform future coastal management actions. Similarly, Hartley et al. (2020) also highlighted that little is known about the role of winter shore ice in coastal erosion and transport processes and that this lack of understanding is hindering the accurate modeling of coastal evolution processes throughout the Great Lakes. These studies both recognized the coastal protection services shore-fast ice can provide from winter storms and underscored how annual erosion dynamics in some coastal regions of the Great Lakes may be significantly altered if this ice ceases to form. Recent studies have focused on sediment entrainment in ice in the Great Lakes (Dodge et al., 2022, 2024).

2.4.3 Temperature, Heat Flux, and Thermal Structure

Winter temperature data is revealing warming trends across North America; average winter temperatures across Canada indicate that winters have warmed by 3.3°C over the past 75 years (Environment and Climate Change Canada, 2022). Much of the physical limnology data available about thermal structure are taken at or near the surface, were collected on small lakes, and have been collected during milder, ice-free seasons resulting in few published winter thermal structure datasets for the larger Great Lakes (Titze & Austin, 2014). Currently, Lakes Michigan and Superior are the only Great Lakes for which depth-resolved temperature measurements are available year-round. Thus, continuous wintertime observations of lake thermal structure remain a critical data gap (Ozersky et al., 2021). Titze & Austin (2014) analyzed the annual thermal structure of Lake Superior from 2005 and 2013 and found a significant contrast between colder, high-ice winters in which the lake experienced a strong negative stratification, as compared to warmer winters where weaker stratification was observed. Because ice cover inhibits heat flux both into and out of the lake, ice cover and timing influence end-of-winter heat content, which in turn influences the onset of summer stratification (Titze & Austin, 2014). Similarly, there have been few studies of the radiatively driven convective processes associated with spring lake turnover, specifically in the deep Great Lakes, indicating a significant portion of the year for which there is little known about the changing heat content and mixing dynamics. One such study utilized an autonomous glider and a set of sensor-equipped mooring stations to characterize the spatial and temporal scales of radiatively driven convection in Lake Superior. Glider-based phytoplankton and temperature observations suggested the development of vertical convective chimneys associated with this mixing phenomenon (Austin, 2019). This body of work highlights the need to determine the abundance and lateral scale of these convective cells to better understand their contributions to lake turnover and the resulting seasonal redistribution of biogeochemical resources throughout the lake (Austin et al., 2022; Austin, 2019). Further, more coupled temperature and current datasets, such as that compiled for Lake Superior (Austin & Elmer, 2022) are needed throughout each of the Great Lakes.

Several recently published lake heat studies sought to address this research gap in lake heat flux and thermal structure, focusing on air and surface water temperature, total lake heat content, and thermal lake stratification. Anderson et al. (2021) analyzed three decades of subsurface temperature data from Lake Michigan and identified a cascade of winter thermal changes occurring within it. This study concluded that winter deep water temperatures are rising because of shorter winter seasons, which is also contributing to an earlier onset of summer lake stratification. Fichot et al. (2019) concluded that while general lake overturning patterns have long been realized, specific observations of timing, duration, spatial-temporal progression, and seasonal and interannual variability are lacking and therefore inhibiting the understanding of climate-driven changes in lake thermal dynamics. Related to lake overturning, surface water warming in the Great Lakes was found to be reducing the annual contributions of convective water mixing toward nutrient cycling, primary production, and benthic-pelagic coupling (Cannon et al., 2021). Ye et al. (2019) posed the question of how these changes in lake heat content and mixing will impact aquatic ecosystems' phytoplankton, bacterioplankton, and zooplankton populations, as well as metabolic processes. This study noted that lake heat content changes have not yet been accurately estimated throughout the Great Lakes due to a lack of in-situ direct observations. Ye et al.'s (2019) study, which focused primarily on Lake Superior, also pointed out that the effects of ice albedo on surface heat flux, ice mass, and thermal structure are major research gaps within this lake (Ye et al., 2019).

Woolway et al. (2021) investigated the spatial extent of lake heatwaves and found them to be sensitive to variations in ice cover and stratification onset timing, highlighting the need to study how increased heatwave occurrences will impact aquatic species throughout the Great Lakes. Lastly, Casson et al. (2019) introduced the concept of winter weather whiplash to describe the rapid and forceful oscillations in winter weather, such as extremely warm and rainy weather in the depths of winter, or extremely cold and snowy winter conditions during the fall or spring shoulder seasons. Emphasizing the extreme biophysical impacts these whiplash events have, this paper also highlighted that the mismatch in dataset spatial and temporal resolution, coupled with the lack of event-specific socioeconomic data available, make it challenging to assess the winter whiplash event impacts on coupled human-natural systems. Overall, the thermal dynamics of the Great Lakes are changing, from the benthos to the surface, and the literature calls for more wintertime, lake-specific measurements to better understand the chemical, biological, and physical consequences of these changes across each of the Great Lakes. Other papers (García-Carreras and Reuman, 2011; Núñez-Riboni et al., 2023; Vasseur et al. 2014; Zhang et al., 2021) have investigated the relationship between temperature and precipitation, and have found that these variables are becoming decoupled, leading to increased variability. As a result, weather patterns are likely to become less predictable and more prone to extreme highs and lows.

2.4.4 Hydrological Cycle: Snow, Rain, and Evaporation, Groundwater

The Great Lakes hydrologic cycle is also changing, specifically concerning the timing and amount of water the basin receives in the wintertime. Over-lake precipitation is expected to increase for all lakes, especially in the fall, winter, and spring seasons. Modeled projections of future climate scenarios anticipate more precipitation falling as rain rather than snow, and that Lake Superior and Lake Ontario will experience the most significant increase in over-lake precipitation (Lam & Dokoska, 2022). Shao et al. (2020) utilized eddy covariance towers to assess changes in evaporation trends and drivers in Lake Erie, concluding that lake-specific heat storage and spatial heterogeneity need to be considered within predictive models for seasonal dynamics of lake evaporation to be accurately simulated. Kulie et al. (2021) studied snowfall regimes in the northern Great Lakes from Michigan's Upper Peninsula near Marquette and concluded that the area, as well as the regimes by which it receives snow, are relatively understudied as compared to the rest of the Great Lakes region. In Michigan's lower peninsula, Meng et al. (2021) statistically evaluated snowfall trends from 1932 to 2015 and found that annual total snowfall generally increased throughout this period, with regional air temperature found to be the dominant influencing factor, and most snowfall occurring before ice cover peaks in February/March.

Warming winters throughout the United States are changing the volume and timing of winter runoff. Conditions that have historically limited winter runoff, including consistently cold, snowpack-insulated soils with no winter melt or rain-on-snow events, are being replaced with inconsistent temperatures, lower snowfall totals, and frequent freeze-thaw as well as rain-on-snow events. The assumption held across historically snow-covered regions, such as the Great Lakes, of low wintertime discharge no longer holds, as midwinter snowmelt, rain-on-snow, and winter rainfall onto frozen or already saturated soils can drive substantial winter flood events (Seybold et al., 2022). Hrycik et al. (2021) investigated changes in winter-spring runoff timing, duration, and volume using 70 years of stream gauge data. This study concluded that runoff regimes have changed across the Great Lakes, with earlier runoff occurring in each of the lakes except for Lake Erie, longer than expected winter-spring runoff throughout the entire basin, and a higher total runoff volume for all lakes except Lake Superior. These results emphasized the need to better understand how changes in runoff regimes may influence changes in nutrient loading, mixing, and primary production (Hrycik et al., 2021; Seybold et al., 2022). Results of hydrologic modeling experiments conducted by Byun & Hamlet (2018) indicate that for many snowmelt-dominated watersheds in the midwestern U.S., a 10-30% increase in total precipitation and precipitation falling as rainfall in the winter and spring is expected by 2080. The model results also predicted a shift toward earlier peak flows resulting from maximum snow-water equivalent trends throughout the region. Motiee & McBean (2017) used three global circulation models to assess climate change impacts on groundwater recharge in a Canadian river basin within the Lake Erie watershed and estimated a net increase in groundwater recharge by an average of 10% by 2050. This study underscored the importance of year-round temperature and precipitation observations, as well as soil type observations, for making accurate groundwater recharge projections. Lastly, Xu et al. (2021) characterized monthly groundwater interactions across each of the Great Lakes using a fully integrated surface water–groundwater model and indicated that the ability to accurately model groundwater-lake interactions is currently limited by a lack of hydro-stratigraphic and hydraulic property observations at the basin-scale.

2.4.5 Light Exposure

A scarcity of recent information on lake ice optical properties was identified; however, the literature called for more studies to be conducted on the effects of snow-on-ice on photosynthetically active light radiation exposure and temperature changes, how these changes influence lake metabolism, and how adaptability to light levels influences the structure and distribution of under-ice autotrophs (Jansen et al., 2021). Older Great Lakes studies on this topic include Bolsenga et al. (1996). Light transmission data are also available through Pu et al. (2025).

Bramburger et al. (2023) reported on underwater light and productivity under snow and ice cover in inland lakes in Minnesota. Finally, Culpepper et al. (2024) investigated the effects of changing ice quality on below-ice productivity; preliminary evidence suggests decreasing black ice and increasing white ice, which will reduce the amount of light reaching the water column, minimizing primary production, and altering community composition.

2.5 Biogeochemistry

Tightly coupled with the Great Lakes' physical characteristics is its chemistry and biology. Recent literature focused primarily on lake biogeochemical dynamics pertaining to carbon, nutrients, oxygen, and salt concentrations, and understanding how winter influences these fluxes. For example, there is evidence that some biogeochemical cycles are active in the winter under ice (Powers et al., 2017). Basin-wide synoptic sampling in February 2022 included analysis of multiple biogeochemical parameters, among other measurements and analyses (Figure 3).

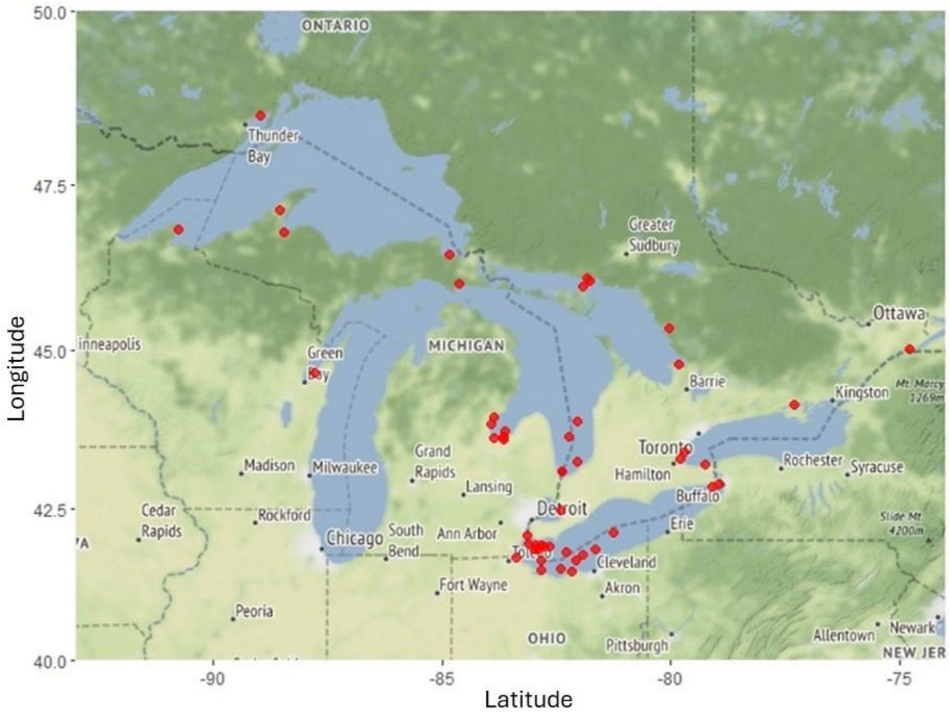


Figure 3: Sampling locations from the February 2022 Winter Grab, coordinated by the GLWin Network, a coordinated sampling and measurement event that occurred across all five lakes to collect data on a consistent set of physical, chemical, and biological parameters (Pu et al., 2025).

2.5.1 Greenhouse gases: CO_2, and CH_4 Fluxes

Recent literature pertaining to carbon focused primarily on the impacts of ice on carbon storage, understanding how ice phenology regulates the timing of carbon availability to the rest of the lake ecosystems, and what implications this has for annual lake carbon budgets. Imbeau et al. (2021) sampled freshwater ice across 19 boreal and polar lakes and found that the ice contained bio-labile dissolved organic compounds, suggesting that ice may play an understated role in the storage, transformation, and cycling of carbon in ice-covered freshwater ecosystems. These results raise the questions of how these services may stimulate spring production during ice-off and what limnological consequences may arise from shortened ice cover duration pertaining to both microbial and whole-lake production. Sawakuchi et al. (2021) raised the question of whether shorter ice periods may impact other carbon exports, such as spring methane emissions. Similarly, McAdams et al.'s (2021) research on ice-covered sediment cores from the Prairie Pothole Region suggests that changing ice cover within the Great Lakes' wetlands may impact greenhouse gas emissions and carbon sequestration abilities of these ecosystems. Positive relationships between phosphorus concentrations and methane oxidation were observed by Sawakuchi et al. (2021) across 12 different lakes, suggesting that nutrient-rich lakes may more effectively oxidize under-ice methane and therefore minimize ice-off methane emissions. However, Gorsky et al. (2021) emphasized the importance of shoulder seasons in the annual greenhouse gas budget of lakes and that most carbon emission budgets are biased as they are calculated from studies of only the summer months and neglect to include measurements from under-ice and ice-out emissions. Fernandez et al (2020) include winter measures from Lake Erie in a seasonal analysis of methane flux; data suggest low methane emissions in winter. Both Fernandez et a. and Townsend-Small et al. (2016) note that gas wells on the bottom of Lake Erie are a confounding factor in these surveys. Further, methane is highly soluble in water at typical winter temperatures but is off gassed in warmer seasons when most surveys are conducted.

2.5.1a Organic carbon

Another carbon source, oil, was studied by Gunn et al. (2021) who investigated the roughness of the ice in the Straits of Mackinac and its storage capacity to contain an under-ice, upwelled oil spill in this region. This study derived a digital elevation model of the ice bottom using Ground-Penetrating Radar (GPR) to estimate the under-ice storage capacity to be 0.03 m^3/m^2, indicating that a considerably different remediation treatment may be needed to manage an under-ice oil spill in this region as compared to an open-water or sea-ice oil spill.

2.5.2 Nutrients

As winter hydrological flows increase in response to more frequent winter melts and winter precipitation falling as rain rather than snow, winter sediment and nutrient transport are also expected to increase, particularly in the more nutrient-rich parts of the Great Lakes Basin. Historically, the snowmelt-controlled spring nutrient flux coincided with springtime plant growth, promoting nutrient uptake. The disruption of this plant-nutrient synchrony may therefore result in substantial nutrient losses from terrestrial systems into aquatic ecosystems, with unquantified and potentially detrimental impacts on downstream water quality. Currently, sufficient data to accurately assess and predict such episodic nutrient exports at regional scales is lacking, as most existing data focuses only on the largest tributaries to the lower Great Lakes (Seybold et al., 2022; Singh et al., 2023). Pu et al. (2005) discuss a recent, coordinated Basin-wide sampling effort to collect data on a consistent set of physical, chemical, and biological parameters.

Several papers investigated nitrogen dynamics as well as the timing of nutrient availability. For example, Massé et al.'s (2019) study highlighted the need to better understand winter as a controller for nitrification in lakes and how modified ice duration may influence the global inland water nitrogen cycle. Bluteau et al. (2021) sampled winter nitrogen concentrations in the St. Lawrence Estuary and the Gulf of St. Lawrence via an ice breaker to investigate nitrogen sources. This study concluded that the most significant source of nitrate in the estuary is fluvial inputs, not vertical mixing processes as was previously thought, but emphasized how more research is needed to assess the impacts of peak tides on surface nitrate concentrations. Nelligan et al. (2021) compared changes in the hydrology and nutrient exports of six watersheds within southern Ontario between the mid-1970s and late-2010s and found that the timing of nutrient export had shifted across most sites from peak exports previously occurring in the spring and summer to more recently occurring in the winter and fall seasons. This article stressed the need to develop fall and winter season-specific best management practices for managing nutrient exports from agricultural watersheds across the Great Lakes to account for this shift in nutrient delivery timing. Further, Mooney et al. (2020) investigated nutrient inputs across nearly every Lake Michigan tributary and found that while around 70% of the nitrogen and phosphorus delivered to Lake Michigan came from the six largest tributaries, smaller tributaries demonstrated nutrient loads more biased towards bioavailable, dissolved inorganic nutrients.

Regarding phosphorus, a recent study by Singh et al. (2023) of changes in annual and seasonal concentrations of soluble reactive phosphorus (SRP) and total phosphorus (TP) across 370 Great Lakes Basin watersheds between 2003 and 2019 found that despite stable or decreasing TP trends, there were widespread increases in SRP concentrations, with 46% of watersheds showing significant SRP increases. This study also uncovered a clear latitudinal gradient concerning SRP and SRP: TP ratios, with northernmost watersheds demonstrating the largest relative SRP:TP increases. Furthermore, northern forested watersheds with steep terrain demonstrated the greatest relative SRP increases, and temperature was identified to be a key driver of this increase in winter phosphorus concentrations (Singh et al., 2023). Similarly, Isles et al. (2023) investigated the effects of climate on lake TP concentrations across North America and North Europe and likewise observed declining trends in northern lake TP associated with increasing winter temperatures. These results further indicate the importance of climate factors, particularly winter temperature and changing precipitation patterns, in controlling phosphorus cycling within northern lakes (Isles et al., 2023). These findings suggest that best management practices for wintertime nutrient control may also need to be developed specifically for small tributaries as winter nutrient fluxes increase to reduce ecological impacts to lake ecosystems.

2.5.3 Oxygen

Compared to the dissolved oxygen concentration declines in coastal and oceanic waters, relatively little is known about lacustrine dissolved oxygen concentration changes in response to changing climate (Jane et al., 2021). Jane et al. (2021) investigated dissolved oxygen and temperature profiles of 393 temperate lakes between 1941 and 2017 and found freshwater dissolved oxygen declines to be between 2.75 and 9.3 times greater than those observed in the oceans, posing a threat to essential lake ecosystem services. Much of the research pertaining to lake oxygen dynamics to date has focused on summer hypoxia associated with lake stratification, much of which has been performed exclusively on Lake Erie. Summertime hypoxia in Lake Erie is strongly influenced by winter diatom blooms (Reavie et al., 2016; Wilhelm et al., 2014). Other studies emphasize observations made during shoulder seasons (particularly fall) where summer hypoxia can persist (Oldham and Krause, 2023; Stow et al. 2023).

There are few studies to date documenting over-winter hypoxia in the Great Lakes, and Tellier et al. (2022) highlighted that recent in-situ sensing advancements can be leveraged to help fill these over-winter hypoxia research gaps. Another study in Lake Superior investigated under-ice dissolved oxygen concentrations at three tributary locations and underscored that more research is needed on the mechanisms driving low dissolved oxygen in the bottom and middle water column throughout Great Lakes bays (Bockenstedt & Haines, 2020). Recent winter literature emphasized that more research is needed to understand the extent and magnitude of winter hypoxia in areas beyond Lake Erie's central basin, and that winter hypoxia is currently a knowledge gap throughout the Great Lakes region (Tellier et al., 2022).

2.5.4 Salt and Other Solutes

Several papers investigated chloride data throughout Great Lakes waters and watersheds to assess the impacts of road salt use and agricultural activities on water quality. Elevated chloride levels were found to increase organism stress resulting from changes in lake salinity, which was also found to influence lake stratification, drinking water contamination, nutrient availability, metal loading, and pipe corrosion (Kane et al., 2022). Dugan et al. (2021) estimated the salt load from the tributaries of Lake Michigan into the lake to be over 1 teragram (or 1 trillion kilograms) per year and projected that the chloride concentration of Lake Michigan will slowly continue to rise in the future because of these annual tributary loads. The literature also called for more studies to understand how changes in precipitation patterns throughout the Great Lakes, such as an increase in total precipitation or more precipitation as rain rather than snow, may impact chloride loading into the lakes from road salt and agriculture each year (Kane et al., 2022; Snider et al., 2022). There was a general sentiment among the literature to minimize the use of road salt where possible, as well as a recognition that reductions in salt application may not have an immediate effect due to time lags between surface water changes in response to management actions (Dugan et al., 2021; Kane et al., 2022). Mackie et al. (2022) uncovered that groundwater may also be a significant source of road salt contamination within the Lake Ontario watersheds, highlighting the need to investigate groundwater contributions to surface water quality outside the warm seasons. Lastly, DeGrandpre et al. (2021) investigated solute exclusion dynamics related to ice formation and highlighted that few studies have evaluated this phenomenon or its potentially important implications for toxic solute concentrations given the projected increased frequency of freeze-thaw events throughout the year.

2.6 Biology

It is becoming widely recognized that for cold, dark, and snow-adapted ecosystems and organisms, changes in winter patterns will impact critical thresholds driving biological organization, potentially resulting in system-wide consequences. It is thus imperative to understand the effects of winter on organismal biology (Sutton et al., 2021) and how variations in winter conditions may shift fundamental ecosystem processes and structures (Cavaliere et al., 2021).

2.6.1 Fish

With respect to fish, winter fish ecology was highlighted as a major knowledge gap (Studd et al., 2021), and articles called for increasing the number of year-round fish studies to not only fill these gaps but help inform fish conservation measures (Kraus et al., 2021; Marsden et al., 2021; Wolf, 2022). Most direct-observation fish surveys are confined to open-water months to avoid the logistical constraints and safety concerns associated with sampling in ice-covered northern lakes (Block et al., 2019; Ranta & Kapuscinski, 2022). Due to the lack of fish data collected during the cooler months in the Great Lakes, a large information gap exists pertaining to how changes in abiotic environmental factors, including winter temperature, river inflows, ice cover, light exposure, and thermal conditions, affect fish spawning activities, recruitment success, and invasive species abundance (Buchinger et al., 2022; Ivanova et al., 2021; Johnson et al., 2021; Marcaccio et al., 2022; Marcek et al., 2021; Ransom et al., 2021; Stewart et al., 2021, 2022). The need for more observations to better understand fish mass mortality events during winter (Tye et al., 2022), how shrinking periods of winter conditions will impact competition within and between fish species (McMeans et al., 2020), and bathy-thermal distributions of ecotypes (Jasonowicz et al., 2022) are needed to assess how changing ice and temperature regimes will affect fish populations.

Additionally, the literature also called for more research to understand the impacts of changing winter temperatures on food availability and therefore the growth and abundance of key fish species found to be selective feeders even in winter, such as round whitefish (Ranta & Kapuscinski, 2022). Ranta and Kapuscinski (2022) highlighted the need for more wintertime fish stomach content studies to better understand winter feeding behaviors, as well as overwintering strategies and needs of important Great Lakes species. Opportunities for methodological development with which to study winter impacts on fish were also uncovered, including integrating limnological surveys with fisheries science, leveraging fish-implanted bio-loggers to evaluate temperature and depth throughout the Great Lakes (Kraus et al., 2021). Acoustic telemetry networks also emerged as a valuable tool through which to assess fish winter ecology, including overwintering habitats, spawning locations, preferred depths, and movement patterns and winter bioenergetics and survival (Brownscombe et al., 2022; Hessler et al., 2023; Midwood et al., 2019). Overall, recent literature pertaining to fish biology stressed the need to better understand how changes in winter conditions and timing will impact the life cycles of various fish species, and the implications of these changes on fish population structures and food webs throughout the Great Lakes region.

Figure 4: Lake whitefish, photo credit: Michigan Sea Grant.

The restoration of coregonid populations is a major priority in the Great Lakes. Coregonines (such as cisco and lake whitefish) require ice-covered sites for spawning success and abundant very early season (Feb March) zooplankton food for larval survival, and their reproduction may be affected by changing ice cover (Brown et al., 2021, 2024; Stewart et al., 2023; Taylor et al., 1987).

2.6.2 Phytoplankton

The prevalence of wintertime phytoplankton blooms, as well as their importance to lake-wide primary production and summertime hypoxia, has become widely recognized following wintertime observations of viable phytoplankton in the water column and ice at densities comparable to those observed in the lake during summer (Burns et al., 1978; D'souza, 2012; Nicholls & Dillon, 1978; Sze & Stewart, 1974; Twiss et al., 2012; Wallen, 1977; Wright, 1964). This linkage between ice cover and phytoplankton biomass was further strengthened by a survey of Lake Erie conducted by Beall et al. (2016), which demonstrated shifts in phytoplankton and bacterial community structure in response to the presence of ice cover. Results of this study suggested high-ice years were accompanied by a proliferation of filamentous diatom blooms, whereas ice-free conditions resulted in the presence of a community of smaller cell size and lower total biomass due to light limitation due to greater wind mixing and higher turbidity (Beall et al., 2016). Results from recent physiochemical and metatranscriptomic surveys of the Lake Erie winter water column by Zepernick et al. (2024, 2022) suggest that ice-free conditions not only decrease the magnitude of winter planktonic diatom blooms, but also the alter the community composition. This study found evidence of increased gene expressions consistent with well-defined indicators of light limitation in turbid, ice-free water, as well as several indicators of diatom adaptation to these conditions including increasing secondary light-driven energy acquisition pathways and improving buoyancy to optimize light exposure (Zepernick et al., 2024). A study by Wilhelm et al. (2014) investigated the linkage between winter production and summer hypoxia in Lake Erie and observed a significant wintertime export of organic carbon to the water column of a chemical nature suggesting this biomass to have a phytoplankton origin. This study also demonstrated notably reduced wintertime bacterial carbon cycling, suggesting that carbon produced in the winter must be consumed at a later point, potentially contributing to the high summer benthic oxygen demand, and resulting hypoxia in Lake Erie (Wilhelm et al., 2014), a finding that was further reinforced by evidence strongly associating winter diatom production with summer hypoxia in Lake Erie (Reavie et al. 2016)

There are a complex web of interactions impacting lake phytoplankton growth, assemblages, and survival in winter, especially under ice, including light exposure, buoyancy and motility, metabolic pathways, zooplankton predation, nutrient supplies, lake morphometry, and density-driven lake circulation (Hrycik, 2021; Jansen et al., 2021). A study by D'souza et al. (2013) presented evidence that filamentous diatoms found under the ice throughout the Great Lakes may direct frazil ice formation to create buoyancy and facilitate the incorporation of these non-motile organisms into the overlying ice, promoting consistent residence in the photic zone throughout the winter. Bramburger et al. (2022) investigated impacts of light climate on phytoplankton primary production across snow-covered and clear ice-covered lakes and highlighted that more research on under-ice productivity is needed to better understand how changes in snow and ice cover will impact lacustrine communities. To truly understand the ecological function of the Great Lakes, primary production monitoring in winter must be prioritized to fill the regionally persistent data gap (Twiss et al., 2012; Figure 5). Recent work uncovered that more research is needed to better understand the winter dynamics of phytoplankton biomass throughout the water column, how these dynamics shift throughout the succession from ice cover to open water, and which factors trigger these community structure shifts under the ice (Hazuková et al., 2021; Jansen et al., 2021). Impacts of phytoplankton on ice structural integrity is another such research gap, specifically, understanding how the incorporation of phytoplankton disrupts ice lattice structures, reduces ice albedo, and increases absorption of solar heat (Twiss et al., 2012).

Bloom decline follows conventional mechanisms (grazing, nutrient depletion; Zepernick et al. 2024) but also involves parasitism including the mycoloop (Seto et al., 2023; McKindles et al., 2024) and viral shunt (Denison et al., 2024). This recent work has documented hidden diversity amongst the parasitic fungal community, many of which were novel clades of early diverging fungi including single-cell lineages that could not be placed into a phylum (Seto et al., 2023). Likewise, this work expanded the known diversity of viral lineages in the Great Lakes (Denison et al., 2024)

Figure 5: February 2008 image from an icebreaker in the middle of the central basin of Lake Erie, demonstrating the extensive coloration of surface water directly below the ice due to the presence of high concentrations of the filamentous centric diatom Aulacoseira islandica and silt. Photo credit: Michael Twiss.

To holistically understand winter phytoplankton dynamics throughout the waters of the Great Lakes, winter phytoplankton observations in the connected watersheds are also needed. For example, Jankowski et al. (2021) assessed phytoplankton biomass from the upper Mississippi River system and found that samples from warmer winters contained more algae, suggesting that higher winter temperatures may have important implications for the productivity and food webs of tributaries to the Great Lakes. Research by Hrycik (2021) pointed out several pathways through which plankton communities under ice are affected by climate change impacts, including snowmelt-driven nutrient cycling, changes in spring plankton phenology, and changes in ice properties, and therefore the under-ice light environment. Jansen et al. (2021) highlight the need to better understand the relative contributions of factors impacting phytoplankton biomass decline in early winter, if shorter ice periods will diminish winter algal blooms, and the degree of mixotrophy used by these organisms under the ice. Lastly, Hazuková et al.'s (2021) study underscored that under-ice phytoplankton may seed the populations responsible for early spring algae blooms, and that more information on phytoplankton seasonal dynamics is needed to project how aquatic biota may adjust in response to the changing climate. Iwaloye et al. (2024) analyzed DNA and RNA extracted from Lake Erie central basin ice and found that lake ice contained a considerable number of cyanobacterial sequences as well as a large organism diversity indicative of the lake's biological and anthropogenic influences, highlighting the need to better understand under-ice metabolic pathways. Similarly, Butler et al. (2019) underscored the need to better understand how ice cover affects microbial composition, abundance, and diversity, and how this influences the type and magnitude of biogeochemical cycling occurring throughout historically ice-covered periods.

2.6.3 Zooplankton

Certain zooplankton groups (such as cladocerans) dominate during the summer to fall season but significantly decrease or are absent from late fall and into the spring (Balcer et al., 1984). Some copepods will overwinter and dominate during the winter months, and others only produce eggs and reproduce during the winter. The effect of milder winters on this pattern is a major data gap. Several zooplankton-specific knowledge gaps were emphasized in recent literature pertaining to zooplankton community vertical structure under ice, as well as how winter zooplankton migration contributes to the lakes' carbon cycle whereby inorganic nutrients and organic matter are transferred from the chemocline to the surface (Jansen et al., 2021). The understanding of zooplankton diel vertical migration in fresh-water, ice-covered systems remains limited. One study by Chiapella et al. (2021) investigated diel interactions between phytoplankton and zooplankton in a shallow, eutrophic pond in Vermont and found the zooplankton *Daphnia mendotae* demonstrated upward migration at sunset and sunrise while sinking around midnight. Another such zooplankton-specific study utilized an array of moored thermistors as well as an upward-looking ADCP to assess how the breakdown of winter stratification from radiatively driven convection influences zooplankton vertical migration and spatial distribution in Lake Superior. This study observed an abrupt drop in night-time vertical zooplankton migration to the upper 50 meters of water, assumed to occur for feeding, that coincided with the onset of spring water column mixing. The authors hypothesized that this sudden behavioral shift was due to the immediate distribution of phytoplankton at depth in response to full water column convection, eliminating the need for vertical relocation to find available food (Austin et al., 2022). This study highlighted how net tows to study zooplankton abundance have been primarily conducted during the day, resulting in a disparity between daytime and nighttime zooplankton distribution data. The authors postulated that coupled net and ADCP monitoring programs could be leveraged to better resolve the spatial and temporal patterns of zooplankton ecology, and that moored ADCP methods could help characterize under-ice zooplankton movement and aggregation patterns (Austin et al., 2022). A recent study (Shchapov and Ozersky, 2023) sampled five stations in Lake Superior across a nearshore depth gradient through the full year to assess the phenology of crustacean zooplankton communities and the effect of environmental drivers, and found that water temperature and food availability were the main drivers of total zooplankton densities through the year and during the cold seasons, but the effect of these factors varied among taxonomic groups.

Implications of a shortened ice-covered season on zooplankton phenology remains a knowledge gap due to the historical lack of winter freshwater research (Hébert et al., 2021). A study by Hrycik et al. (2022) tracked plankton phenology throughout the winter-spring transition for four years in a shallow, eutrophic temperate lake. The authors observed successional events and species composition for both phytoplankton and zooplankton that were heavily influenced by antecedent winter conditions (Hrycik et al., 2022). While Lakes Huron, Michigan, and Superior are oligotrophic, it is plausible that spring plankton phenology and community composition in each of the Great Lakes are also strongly influenced by antecedent winter conditions (e.g., see Kerfoot et al., 2010). Related to these findings, a survey of crustacean zooplankton abundance, taxonomy, and functional community composition in 13 lakes across a trophic gradient found that while winter zooplankton communities were only a third as abundant as those found in the summertime, higher under-ice zooplankton densities were found in green eutrophic lakes as compared to brown (dystrophic) and blue (oligotrophic) (Shchapov et al., 2021). These results suggest that more productive lake basins and bays, such as western Lake Erie, may provide better winter conditions under ice for zooplankton survival. Because zooplankton are vital to the energy transfer from bacteria and phytoplankton to lake fishes, it is critical to understand how reduction in the ice-period may alter zooplankton communities throughout the Great Lakes, as well as how these changes may affect lake food webs (Dvoretsky & Dvoretsky, 2021; Shchapov et al., 2021).

2.6.4 Food Webs

Few studies were found that specifically investigated winter food web structures, as many of these such observations have been historically made in warmer periods due to the logistical constraints associated with making under-ice observations (Block et al., 2019). (Farmer et al., 2015) documented reduced reproductive success in Lake Erie yellow perch following short, warm winters, which may be caused in part by altered spawning phenology and lack of zooplankton prey for larval perch. A study by Hébert et al. (2021) of impacts of delayed ice-onset on pelagic food web processes and phenology observed cross-seasonal cascading food web effects. Specifically, relatively greater densities of algal resources and primary consumers were observed during early winter under delayed ice onset, followed by an increased prevalence of overwintering consumers throughout ice-on. Active under-ice consumers in the delayed ice-onset scenario were observed to have relatively elevated storages of fatty acid (Hébert et al., 2021), which are thought to increase overwintering success (Grosbois et al., 2017; Hébert et al., 2021) and were hypothesized to be a result of the elongated access to algal resources during early winter. Delayed ice-onset resulted in higher overwintering consumer densities in early springtime following ice-off, driving earlier top-down regulation of spring algae, and thus effectively suppressing the spring algae bloom. This diminished spring food availability may disrupt subsequent open-water trophic linkages and energy flow pathways as it confers a competitive advantage to overwintering consumers and a disadvantage to springtime consumers (Hébert et al., 2021). Another study investigated the ecology of net-spinning caddisflies Tin Lake Superior and observed a relationship between larval pupation and ice out. This paper underscored that winter life on the bottom of Lake Superior remains largely unexplored and has resulted in a limited understanding of overwintering strategies for many insects (Miess et al., 2022). This observation raises the broader question of how changes in ice-off timing or ice-free years will impact the developmental cues of insects, zooplankton, larval fish, and other organisms across the Great Lakes that fill important niches within the regional food web. Assessments of the qualitative relationships between ice quality, primary production, and resource availability are needed to fully understand food webs in seasonally ice-covered lake ecosystems (Jansen et al., 2021). Phytoplankton growth rates and rates of grazing by microzooplankton were closely matched under ice in Lake Erie with no net growth at the time in which the measurements were made (February), suggesting that the high biomass of phytoplankton was a result of an earlier bloom condition (Twiss et al. 2014). Furthermore, year-round, comprehensive food-web studies from bacteria to fish are needed to improve the understanding of community and trophic dynamics and better estimate how future lake food webs structures may change (Shchapov et al., 2021).

2.7 Remote Sensing, Modeling, and Forecasting

Recent research on remote sensing, modeling, and forecasting winter phenomena in the Great Lakes focused primarily on understanding dynamics of teleconnections and oscillations, ice and heat, precipitation and runoff, and lake effect snow.

2.7.1 Teleconnections and Oscillations

Several studies investigated the relationships between global climate patterns and ice cover in the Great Lakes region. Lin et al. (2022) performed a statistical analysis of annual maximum ice cover across all the Great Lakes between 1980 and 2020 and found that recent decades demonstrated “a reduced number of accumulated freezing degree days across the winter months” as well as increased variability in annual maximum ice cover since 1993. Interestingly, this study identified a significant step change in annual maximum ice cover patterns which occurred in the winter of 1997/98, where winter ice cover was “significantly correlated with El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific–North American pattern (PNA)” prior to this winter but was “significantly correlated with the tropical–Northern Hemisphere pattern (TNH) and eastern Pacific oscillation (EPO)” from 1998 onward (Lin et al., 2022). Similarly, Cohn et al. (2021) hindcasted annual maximum ice cover from 1963 – 1972 for all five lakes and compared them to teleconnection patterns, concluding that the Asian-Bering-North American (ABNA) index may be indicative of annual ice cover and emphasizing how this connection could help aid future ice forecasts. Lastly for ice cover, in Lake Superior, Lofgren et al. (2021) focused on identifying atmospheric patterns connected to ice cover and found strong associations with the EPO.

Studies connecting lake effect precipitation and climate oscillations were also found. Lake effect snow in Michigan's lower peninsula was found to be most strongly impacted by warm (El Niño) ENSO phases, as well as the negative NAO phases (Meng & Ma, 2021). Mateling et al. (2021) found that cold-season precipitation in the upper Great Lakes region is often associated with atmospheric rivers, which are significantly correlated with negative phases of the PNA pattern and Pacific Decadal Oscillation. Lastly, Porterfield (2021) suggests that ENSO phases may be a valuable predictor for high wave events in the Great Lakes and therefore could be used to guide winter-time preparations in coastal areas. Overall, the authors emphasized that an improved understanding of the Great Lakes' winter climate connectivity to these larger atmospheric patterns is needed to improve the ability to accurately model and forecast annual maximum ice cover in the future (Lin et al., 2022).

2.7.2 Ice and Heat

Model simulations of lake ice and heat patterns were a key focus of recent winter literature. Ice cover models for a high-emissions scenario project that ice cover will decline across all five Great Lakes, particularly in the months of February and March, with Lakes Superior and Erie experiencing the greatest projected declines in average ice cover. These model outputs also anticipate earlier peak ice growth in the deeper lakes, specifically Lakes Superior and Huron, and that the greatest decrease in ice season length will occur in Lake Michigan, followed by Lakes Erie and Ontario (Lam & Dokoska, 2022). Another such important impact on ice production, duration, and thermal conditions is snow cover. Fujisaki-Manome et al. (2020) used coupled ice-hydrodynamic models to conduct numerical experiments on the impacts of snow cover on ice for all the Great Lakes. A comparison of modeled results between cold, high-ice years and warmer, low-ice years suggest that snow-covered ice not only reduced mean ice thickness and therefore total ice volume but also shortened ice duration and allowed for earlier surface water warming. While snow on ice increased the albedo effect, albedo-driven delays in melting were overcome by thermal insulation provided by the snow, which prevented further ice formation and growth (Fujisaki-Manome et al., 2020). A statistical model simulating ice cover onset timing and ice formation probability near the Apostle Islands National Lakeshore from 1972 to 2015 yielded results in support of previous research that suggested a step change in regional ice cover patterns in the late 1990s. This study found that prior to the late 1990s, coastal ice cover in this region was stable enough for pedestrian utilization; however, after this period, ice cover has been highly variable and increasingly unsafe (Ji et al., 2019). Li et al. (2022) used satellite data and global simulations to study changes in surface water temperature trends associated with an advancement in the timing of ice break up across the last five decades, concluding that the impacts of changing ice phenology on region-wide lake surface temperatures are still not well understood.

Xue et al. (2022) coupled a "regional climate model with a 3-D lake model (GLARM) to resolve 3-D hydrodynamics" and project future climate change scenarios into the mid and late 21st century. Model projections estimated that lake surface temperature will increase in all five lakes, with the most significant occurring in Lake Superior and Lake Ontario. Xue et al.'s (2022) model forecasted that winter stratification will diminish by the end of the century, and that the highest mean ice cover will decrease across all lakes. Liu et al. (2022) developed a machine learning (ML)-guided prediction of ice coverage in the St. Marys River for 7-day and 30-day timescales and found that while the ML models outperformed short term baseline forecasts, they underperformed for 30-day forecasts. While ML has many powerful capabilities, when it comes to ice forecasting capabilities, the authors highlighted several limitations, namely that ML cannot predict unprecedented events as forecasts are generated from past data, and that improvements in model resolution to improve river ice forecasting are needed. Notaro et al. (2021) evaluated NASA's Unified Weather Research and Forecasting (NU-WRF) model for the Great Lakes region and identified several biases for cold season simulations of this region. This study asserted that to accurately simulate complex lake–atmosphere interactions and limnological processes using regional climate models, the next generation of coupled climate and 3D lake models needs to be generated, evaluated, and improved. Lastly, in an effort to advance the in-situ lake ice measurements needed to calibrate and validate these such models, Aslamov et al. (2021) developed the "autonomous system for lake ice monitoring (ASLIM)" and emphasized how recent advances in modern electronic components and sensing capabilities can be used to improve in-situ ice measurements.

2.7.3 Hydrological Modeling

Models with which to simulate winter hydrological changes, including precipitation, streamflow, groundwater, flooding, and lake effect snow are a key research area. These models will be essential tools for estimating and preparing for the changes to come; therefore, many of the reviewed papers uncovered areas in need of improvement to evolve modeling capabilities and enhance simulated wintertime outputs. Xu et al. (2022) investigated the performance of ERA5 and MERRA-2 precipitation products over the Great Lakes Basin on streamflow simulations and uncovered that the influence of these products on "groundwater and groundwater-surface water interaction simulations" needs additional research. Another study modified the soil and water assessment tool (SWAT) model to include rain-on-snow events and assess winter flood phenomena, demonstrating how the unmodified SWAT model may be underrepresenting rain-on-snow events and therefore misrepresenting winter streamflow where these events are happening more frequently. This paper highlighted the need to routinely update hydrological models to account for changes in winter hydrological phenomena, such as increased rain-on-snow events, resulting from changing winter precipitation patterns (Myers et al., 2021). Projected future climate change scenarios into the mid and late 21st century made by the same model developed by Xue et al. (2022) mentioned above, estimated that annual precipitation will increase across the entire basin regardless of future scenarios simulated. Furthermore, Minallah & Steiner (2021) simulated future changes in the atmospheric water cycle in the Great Lakes region using 15 models from the Coupled Model Intercomparison Project. Simulated results indicated a shift toward summer drying accompanied by wetter winters and springs by mid-century, with increased winter evaporation. This paper emphasized the importance of including lakes within regional models for accurate hydroclimatic assessments. Lastly, Chin et al. (2018) used Variable Infiltration Capacity (VIC) model simulations to quantify climate change-driven winter weather and hydrological changes to evaluate potential impacts on the tourism sector, and estimated that snowfall around the holidays, key winter tourism time, is expected to fall by 50% or more by 2080.

2.7.4 Lake Effect Snow

One of the most widely recognized wintertime phenomena throughout the Great Lake region is lake effect snow (Figure 6). Multiple papers were found focusing on the development of models for the specific purpose of understanding and forecasting changes in lake effect snowfall. Ellis & Suriano (2022) identified a general drying of the cool-season lake effect hydroclimate across the Great Lakes over the last 51 years, where the total number of days where lake effect impacts were experienced decreased. This study underscored how different techniques for identifying lake effect days differ in their results, specifically within the shoulder seasons. Similarly, projected changes in heavy lake effect snow from 1979-2100 using a 3D regional climate model estimated that there will be a reduction in heavy lake effect snow in the future despite reduced ice cover enhancing lake-atmosphere interactions. This study also indicated modeled simulations should be extended to include a variety of future climate scenarios (Huziy et al., 2021). Notaro et al. (2022) evaluated global climate model's capability to simulate lake effect snow throughout the Great Lakes and determined that lake temperature and ice cover representations were inadequate and often led to insufficient snowfall simulations throughout lake effect zones, calling for the coupling of more advanced 3D lake models with climate models to better these projections. Likewise, Fujisaki-Manome et al. (2022a) evaluated numerical forecast models for lake effect snow and found that offshore "observations of precipitation, surface meteorology, evaporation, and heat supply from the water surface" are rare and remain a significant research gap inhibiting numerical lake effect snow forecasting abilities. For Michigan's lower peninsula, Meng & Ma (2021) emphasize the need to distinguish lake effect from non-lake effect snow to better identify the meteorological processes and environmental factors influencing the formation of each in Michigan's lower peninsula. Similarly, Jones et al. (2022) investigated the contributions of lake effect versus non-lake effect snow in Lakes Erie, Michigan, and Ontario and raised the question of how changes in the frequency and duration of lake effect snow will influence future surface water quality among these three lakes. Furthermore, the morphological, geographical, and physical characteristics of lake effect snow in Lakes Michigan and Superior were found to be considerably less studied as compared to the eastern Great Lakes (Wiley & Mercer, 2021). Overall, the factors affecting the location and intensity of lake effect snow are not well understood (Shi & Xue, 2019) and more effort is needed for model development, Great Lakes system parameterization, and comprehensive model validation (Ye et al., 2019).

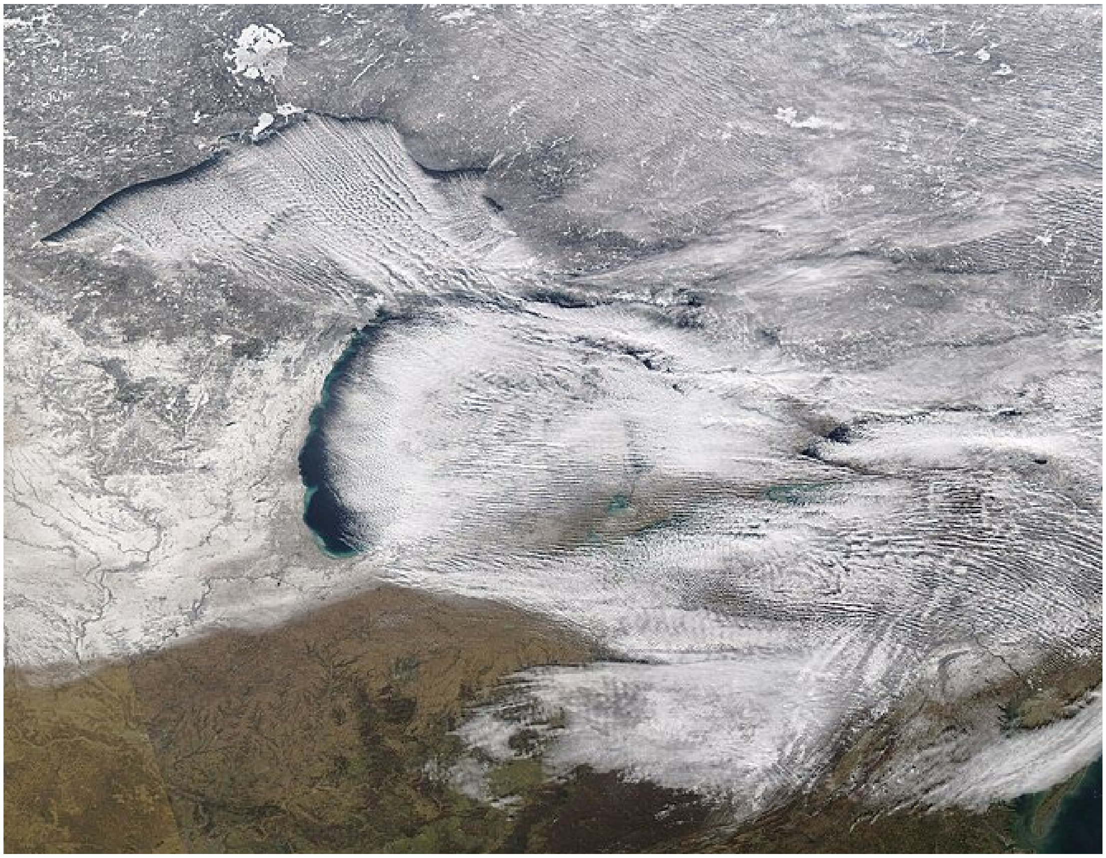


Figure 6: Image of lake effect snow taking place captured by the MODIS instrument on the Aqua satellite. Image from NASA Worldview.

2.8 Socioeconomic and Cultural Services

The last major theme identified through this literature review pertained to socioeconomic and cultural services of winter, specifically as they relate to ecosystem services, shipping, and human wellbeing throughout the Great Lakes region. Hampton et al. (2024) discuss the socioeconomic implications of declining ice including diminished access to ice-based cultural activities, safety concerns in traversing ice, changes in fisheries, increases in shoreline erosion, and declines in water storage, as well as threats to water quality and biodiversity. Wuebbles et al. (2019) assess the impacts of climate change on the Great Lakes across several areas including water quality, lake ecology and fish, and recreation and beach closures.

2.8.1 Ecosystem Services

The consistent supply of water is a key ecosystem service provided by the Great Lakes. A study conducted by Steinman et al. (2022) assessed key challenges, knowledge gaps, and scientific needs pertaining to groundwater resources across urban (developed), agricultural, and coastal wetland ecosystems throughout Michigan. This effort highlighted key research gaps pertaining to groundwater budgets, contamination, forecasting, hydrologic connectivity, and information tools. Another significant ecosystem service is the provision of snow for winter recreation and tourism. One study estimated that by 2080, winters could be over a month shorter, resulting in over a month fewer days of snow depths required for winter recreation, at least 50% less holiday snow, and a 22-30% decrease in the total area considered viable for winter tourism (Chin et al., 2018). Decreasing ice cover and increasing ice safety variability will also impact recreational ice fishing (Chin et al., 2018), commercial, and subsistence fisheries, which comprise sone of the most important ecosystem services throughout this region. Cultural services and winter recreation were found to be most at risk for negative impacts from climate change, and more work is needed to integrate different fields of knowledge to improve resource management decisions (Huber et al., 2022). The loss or reduced access to ice-roads may particularly impact some northern indigenous and island communities. Despite the numerous ecosystem services provided by the Great Lakes, accurate valuation of these services has been challenging and remains a significant research gap (Studd et al., 2021).

2.8.2 Shipping

The ability to ship cargo across the Great Lakes is a key driver of both the region's industry and economy (Figure 7), and this ability is annually regulated by the annual formation of ice. A stakeholder engagement workshop conducted with 27 participants across a variety of agencies and industries dependent on the Great Lakes for transportation concluded that existing satellite and model-based ice condition products for the Great Lakes have both spatial and temporal limitations, resulting in information gaps that inhibit effective decision making (Fujisaki-Manome et al., 2022b). Shipping activities also heavily impact the underwater soundscape throughout the Great Lakes. Putland et al. (2022) provided a baseline soundscape assessment for western Lake Superior using passive acoustic monitoring to investigate seasonal noise patterns and found significantly lower sound pressure levels during winter and spring. This result raises the question of how possible increases in winter shipping due to iceless winters may alter the wintertime acoustic refuge, particularly for species that utilize vocalizations throughout winter spawning. Decreasing winter ice opens the possibility of extending the Great Lakes shipping season; however, coupled social-ecological analyses should be used to evaluate the impacts a lengthened shipping season may have on key winter spawning aquatic species and assess the risk-reward ratios associated with these decisions. This may also impact the operations of agencies

Figure 7: Great Lakes icebreaker. Image from PxHere.

such as law enforcement and US and Canadian Coast Guard that will have to maintain search and rescue infrastructure year-round.

2.8.3 Human Wellbeing

Much of the literature assessing changes in winter water quality across the Great Lakes investigates purely environmental or ecological impacts; thus, the impacts of these changes on human wellbeing remain a significant research gap. One such study to this effect assessed changes in winter drownings across 10 countries in the northern hemisphere and found that the number of winter drownings has increased exponentially when winter temperatures reached 0°C, and that the highest drowning rates were observed in late winter. This study called for the development of drowning prevention plans in response to climate change (Sharma et al., 2020). For many Great Lakes region residents, lake ice is an essential component of their sense of place and identity (Briscoe & O'Connell, 2020). Lake ice provides critical winter transportation and access to resources for many island residents via ice roads and enables many winter recreational and sustenance activities, such as snowmobiling and ice fishing, that are central to the life and culture of those living around the lakes (Figure 8; Lam & Dokoska, 2022). Evaluations of the socioeconomic impacts from winter phenomena specific to the Great Lakes, such as lake effect snow (Fujisaki-Manome et al., 2022a) and the importance of shore-fast ice for minimizing winter coastal erosion and storm-driven scour (Hartley et al., 2020), are lacking and will be needed to understand how changing winters are truly affecting those living in the Great Lakes region.

Figure 8: Image of an ice road between Bayfield WI and Madeline Island. Image from Madeline Island Ferry Line.

3. Databases

Forty-two databases containing Great Lakes winter science data were identified and compiled into a table that includes a description of the contents and accessibility of each database. These databases were identified through public internet searches using keywords related to Great Lakes and winter science. These databases are maintained by U.S. and Canadian federal agencies, state, provincial, and municipal governments, and commercial and non-profit organizations.

The full set of identified databases can be viewed in Appendix B. Primary data themes included:

- Ice cover (10 databases)
- Precipitation (3 databases)
- Water (20 databases)
- Other (9 databases), including hunting and recreational activity, fish telemetry and bird counts, and shipping in the Great Lakes.

4. Interview Synthesis

Task 3 of the Winter Science Study was to identify the needs of stakeholders and rights holders as they relate to winter science by conducting a series of interviews with subject matter experts across federal and state/provincial, university, and Indigenous groups. The objective of these interviews was to uncover coordination needs, shared long-term goals, and strategies to improve institutional effectiveness of winter monitoring to better understand the impacts of changing winter climate on water quality. The contractor team conducted a series of 12 interviews with academic groups, agencies, and non-governmental organizations, seven of which were from the United States and five from Canada. Interviews lasted between 30-60 minutes and were conducted in a semi-structured format using a list of pre-determined guiding questions.

Respondents identified several groups of key concerns pertaining to winter science, with the most universally shared being a shortage of available winter data, as well as consistent funding and research resources with which to perform data collection. Respondents noted that the winter data that has been collected is often not maximally utilized as there is low awareness of existing data. Interviewees also emphasized the importance of collecting continuous data to address both spatial and temporal concerns, as well as to improve model parameterization and validation. Respondents noted several barriers to consistent winter data collection, including competition for ship time on ice breakers, as well as the ability to perform intentional rather than opportunistic research. Further, several respondents noted fiscal year (Canadian) and academic year (both Canada and US) conflicts, where resources and funds to conduct winter research are low during the months in which they are needed, and academic or graduate student support to conduct winter research is also low due to winter break. Others noted that even if personnel and funds are available, a general lack of training exists related to specialized methods and safety for conducting winter research out on the Great Lakes.

Other concerns mentioned included the larger fluctuations and higher variability of winter weather and ice phenology, the larger magnitude of differences in winter conditions between consecutive years, and concerns that the drivers of this variability are changing in response to climate related stimuli. Related to ice and winter weather variability, several respondents noted the lack of reliable winter conditions, ice condition, and ice jam forecasts as a big concern for both shipping and national defense capabilities. Several interviewees noted large discrepancies between what is forecasted and what is experienced on the lakes in the winter regarding wave conditions and winds, noting the danger this poses to ships and crews who are under equipped for large swells. Respondents noted that many climate models do not have sufficient resolution over the Great Lakes to effectively represent them in models, limiting the ability to reliably forecast future conditions.

Another significant theme that emerged from the interviews was concern about the impacts of ice loss and warming winters on lake ecology. Respondents noted concerns about changes in phytoplankton community structure and how changing ice and temperature regimes may impact overwintering, resulting in increased overwinter survival of some species and therefore shifts in resource competition or pressure. Additionally, phenological mismatches between the timing of spring phytoplankton blooms, zooplankton population peaks, and fish larval survival in response to ice cover changes were also mentioned as key concerns. Related to fish specifically, respondents noted concerns about how changing water temperature, ice cover, and winter weather may impact fish spawning success. Interviewees described how warmer winters negatively impact key cold-water species, such as yellow perch and walleye, resulting in poorer egg quality, lower hatching success, smaller larvae, and an overall increased vulnerability to mortality and predation.

4.1 Key Research Gaps Identified

Respondents characterized key research gaps related to winter science, the largest of which being wintertime physical, chemical, and ecological observations within the Great Lakes. Specifically, respondents noted how continuous temperature time series are needed to improve model calibration, and that under-ice turbulence observations are also needed to improve lake models. The formation, duration, and effects of thermal bars within the lakes was also mentioned as a research gap. Related to chemical observations, respondents noted a need to improve understanding of the timing and dynamics of winter chloride loading and winter melt and/or early spring phosphorus loading. Another research gap mentioned was understanding how changes in winter water quality and chemistry may impact the effectiveness of drinking water treatment. Related to shoulder season data, changes to benthic growth were noted as a research gap, with one respondent mentioning how changes occurring in the water column have largely overshadowed changes occurring on the lake bottoms. Open coast fisheries data in both shoulder seasons, as well as the predictability of both fall and spring overturn timing and dynamics were also listed as research gaps. Other needs include better estimates across spatial and temporal scales of primary productivity, phytoplankton production and light climate (spectral quality and quantity) in winter.

Interviewees noted that the warming associated with climate change is shifting seasons, with summer stratified periods going later into the fall and starting earlier in the spring. The fall shoulder season is extending into months typically considered to be winter, and spring is happening earlier, which can lead to mismatches in ecological timing. Winter food web ecology, as well as the impacts of winter conditions on spring phytoplankton, zooplankton, and fish production was noted as a major research gap for which many hypotheses exist but few have been rigorously tested. For example, poor ice cover is thought to lower diatom production, which could in turn lowers copepod production, a key food item for early spring juvenile fish. Further, research gaps pertaining to the impacts of warmer winters on the energetic value and fatty acid content on zooplankton also exist. The ecological impact of ice breaking on habitat (e.g., creation of open-water areas for waterfowl, disturbance of sediment in connecting waters) and other environmental conditions was also noted as a research gap, particularly as ice becomes less pervasive on the lakes and ice-breaking missions and shipping change. Respondents noted how there is almost no data on winter fish metabolism, which has led to a lack of understanding in how warmer winters may change reproductive costs and recruitment success for various species. It is thought that ice-free winters may significantly negatively impact spawning success for fall spawners such as trout and whitefish as they rely on ice to protect their eggs throughout the winter. Further, warmer winters may also result in higher winter metabolism for spring spawners, resulting in less energy storage available to put into each egg laid in the spring.

4.2 Key Opportunities and Priorities Identified

Respondents also identified key opportunities through which to address these priority concerns and research gaps, and almost universally agreed that the singular most impactful and important opportunity through which to improve winter science is high-level collaboration and coordinated, cooperative ecosystem-based management. Respondents noted a general lack of collective objectives related to winter monitoring efforts and highlighted that formalized coordination across winter science would help to unify the field. Interviewees mentioned that the winter science field can no longer afford to operate in siloed monitoring and assessment entities and that “the biggest roadblock to doing good work is working better together”. The Great Lakes Winter Network (GLWiN) has fostered several collaborative “Winter Grab” sampling events (Pu et al., 2025) and other activities associated with fostering a community of practice .Related to coordination, many respondents mentioned the need for funding to support the development and sustainment of mass databases and integrative ecosystem analyses. It was also suggested that emerging technologies, including remote sensing, autonomous underwater vehicles, observational buoys and sensors, and improved telemetry systems could be leveraged to help fill data gaps and populate continuous databases. Improved mechanistic and correlational models can then be generated from these long-term datasets to improve winter forecasts for both weather, ice cover, and lake phenomenon. It was also suggested that the roles of the United States Coast Guard (USCG’s), Fisheries and Oceans Canada, and the Canadian Coast Guard in winter sampling be formalized so that sample collection from ice breakers can become a more consistent and prioritized part of their operations to protect that important data stream which currently only ice-hardened vessels are able to provide. One respondent recommended lobbying for the new U.S. ice breakers which are to be commissioned for the Great Lakes to be outfitted with automated sampling equipment and wet laboratories to improve water sampling, storage, and quality assurance.

5. Expert Workshops

Three expert workshops were held in support of the project. A summary of the proceedings of each is included in the following three sections, and the workshop reports are included as Appendices B, C, and D.

5.1 Workshop #1

Workshop #1, focused on winter science gaps, needs, and science priorities, was held virtually over two half-days on May 1st and 2nd, 2023. The workshop agenda and report are provided in Appendix C. In addition to IJC staff and the support contractor team, 21 experts participated in the workshop. The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group had the opportunity to speak and present their points of view. Breakout session discussion topics included fisheries and biology, economy and culture, drinking water, winter methodology, shorelines and offshore, shoulder seasons, disciplinary needs, and differences between Great Lakes, as well as differences between connecting waters.

Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations. High-level observations and recommendations from workshop general discussions and breakout sessions are included in the list below:

- Any advancement in Great Lakes winter science is likely to have a high impact on the field, as few low-impact gaps or needs were identified by workshop participants.
- Lake access in winter is a key barrier to filling research gaps, as evidenced by the fact that this theme appeared in some form in almost every discussion topic. Lake access is further restricted by an overall lack of resources for winter science including funding, training, staff, ships, sensors, and data platforms.
- Interdisciplinary efforts are essential to understand complex research questions, including crossing disciplinary data collection and analysis and integrating social science, economics, and traditional knowledge.
- Opportunities exist to improve coordination and collaboration, including leveraging and formalizing existing collaborations to improve winter sampling and developing central platforms for winter science. Examples include:
    - Equipping USCG vessels for sample collection and storage
    - Better utilization/expansion of water intake monitoring for year-round data collection
    - Contracting/ coordinating with the winter fishing communities to increase volume and locations of samples

Workshop attendees were additionally prompted for their most pressing concern, as well as their hope spots regarding winter science. Tables 3 and 4 summarize these concerns and hope spots, respectively.

Table 3: Workshop 1 attendee concerns regarding winter in the Great Lakes

Capacity and General Concerns
Lack of winter research platforms; How to do winter science well; Lack of under-ice observations; The unknown unknowns related to winter impacts on the Great Lakes; Lack of knowledge about winter processes; So much to be done at every level; Lack of continuity and a systems approach in addressing problems; Lack of sampling capabilities.
Emerging or Understudied Issues
Chloride/road salt; Ecological mismatches as seasons change; Phenology; Wellbeing of fish and wildlife that use the lakes not knowing what's coming or not be able to adapt; Concerns about permanent stratification and what that means for the ecosystem; Effects on the recruitment of fish due to the changes.
Perceptions and Beliefs
That the public is welcoming warmer winters in the region; The misconception that nothing much happens in winter (especially for fish) - translated partly as 'I don't want to work in winter, it's cold and dangerous on the lakes' - leading to disinterest in winter work; Loss of our identity as hearty ice-adept Northerners.
Culture and Recreation
Inability of fishers to fish due to lack of ice or too much wind over the open waters; Not being able to finally catch a fish ice-fishing - not about me but the impact that has on many, many others is profound.
Infrastructure
Rapid rate of erosion along Lake Huron shoreline; January rain storms that may knock out water treatment plants; Lack of federal investment based on the belief ice seasons will end on the lakes.

Table 4: Workshop 1 attendee "hope" spots regarding winter science in the Great Lakes

Prioritization and Awareness
General agreement about main priorities; People are noticing, and they are very concerned; Increasing consolidation of prioritization; awareness.
Collaboration
The opportunity to network and work together; Collaborative projects using the limited ice-capable vessels, especially for water properties and lower trophic measures - making best use of a limited resource.
Technology
Development of affordable in-situ biogeochemical sensors; Technological improvements in sensors and capacity for long deployments; Increasingly finer scales of remote sensing data on ice and water quality parameters to help us understand changes in big landscapes; Under ice, unmanned capabilities to monitor biotic and abiotic variables.

5.2 Workshop #2

Workshop #2, focused on identifying management agency needs and recommended actions related to winter science, was held virtually over two half days on September 5th and 6th, 2023. The workshop agenda and report are provided in Appendix D. The workshop included over 40 participants, including IJC staff and contractor support. The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group had the opportunity to speak and present their points of view. Breakout discussion topics included:

- Identifying organizational mandates and needs,
- Identifying infrastructure and training resources and actions,
- Identifying actions to increase inter-agency coordination and resource/data sharing, and
- Interdisciplinary efforts and communication.

Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations. High-level observations and recommendations from workshop general discussions and breakout sessions are included in the list below:

- Funding for conducting winter science, including funding for expanded monitoring, data sharing, and interdisciplinary collaboration is a critical need.
- Need for winter science resources includes, but is not limited to, ice-hardened vessels, ice-capable AUVs, hovercrafts, mooring, and ice-capable buoys.
- Centralized, cross-disciplinary databases, data integration, and data sharing pipelines are needed to support advancements in the field. Some participants suggested that data sharing may need to be a topic for a separate workshop.
- Better leveraging of available resources is needed including inter-agency collaborations, incorporating traditional knowledge to better characterize seasonal changes, and utilization of lessons learned in marine science.
- Increasing education and awareness among the public is needed regarding the importance of winter science and the consequences if key knowledge gaps are not filled. A focused and consistent message needs to be developed on this topic.

5.3 Workshop #3

The objective of Workshop 3 was to develop recommendations to address winter science needs that integrate science priorities with existing and future capacities. The target workshop outcome was to have developed specific, measurable, achievable, relevant, and time-bound (SMART) recommendations for meeting the winter science needs identified through the previous two workshops. The workshop was held in person over one full day on January 31st and the morning of February 1st, 2024. The workshop agenda and report are provided in Appendix E. The workshop included 25 participants (Figure 9), including IJC staff and contractor support.

Figure 9: Workshop 3 attendees in Windsor, Canada, January 31, 2024.

The workshop began with an introductory session that described activities completed to date under this project and discussed the goals for the workshop. This was followed by a series of breakout sessions in which participants were divided into smaller teams to develop binational, interdisciplinary, conceptual winter science project work plans. Breakout groups consisted of 4-5 participants and either an IJC staff or contractor team member who acted as a note-taker. Each group appointed a group leader to synthesize discussion and a rapporteur to update the "official" work plan and report out to the larger group at the end of breakout sessions. Breakout sessions varied in duration, ranging from approximately 45 minutes to an hour and a half. On Day 1, Breakout Session 3 was followed by a whole-group discussion where each team reported to the full group on the work plan topics they came up with and all participants had the opportunity to discuss ideas, ask questions, and give feedback. On Day 2, Breakout Session 4 was followed by a full group discussion on recommendations to prioritize a consolidated list of SMART recommendations.

The following recommendations (one short-term and one long-term) have been synthesized from workshop #3 discussions:

Immediate Recommendation:

Within the next 18 months, the IJC Science Advisory Board should encourage the GLWQA Annex 10 (Science) to perform a binational analysis to articulate the specific winter data gaps that can be met by monitoring and that are limiting policy development and lake management decision making (Annex 2, etc.).

Long-Term Recommendations:

In the next 5 years, the IJC Science Advisory Board should facilitate a process, in partnership with academia and government agencies including NSF, NSERC, Sea Grant, and others as appropriate to establish a bi-national, competitive, and open funding program(s) to address the following priorities:

- **Improve ice modeling and condition forecasting** for both short-term and long-term time horizons through targeted winter data validation.
- **Improve winter data collection** through the establishment and improvement of winter science monitoring infrastructure (both offshore and shore-based) to lower the barriers to winter science monitoring participation and improve the understanding of watershed linkages as well as the role of winter in the basin-wide delivery of ecosystem services.
- **Expand upon existing CSMI sampling** effort and framework to include all seasons and fill the gaps between CSMI sampling years by dedicating ice-breaking and ice-hardened vessels to science activities on one lake per year in conjunction with CSMI priorities.
- **Develop a master, open access, winter science database** that leverages AI to consolidate and pull from existing databases and makes collected winter data more F.A.I.R. (findable, accessible, interoperable, and reusable) while ensuring data QA/QC standards are met.
- **Build winter science capacity** by lowering barriers to entry and emphasizing early career training, internships, outreach, and inclusive hiring across many natural science, social science, and engineering disciplines.

6. Recommendations

The following recommendations have been synthesized from the above-described project activities and detail important actions and investments for the IJC SAB to consider making to address the identified winter science needs and priorities:

- Within the next 18 months, the IJC Science Advisory Board should encourage the GLWQA Annex 10 (Science) to perform a binational analysis to articulate the specific winter data gaps that can be met by monitoring and that are limiting policy development and lake management decision making (e.g., Annex 2).
- Promote the development of a coordinated binational plan by 2027 to improve modeling and forecasting of ice properties for both short-term and long-term time horizons through targeted winter data validation.
- Improve winter data collection through the support of the nascent GLWiN Network or a similar coordination group, to improve winter science monitoring coordination and infrastructure (both offshore and shore-based) and lower the barriers to winter science monitoring participation.
- Encourage improved understanding of watershed linkages as well as the role of winter in the basin-wide delivery of ecosystem services by requesting that a short scoping document be developed collaboratively by 2027 among all IJC advisory boards with Great Lakes roles.
- Charge the lead coordinating agencies of the Cooperative Science and Monitoring Initiative (CSMI) with developing guidance language and programmatic approaches to include all seasons and fill the gaps between CSMI sampling years by securing access to ice-breaking and ice-hardened vessels to support science activities on one lake and associated connecting waters per year, in conjunction with CSMI priorities.
- Request that federal agencies including NSF, NSERC, and Sea Grant develop an architecture by 2027 for a master, open-access, winter science database that leverages AI to consolidate information from existing databases and makes collected winter data more consistent with F.A.I.R. principles (findable, accessible, interoperable, and reusable) while ensuring data quality standards are met.
- Formally communicate the IJC's support for building winter science capacity by lowering barriers to entry and emphasizing early career training, internships, outreach, and inclusive hiring to the governments of Canada and the U.S. and federal science funding agencies, as well as major research institutions in the region, as part of the implementation plan for the Great Lakes science strategy.

Implementing this combination of immediate (within the next 18 months) and long-term (within the next three to five years) recommendations will serve to capitalize on current winter science momentum, while helping to support the foundation of a long-term winter science vision that enables more collaborative and impactful winter science to inform Great Lakes policy and management decisions.

7. References

Agbeti, M. D., & Smol, J. P. (1995). Winter limnology: A comparison of physical, chemical and biological characteristics in two temperate lakes during ice cover. Hydrobiologia, 304(3), 221–234. https://doi.org/10.1007/BF02329316

Anderson, E. J., Stow, C. A., Gronewold, A. D., Mason, L. A., McCormick, M. J., Qian, S. S., Ruberg, S. A., Beadle, K., Constant, S. A., & Hawley, N. (2021). Seasonal overturn and stratification changes drive deep-water warming in one of Earth's largest lakes. Nature Communications, 12(1), Article 1. https://doi.org/10.1038/s41467-021-21971-1

Aslamov, I., Kirillin, G., Makarov, M., Kucher, K., Gnatovsky, R., & Granin, N. (2021). Autonomous System for Lake Ice Monitoring. Sensors, 21(24), Article 24. https://doi.org/10.3390/s21248505

Assel, R. A. (2005). Classification of Annual Great Lakes Ice Cycles: Winters of 1973–2002. Journal of Climate, 18(22), 4895–4905. https://doi.org/10.1175/JCLI3571.1

Austin, J. A. (2019). Observations of radiatively driven convection in a deep lake. Limnology and Oceanography, 64(5), 2152–2160. https://doi.org/10.1002/lno.11175

Austin, J., & Elmer, C. (2022). An archive of Lake Superior temperature and current measurements, 2005–2020. Limnology and Oceanography Letters, n/a(n/a). https://doi.org/10.1002/lol2.10293

Austin, J., Hill, C., Fredrickson, J., Weber, G., & Weiss, K. (2022). Characterizing temporal and spatial scales of radiatively driven convection in a deep, ice-free lake. Limnology and Oceanography, 67(10), 2296–2308. https://doi.org/10.1002/lno.12203

Basu, A., Culpepper, J., Blagrave, K. & Sharma, S. (2024). Phenological shifts in lake ice cover across the Northern Hemisphere: A glimpse into the past, present, and the future of lake ice phenology. Water Resources Research, 60(9), p.e2023WR036392.

Beall, B. F. N., Twiss, M. R., Smith, D. E., Oyserman, B. O., Rozmarynowycz, M. J., Binding, C. E., Bourbonniere, R. A., Bullerjahn, G. S., Palmer, M. E., Reavie, E. D., Waters, L. M. K., Woityra, L. W. C., & McKay, R. M. L. (2016). Ice cover extent drives phytoplankton and bacterial community structure in a large north-temperate lake: Implications for a warming climate: Effect of ice cover on microbial community structure. Environmental Microbiology, 18(6), 1704–1719. https://doi.org/10.1111/1462-2920.12819

Block, B. D., Denfeld, B. A., Stockwell, J. D., Flaim, G., Grossart, H.-P. F., Knoll, L. B., Maier, D. B., North, R. L., Rautio, M., Rusak, J. A., Sadro, S., Weyhenmeyer, G. A., Bramburger, A. J., Branstrator, D. K., Salonen, K., & Hampton, S. E. (2019). The unique methodological challenges of winter limnology. Limnology and Oceanography: Methods, 17(1), 42–57. https://doi.org/10.1002/lom3.10295

Bluteau, C. E., Galbraith, P. S., Bourgault, D., Villeneuve, V., & Tremblay, J.-É. (2021). Winter observations alter the seasonal perspectives of the nutrient transport pathways into the lower St. Lawrence Estuary. Ocean Science, 17(5), 1509–1525. https://doi.org/10.5194/os-17-1509-2021

Bockenstedt, V., & Haines, D. (2020). Under-Ice Water Quality Assessment in Perch Lake, Mud Lake, and Kimballs Bay.

Bramburger, A. J., Ozersky, T., Silsbe, G. M., Crawford, C. J., Olmanson, L. G., & Shchapov, K. (2023). The not-so-dead of winter: underwater light climate and primary productivity under snow and ice cover in inland lakes. Inland Waters, 13(1), 1–12. https://doi.org/10.1080/20442041.2022.2102870

Briscoe, T., & O'Connell, P. (2020). Ice Shapes Economy, Identity of Lake Superior's Coastal Towns. But It's Disappearing: 'Culture Is Defined by How the World Around Us Looks — and Now That's Changing.' Chicago Tribune. https://pulitzercenter.org/stories/ice-shapes-economy-identity-lake-superiors-coastal-towns-its-disappearing-culture-defined

Brownscombe, J. W., Griffin, L. P., Brooks, J. L., Danylchuk, A. J., Cooke, S. J., & Midwood, J. D. (2022). Applications of telemetry to fish habitat science and management. Canadian Journal of Fisheries and Aquatic Sciences, 79(8), 1347–1359. https://doi.org/10.1139/cjfas-2021-0101

Buchinger, T. J., Hondorp, D. W., & Krueger, C. C. (2022). Local diversity in phenological responses of migratory lake sturgeon to warm winters. Oikos, 2022(6), e08977. https://doi.org/10.1111/oik.08977

Burns, N. M., Rosa, F., & Gedeon, A. (1978). Lake Erie in Mid-Winter. Journal of Great Lakes Research, 4(2), 134–141. https://doi.org/10.1016/S0380-1330(78)72178-7

Butler, T. M., Wilhelm, A.-C., Dwyer, A. C., Webb, P. N., Baldwin, A. L., & Techtmann, S. M. (2019). Microbial community dynamics during lake ice freezing. Scientific Reports, 9(1), Article 1. https://doi.org/10.1038/s41598-019-42609-9

Byun, K., & Hamlet, A. F. (2018). Projected changes in future climate over the Midwest and Great Lakes region using downscaled CMIP5 ensembles. International Journal of Climatology, 38(S1), e531–e553. https://doi.org/10.1002/joc.5388

Cannon, D. J., Troy, C., Bootsma, H., Liao, Q., & MacLellan-Hurd, R.-A. (2021). Characterizing the Seasonal Variability of Hypolimnetic Mixing in a Large, Deep Lake. Journal of Geophysical Research: Oceans, 126(11), e2021JC017533. https://doi.org/10.1029/2021JC017533

Casson, N. J., Contosta, A. R., Burakowski, E. A., Campbell, J. L., Crandall, M. S., Creed, I. F., Eimers, M. C., Garlick, S., Lutz, D. A., Morison, M. Q., Morzillo, A. T., & Nelson, S. J. (2019). Winter Weather Whiplash: Impacts of Meteorological Events Misaligned With Natural and Human Systems in Seasonally Snow-Covered Regions. Earth's Future, 7(12), 1434–1450. https://doi.org/10.1029/2019EF001224

Cavaliere, E., Fournier, I. B., Hazuková, V., Rue, G. P., Sadro, S., Berger, S. A., Cotner, J. B., Dugan, H. A., Hampton, S. E., Lottig, N. R., McMeans, B. C., Ozersky, T., Powers, S. M., Rautio, M., & O'Reilly, C. M. (2021). The Lake Ice Continuum Concept: Influence of Winter Conditions on Energy and Ecosystem Dynamics. Journal of Geophysical Research: Biogeosciences, 126(11), e2020JG006165. https://doi.org/10.1029/2020JG006165

Chiapella, A. M., Grigel, H., Lister, H., Hrycik, A., O'Malley, B. P., & Stockwell, J. D. (2021). A day in the life of winter plankton: Under-ice community dynamics during 24 h in a eutrophic lake. Journal of Plankton Research, 43(6), 865–883. https://doi.org/10.1093/plankt/fbab061

Chin, N., Byun, K., Hamlet, A. F., & Cherkauer, K. A. (2018). Assessing potential winter weather response to climate change and implications for tourism in the U.S. Great Lakes and Midwest. Journal of Hydrology: Regional Studies, 19, 42–56. https://doi.org/10.1016/j.ejrh.2018.06.005

Cotner, J. B., Powers, S. M., Sadro, S., & McKnight, D. (2022). Whither Winter: The Altered Role of Winter for Freshwaters as the Climate Changes. Journal of Geophysical Research: Biogeosciences, 127(6), e2021JG006761. https://doi.org/10.1029/2021JG006761

DeGrandpre, E. L., DeGrandpre, M. D., Colman, B. P., & Valett, H. M. (2021). Observations of River Solute Concentrations during Ice Formation. ACS ES&T Water, 1(8), 1695–1701. https://doi.org/10.1021/acsestwater.1c00064

D'souza, N. A. (2012). Psychrophilic diatoms in ice-covered Lake Erie [Bowling Green State University]. https://www.proquest.com/docview/1019991213?pq-origsite=gscholar&fromopenview=true

D'souza, N. A., Kawarasaki, Y., Gantz, J. D., Lee, R. E., Beall, B. F. N., Shtarkman, Y. M., Koçer, Z. A., Rogers, S. O., Wildschutte, H., Bullerjahn, G. S., & McKay, R. M. L. (2013). Diatom assemblages promote ice formation in large lakes. The ISME Journal, 7(8), 1632–1640. https://doi.org/10.1038/ismej.2013.49

Dugan, H. A. (2021). A Comparison of Ecological Memory of Lake Ice-Off in Eight North-Temperate Lakes. Journal of Geophysical Research: Biogeosciences, 126(6), e2020JG006232. https://doi.org/10.1029/2020JG006232

Dugan, H. A., Rock, L. A., Kendall, A. D., & Mooney, R. J. (2021). Tributary chloride loading into Lake Michigan. Limnology and Oceanography Letters, n/a(n/a). https://doi.org/10.1002/lol2.10228

Dvoretsky, V. G., & Dvoretsky, A. G. (2021). Winter Zooplankton in a Small Arctic Lake: Abundance and Vertical Distribution. Water, 13(7), Article 7. https://doi.org/10.3390/w13070912

Ellis, A. W., & Suriano, Z. J. (2022). A Hybrid Dataset of Historical Cool-Season Lake Effects From the Eastern Great Lakes of North America. https://doi.org/10.3389/frwa.2022.788493

Environment and Climate Change Canada. (2022). Climate trends and variations bulletin: Winter 2021-2022. https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/trends-variations/winter2022/Climate%20Trends-Winter2022-EN.pdf

Fichot, C. G., Matsumoto, K., Holt, B., Gierach, M. M., & Tokos, K. S. (2019). Assessing change in the overturning behavior of the Laurentian Great Lakes using remotely sensed lake surface water temperatures. Remote Sensing of Environment, 235, 111427. https://doi.org/10.1016/j.rse.2019.111427

Fujisaki-Manome, A., Anderson, E. J., Kessler, J. A., Chu, P. Y., Wang, J., & Gronewold, A. D. (2020). Simulating Impacts of Precipitation on Ice Cover and Surface Water Temperature Across Large Lakes. Journal of Geophysical Research: Oceans, 125(5), e2019JC015950. https://doi.org/10.1029/2019JC015950

Fujisaki-Manome, A., Wright, D. M., Mann, G. E., Anderson, E. J., Chu, P., Jablonowski, C., & Benjamin, S. G. (2022a). Forecasting lake-/sea-effect snowstorms, advancement, and challenges. WIREs Water, 9(4), e1594. https://doi.org/10.1002/wat2.1594

Fujisaki-Manome, A., Gill, D., Channell, K., Graves, V., Jagannathan, K. A., Anderson, E. J., & Lemos, M. C. (2022b). Scaling-up Stakeholder Engagement Efforts to Inform Better Communication & Uptake of NOAA Great Lakes Ice Forecast Information. https://doi.org/10.7302/4389

Fujisaki-Manome, A., Cannon, D., & King, K. (2024). Daily mean air temperature data for the North American Great Lakes based on coastal weather stations; 1897-2023 (NCEI Accession 0291722). NOAA National Centers for Environmental Information. Dataset. https://doi.org/10.25921/ws45-s314. Accessed Dec 12, 2024.

Gorsky, A. L., Lottig, N. R., Stoy, P. C., Desai, A. R., & Dugan, H. A. (2021). The Importance of Spring Mixing in Evaluating Carbon Dioxide and Methane Flux From a Small North-Temperate Lake in Wisconsin, United States. Journal of Geophysical Research: Biogeosciences, 126(12), e2021JG006537. https://doi.org/10.1029/2021JG006537

Grosbois, G., Mariash, H., Schneider, T., & Rautio, M. (2017). Under-ice availability of phytoplankton lipids is key to freshwater zooplankton winter survival. Scientific Reports, 7(1), 11543. https://doi.org/10.1038/s41598-017-10956-0

Gunn, G. E., Tarabara, V., Rutty, M., Bessette, D. L., & Richardson, R. B. (2021). Roughness and storage capacity of freshwater ice in the Straits of Mackinac. Cold Regions Science and Technology, 186, 103278. https://doi.org/10.1016/j.coldregions.2021.103278

Hampton, S., Dugan, H., Sadro, S., Vick-Majors, T., Ozersky, T. (2024). Winter limnology on the rise. Limnology & Oceanography Bulletin 33 (3): 132-133. https://doi.org/10.1002/lob.10643

Hartley, B., Theuerkauf, E. J., Zoet, L., Rawling, J. E., III, & Dodge, S. (2020). Relationship between nearshore bathymetry, winter shore ice and coastal erosion: A case study from the Laurentian Great Lakes, USA. 2020, EP061-0026.

Hazuková, V., Burpee, B. T., McFarlane-Wilson, I., & Saros, J. E. (2021). Under Ice and Early Summer Phytoplankton Dynamics in Two Arctic Lakes with Differing DOC. Journal of Geophysical Research: Biogeosciences, 126(4), e2020JG005972. https://doi.org/10.1029/2020JG005972

Hébert, M.-P., Beisner, B. E., Rautio, M., & Fussmann, G. F. (2021). Warming winters in lakes: Later ice onset promotes consumer overwintering and shapes springtime planktonic food webs. Proceedings of the National Academy of Sciences, 118(48), e2114840118. https://doi.org/10.1073/pnas.2114840118

Hessler, T. M., Chapman, D. C., Paukert, C. P., Jolley, J. C., & Byrne, M. E. (2023). Winter Habitat Selection and Efficacy of Telemetry to Aid Grass Carp Removal Efforts in a Large Reservoir. North American Journal of Fisheries Management, 43(1), 189–202. https://doi.org/10.1002/nafm.10693

Higgins, S. N., Desjardins, C. M., Drouin, H., Hrenchuk, L. E., & van der Sanden, J. J. (2021). The Role of Climate and Lake Size in Regulating the Ice Phenology of Boreal Lakes. Journal of Geophysical Research: Biogeosciences, 126(3), e2020JG005898. https://doi.org/10.1029/2020JG005898

Hrycik, A. (2021). Effects of changing winter severity on plankton ecology in temperate lakes. Graduate College Dissertations and Theses. https://scholarworks.uvm.edu/graddis/1371

Hrycik, A., Isles, P., Pierson, D., & Stockwell, J. (2021). Winter/Spring Runoff is Earlier, More Protracted, and Increasing in Volume in the Laurentian Great Lakes Basin. 2021, H53E-01.

Hrycik, A. R., McFarland, S., Morales-Williams, A., & Stockwell, J. D. (2022). Winter severity shapes spring plankton succession in a small, eutrophic lake. Hydrobiologia, 849(9), 2127–2144. https://doi.org/10.1007/s10750-022-04854-4

Huber, J., Shrethsa, P., Vander Bilt, L., & Nowicki, A. (2022). Using Fuzzy Cognitive Mapping to Assess the Impacts of Climate Change on Great Lakes Ecosystem Services. http://deepblue.lib.umich.edu/handle/2027.42/172215

Huziy, O., Teufel, B., Sushama, L., & Yerubandi, R. (2021). Heavy Lake effect Snowfall Changes and Mechanisms for the Laurentian Great Lakes Region. Atmosphere, 12(12), Article 12. https://doi.org/10.3390/atmos12121577

IJC (International Joint Commission). (2012). Great Lakes Water Quality Agreement. https://www.ijc.org/sites/default/files/2018-07/GLWQA_2012.pdf. Accessed Dec 13, 2024.

Imrit, M. A., & Sharma, S. (2021). Climate Change is Contributing to Faster Rates of Lake Ice Loss in Lakes Around the Northern Hemisphere. Journal of Geophysical Research: Biogeosciences, 126(7), e2020JG006134. https://doi.org/10.1029/2020JG006134

IPCC (Intergovernmental Panel on Climate Change). (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) Cambridge University Press. https://doi.org/10.1017/9781009157940

Isles, P. D. F., Creed, I. F., Hessen, D. O., Kortelainen, P., Paterson, M., Pomati, F., Rusak, J. A., Vuorenmaa, J., & Bergström, A.-K. (2023). Widespread synchrony in phosphorus concentrations in northern lakes linked to winter temperature and summer precipitation. Limnology and Oceanography Letters, 8(4), 639–648. https://doi.org/10.1002/lol2.10318

Ivanova, S. V., Johnson, T. B., Metcalfe, B., & Fisk, A. T. (2021). Spatial distribution of lake trout (Salvelinus namaycush) across seasonal thermal cycles in a large lake. Freshwater Biology, 66(4), 615–627. https://doi.org/10.1111/fwb.13665

Iwaloye, O. F. (2021). Metagenomics and Metatranscriptomics of Lake Erie Ice [Bowling Green State University]. https://www.proquest.com/openview/d3396798accf70c2c325dafb18de7dde/1?pq-origsite=gscholar&cbl=18750&diss=y

Jane, S. F., Hansen, G. J. A., Kraemer, B. M., Leavitt, P. R., Mincer, J. L., North, R. L., Pilla, R. M., Stetler, J. T., Williamson, C. E., Woolway, R. I., Arvola, L., Chandra, S., DeGasperi, C. L., Diemer, L., Dunalska, J., Erina, O., Flaim, G., Grossart, H.-P., Hambright, K. D., … Rose, K. C. (2021). Widespread deoxygenation of temperate lakes. Nature, 594(7861), Article 7861. https://doi.org/10.1038/s41586-021-03550-y

Jankowski, K. J., Houser, J. N., Scheuerell, M. D., & Smits, A. P. (2021). Warmer Winters Increase the Biomass of Phytoplankton in a Large Floodplain River. Journal of Geophysical Research: Biogeosciences, 126(9), e2020JG006135. https://doi.org/10.1029/2020JG006135

Jansen, J., MacIntyre, S., Barrett, D. C., Chin, Y.-P., Cortés, A., Forrest, A. L., Hrycik, A. R., Martin, R., McMeans, B. C., Rautio, M., & Schwefel, R. (2021). Winter Limnology: How do Hydrodynamics and Biogeochemistry Shape Ecosystems Under Ice? Journal of Geophysical Research: Biogeosciences, 126(6), e2020JG006237. https://doi.org/10.1029/2020JG006237

Jasonowicz, A., Sitar, S., Seider, M., & Goetz, F. (2022). Depth and temperature selection of lake charr (Salvelinus namaycush) ecotypes in Lake Superior revealed by popup satellite archival tags. Journal of Great Lakes Research, 48(4), 1050–1066. https://doi.org/10.1016/j.jglr.2022.05.003

Ji, X., Gronewold, A. D., Daher, H., & Rood, R. B. (2019). Modeling seasonal onset of coastal ice. Climatic Change, 154(1), 125–141. https://doi.org/10.1007/s10584-019-02400-1

Johnson, N. S., Adams, J. V., Bravener, G., Barber, J., Treska, T., & Siefkes, M. J. (2021). Winter severity, fish community, and availability to traps explain most of the variability in estimates of adult sea lamprey in Lake Superior. Journal of Great Lakes Research, 47, S347–S356. https://doi.org/10.1016/j.jglr.2020.08.011

Kane, D. D., Manning, N. F., & Johnson, L. T. (2022). When it snows it pours: Increased chloride concentrations in the Cuyahoga River during the last half century. Journal of Great Lakes Research. https://doi.org/10.1016/j.jglr.2022.08.017

Kraus, R. T., Bontrager, H., Vandergoot, C. S., & Faust, M. D. (2021). Expanding freshwater biologger studies to view fish as environmental sensing platforms. Marine and Freshwater Research, 73(1), 133–139. https://doi.org/10.1071/MF21046

Kulie, M. S., Pettersen, C., Merrelli, A. J., Wagner, T. J., Wood, N. B., Dutter, M., Beachler, D., Kluber, T., Turner, R., Mateling, M., Lenters, J., Blanken, P., Maahn, M., Spence, C., Kneifel, S., Kucera, P. A., Tokay, A., Bliven, L. F., Wolff, D. B., & Petersen, W. A. (2021). Snowfall in the Northern Great Lakes: Lessons Learned from a Multisensor Observatory. Bulletin of the American Meteorological Society, 102(7), E1317–E1339. https://doi.org/10.1175/BAMS-D-19-0128.1

Lam, S., & Dokoska, K. (2022). Climate Change in the Great Lakes Basin: Summary of Trends and Impacts. Toronto and Region Conservation Authority. https://binational.net/wp-content/uploads/2022/11/Climate-Change-in-the-Great-Lakes-Basin_English-1.pdf

Li, X., Peng, S., Xi, Y., Woolway, R. I., & Liu, G. (2022). Earlier ice loss accelerates lake warming in the Northern Hemisphere. Nature Communications, 13(1), Article 1. https://doi.org/10.1038/s41467-022-32830-y

Lin, Y.-C., Fujisaki-Manome, A., & Wang, J. (2022). Recently amplified interannual variability of the Great Lakes ice cover in response to changing teleconnections. Journal of Climate, 1(aop), 1–52. https://doi.org/10.1175/JCLI-D-21-0448.1

Liu, L., Davedu, S., Fujisaki-Manome, A., Hu, H., Jablonowski, C., & Chu, P. Y. (2022). Machine Learning Model-Based Ice Cover Forecasting for a Vital Waterway in Large Lakes. Journal of Marine Science and Engineering, 10(8), Article 8. https://doi.org/10.3390/jmse10081022

Lofgren, B., Wang, J., & DeYoung, C. (2021). Teleconnection and Other Patterns Associated with Laurentian Great Lakes Ice Cover. 2021, H52G-01.

Mackie, C., Lackey, R., Levison, J., & Rodrigues, L. (2022). Groundwater as a source and pathway for road salt contamination of surface water in the Lake Ontario Basin: A review. Journal of Great Lakes Research, 48(1), 24–36. https://doi.org/10.1016/j.jglr.2021.11.015

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., Kuusisto, E., Granin, N. G., Prowse, T. D., Stewart, K. M., & Vuglinski, V. S. (2000). Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science, 289(5485), 1743–1746. https://doi.org/10.1126/science.289.5485.1743

Marcaccio, J. V., Gardner Costa, J., Brooks, J. L., Boston, C. M., Cooke, S. J., & Midwood, J. D. (2022). Automated Coastal Ice Mapping with SAR Can Inform Winter Fish Ecology in the Laurentian Great Lakes. Canadian Journal of Remote Sensing, 48(1), 19–36. https://doi.org/10.1080/07038992.2021.1946385

Marcek, B. J., Farmer, T. M., Marschall, E. A., Petris, G., & Ludsin, S. A. (2021). Ecosystem change as a driver of fish recruitment dynamics: A case study of two Lake Erie yellow perch populations. Freshwater Biology, 66(6), 1149–1168. https://doi.org/10.1111/fwb.13707

Marsden, J. E., Blanchfield, P. J., Brooks, J. L., Fernandes, T., Fisk, A. T., Futia, M. H., Hlina, B. L., Ivanova, S. V., Johnson, T. B., Klinard, N. V., Krueger, C. C., Larocque, S. M., Matley, J. K., McMeans, B., O'Connor, L. M., Raby, G. D., & Cooke, S. J. (2021). Using untapped telemetry data to explore the winter biology of freshwater fish. Reviews in Fish Biology and Fisheries, 31(1), 115–134. https://doi.org/10.1007/s11160-021-09634-2

Massé, S., Botrel, M., Walsh, D. A., & Maranger, R. (2019). Annual nitrification dynamics in a seasonally ice-covered lake. PLOS ONE, 14(3), e0213748. https://doi.org/10.1371/journal.pone.0213748

Mateling, M. E., Pettersen, C., Kulie, M. S., Mattingly, K. S., Henderson, S. A., & L'Ecuyer, T. S. (2021). The Influence of Atmospheric Rivers on Cold-Season Precipitation in the Upper Great Lakes Region. Journal of Geophysical Research: Atmospheres, 126(13), e2021JD034754. https://doi.org/10.1029/2021JD034754

McAdams, B. C., Arnold, W. A., Wilkins, M. J., & Chin, Y. P. (2021). Ice Cover Influences Redox Dynamics in Prairie Pothole Wetland Sediments. Journal of Geophysical Research: Biogeosciences, 126(10), e2021JG006318. https://doi.org/10.1029/2021JG006318

McMeans, B. C., McCann, K. S., Guzzo, M. M., Bartley, T. J., Bieg, C., Blanchfield, P. J., Fernandes, T., Giacomini, H. C., Middel, T., Rennie, M. D., Ridgway, M. S., & Shuter, B. J. (2020). Winter in water: Differential responses and the maintenance of biodiversity. Ecology Letters, 23(6), 922–938. https://doi.org/10.1111/ele.13504

Meng, L., Ayon, B. D., Koirala, N., & Baker, K. M. (2021). Inter-annual Variability of Snowfall in the Lower Peninsula of Michigan. Frontiers in Water, 3, 746354.

Meng, L., & Ma, Y. (2021). On the relationship of lake effect snowfall and teleconnections in the Lower Peninsula of Michigan, USA. Journal of Great Lakes Research, 47(1), 134–144. https://doi.org/10.1016/j.jglr.2020.11.013

Midwood, J. D., Rous, A. M., Doka, S. E., & Cooke, S. J. (2019). Acoustic telemetry in Toronto Harbour: Assessing residency, habitat selection, and within-harbour movements of fishes over a five-year period.

Miess, S., Chrisekos, A., & Strand, M. (2022). An Ecological Profile of Hydropsyche alternans (Trichoptera: Hydropsychidae) in Lake Superior, the Last Stronghold of a Once-Dominant Great Lakes Surf Zone Caddisfly. Insects, 13(7), Article 7. https://doi.org/10.3390/insects13070659

Minallah, S., & Steiner, A. L. (2021). Analysis of the Atmospheric Water Cycle for the Laurentian Great Lakes Region Using CMIP6 Models. Journal of Climate, 34(12), 4693–4710. https://doi.org/10.1175/JCLI-D-20-0751.1

Mooney, R. J., Stanley, E. H., Rosenthal, W. C., Esselman, P. C., Kendall, A. D., & McIntyre, P. B. (2020). Outsized nutrient contributions from small tributaries to a Great Lake. Proceedings of the National Academy of Sciences, 117(45), 28175–28182. https://doi.org/10.1073/pnas.2001376117

Motiee, H., & McBean, E. (2017). Assessment of Climate Change Impacts on Groundwater Recharge for Different Soil Types-Guelph Region in Grand River Basin, Canada. 5.

Myers, D. T., Ficklin, D. L., & Robeson, S. M. (2021). Incorporating rain-on-snow into the SWAT model results in more accurate simulations of hydrologic extremes. Journal of Hydrology, 603, 126972. https://doi.org/10.1016/j.jhydrol.2021.126972

National Research Council of the United States and the Royal Society of Canada. (1985). The Great Lakes water quality agreement: An evolving instrument for ecosystem management. Washington, D.C.: National Academy Press ; Ottawa, Ontario: Royal Society of Canada, 1985. https://search.library.wisc.edu/catalog/999596629102121

Nelligan, C., Sorichetti, R. J., Yousif, M., Thomas, J. L., Wellen, C. C., Parsons, C. T., & Mohamed, M. N. (2021). Then and now: Revisiting nutrient export in agricultural watersheds within southern Ontario's lower Great Lakes basin. Journal of Great Lakes Research, 47(6), 1689–1701. https://doi.org/10.1016/j.jglr.2021.08.010

Nicholls, K. H., & Dillon, P. J. (1978). An Evaluation of Phosphorus-Chlorophyll-Phytoplankton Relationships for Lakes. Internationale Revue Der Gesamten Hydrobiologie Und Hydrographie, 63(2), 141–154. https://doi.org/10.1002/iroh.19780630203

Notaro, M., Jorns, J., & Briley, L. (2022). Representation of Lake–Atmosphere Interactions and Lake effect Snowfall in the Laurentian Great Lakes Basin among HighResMIP Global Climate Models. Journal of the Atmospheric Sciences, 79(5), 1325–1347. https://doi.org/10.1175/JAS-D-21-0249.1

Notaro, M., Zhong, Y., Xue, P., Peters-Lidard, C., Cruz, C., Kemp, E., Kristovich, D., Kulie, M., Wang, J., Huang, C., & Vavrus, S. J. (2021). Cold Season Performance of the NU-WRF Regional Climate Model in the Great Lakes Region. Journal of Hydrometeorology, 22(9), 2423–2454. https://doi.org/10.1175/JHM-D-21-0025.1

Ozersky, T., Bramburger, A. J., Elgin, A. K., Vanderploeg, H. A., Wang, J., Austin, J. A., Carrick, H. J., Chavarie, L., Depew, D. C., Fisk, A. T., Hampton, S. E., Hinchey, E. K., North, R. L., Wells, M. G., Xenopoulos, M. A., Coleman, M. L., Duhaime, M. B., Fujisaki-Manome, A., McKay, R. M., … Zastepa, A. (2021). The Changing Face of Winter: Lessons and Questions from the Laurentian Great Lakes. Journal of Geophysical Research: Biogeosciences, 126(6), e2021JG006247. https://doi.org/10.1029/2021JG006247

Porterfield, J. (2021). High Wave Events on the Great Lakes in Relation to El Niño-Southern Oscillation Influences on Mid-Latitude Cyclones: What Can Storm Patterns Tell Us about Extreme Wave Events in the Future? [Northeastern Illinois University]. https://www.proquest.com/openview/290c24bcce10783ddbc9bf7742aacc33/1?pq-origsite=gscholar&cbl=18750&diss=y

Powers, S. M., & Hampton, S. E. (2016). Winter Limnology as a New Frontier. Limnology and Oceanography Bulletin, 25(4), 103–108. https://doi.org/10.1002/lob.10152

Powers, S.M., Baulch, H.M., Hampton, S.E., Labou, S.G., Lottig, N.R., & Stanley, E.H. Nitrification contributes to winter oxygen depletion in seasonally frozen forested lakes. Biogeochemistry 136, 119–129 (2017). https://doi.org/10.1007/s10533-017-0382-1

Pu et al. (2025). The Great Lakes Winter Grab: Limnological data from a multi-institutional winter sampling campaign on the Laurentian Great Lakes.. Limnology & Oceanography Letters 10, 37-61. https://aslopubs.onlinelibrary.wiley.com/doi/epdf/10.1002/lol2.10447

Putland, R. L., Austin, J. A., Hill, C. S., & Mensinger, A. F. (2022). A song of ice and vessels: Seasonal trends in the soundscape of the western arm of Lake Superior. Journal of Great Lakes Research, 48(2), 478–488. https://doi.org/10.1016/j.jglr.2022.01.003

Rabaey, J. S., Domine, L. M., Zimmer, K. D., & Cotner, J. B. (2021). Winter Oxygen Regimes in Clear and Turbid Shallow Lakes. Journal of Geophysical Research: Biogeosciences, 126(3), e2020JG006065. https://doi.org/10.1029/2020JG006065

Ransom, A. L., Houghton, C. J., Hanson, S. D., Hansen, S. P., Doerr, L. R., & Forsythe, P. S. (2021). Recolonization of lake whitefish river spawning ecotypes and estimates of riverine larval production in Green Bay, Lake Michigan. Journal of Great Lakes Research, 47(1), 213–225. https://doi.org/10.1016/j.jglr.2020.11.011

Ranta, M. P., & Kapuscinski, K. L. (2022). Winter diets of round whitefish *Prosopium cylindraceum* in the St. Marys River. Journal of Great Lakes Research, 48(1), 238–244. https://doi.org/10.1016/j.jglr.2021.11.012

Sadro, S. and M. A. Xenopoulos (2022), A future without ice cover, Eos, 103, https://doi.org/10.1029/2022EO225021

Sawakuchi, H. O., Martin, G., Peura, S., Bertilsson, S., Karlsson, J., & Bastviken, D. (2021). Phosphorus Regulation of Methane Oxidation in Water from Ice-Covered Lakes. Journal of Geophysical Research: Biogeosciences, 126(9), e2020JG006190. https://doi.org/10.1029/2020JG006190

Seybold, E. C., Dwivedi, R., Musselman, K. N., Kincaid, D. W., Schroth, A. W., Classen, A. T., Perdrial, J. N., & Adair, E. C. (2022). Winter runoff events pose an unquantified continental-scale risk of high wintertime nutrient export. Environmental Research Letters, 17(10), 104044. https://doi.org/10.1088/1748-9326/ac8be5

Shao, C., Chen, J., Chu, H., Stepien, C. A., & Ouyang, Z. (2020). Intra-Annual and Interannual Dynamics of Evaporation Over Western Lake Erie. Earth and Space Science, 7(11), e2020EA001091. https://doi.org/10.1029/2020EA001091

Sharma, S., Blagrave, K., Watson, S. R., O'Reilly, C. M., Batt, R., Magnuson, J. J., Clemens, T., Denfeld, B. A., Flaim, G., Grinberga, L., Hori, Y., Laas, A., Knoll, L. B., Straile, D., Takamura, N., & Weyhenmeyer, G. A. (2020). Increased winter drownings in ice-covered regions with warmer winters. PLOS ONE, 15(11), e0241222. https://doi.org/10.1371/journal.pone.0241222

Sharma, S., Meyer, M. F., Culpepper, J., Yang, X., Hampton, S., Berger, S. A., Brousil, M. R., Fradkin, S. C., Higgins, S. N., Jankowski, K. J., Kirillin, G., Smits, A. P., Whitaker, E. C., Yousef, F., & Zhang, S. (2020). Integrating Perspectives to Understand Lake Ice Dynamics in a Changing World. Journal of Geophysical Research: Biogeosciences, 125(8), e2020JG005799. https://doi.org/10.1029/2020JG005799

Sharma, S., Richardson, D. C., Woolway, R. I., Imrit, M. A., Bouffard, D., Blagrave, K., Daly, J., Filazzola, A., Granin, N., Korhonen, J., Magnuson, J., Marszelewski, W., Matsuzaki, S.-I. S., Perry, W., Robertson, D. M., Rudstam, L. G., Weyhenmeyer, G. A., & Yao, H. (2021). Loss of Ice Cover, Shifting Phenology, and More Extreme Events in Northern Hemisphere Lakes. Journal of Geophysical Research: Biogeosciences, 126(10), e2021JG006348. https://doi.org/10.1029/2021JG006348

Shchapov, K., Wilburn, P., Bramburger, A. J., Silsbe, G. M., Olmanson, L., Crawford, C. J., Litchman, E., & Ozersky, T. (2021). Taxonomic and functional differences between winter and summer crustacean zooplankton communities in lakes across a trophic gradient. Journal of Plankton Research, 43(5), 732–750. https://doi.org/10.1093/plankt/fbab050

Shi, Q., & Xue, P. (2019). Impact of Lake Surface Temperature Variations on Lake Effect Snow Over the Great Lakes Region. Journal of Geophysical Research: Atmospheres, 124(23), 12553–12567. https://doi.org/10.1029/2019JD031261

Singh, N. K., Van Meter, K. J., & Basu, N. B. (2023). Widespread increases in soluble phosphorus concentrations in streams across the transboundary Great Lakes Basin. Nature Geoscience, 16(10), 893–900. https://doi.org/10.1038/s41561-023-01257-5

Snider, R., James, A. L., Yao, H., Paterson, A. M., Walters, D., & Mattson, E. (2022). Chloride and total phosphorus budgets for Lake Nipissing, headwater of Lake Huron, Ontario, Canada. Journal of Great Lakes Research, 48(4), 985–998. https://doi.org/10.1016/j.jglr.2022.05.015

Song, Z., Chomicki, K. M., Drouillard, K., & Weidman, R. P. (2022). A statistical framework for testing impacts of multiple drivers of surface water quality in nearshore regions of large lakes. Science of The Total Environment, 811, 152362. https://doi.org/10.1016/j.scitotenv.2021.152362

Steinman, A. D., Uzarski, D. G., Lusch, D. P., Miller, C., Doran, P., Zimnicki, T., Chu, P., Allan, J., Asher, J., Bratton, J., Carpenter, D., Dempsey, D., Drummond, C., Esch, J., Garwood, A., Harrison, A., Lemke, L. D., Nicholas, J., Ogilvie, W., … Yellich, J. (2022). Groundwater in Crisis? Addressing Groundwater Challenges in Michigan (USA) as a Template for the Great Lakes. Sustainability, 14(5), Article 5. https://doi.org/10.3390/su14053008

Stewart, T. R., Vinson, M. R., & Stockwell, J. D. (2021). Shining a light on Laurentian Great Lakes cisco (Coregonus artedi): How ice coverage may impact embryonic development☆. Journal of Great Lakes Research, 47(5), 1410–1418. https://doi.org/10.1016/j.jglr.2021.07.002

Stewart, T. R., Vinson, M. R., & Stockwell, J. D. (2022). Effects of warming winter embryo incubation temperatures on larval cisco (Coregonus artedi) survival, growth, and critical thermal maximum. Journal of Great Lakes Research, 48(4), 1042–1049. https://doi.org/10.1016/j.jglr.2022.04.013

Studd, E. K., Bates, A. E., Bramburger, A. J., Fernandes, T., Hayden, B., Henry, H. A. L., Humphries, M. M., Martin, R., McMeans, B. C., Moise, E. R. D., O'Sullivan, A. M., Sharma, S., Sinclair, B. J., Sutton, A. O., Templer, P. H., & Cooke, S. J. (2021). Nine Maxims for the Ecology of Cold-Climate Winters. BioScience, 71(8), 820–830. https://doi.org/10.1093/biosci/biab032

Sze, P., & Stewart, K. M. (1974). Phytoplankton succession under the ice in Lake Erie. Phycologia, 13(3), 265–266. https://doi.org/10.2216/i0031-8884-13-3-265.1

Tellier, J. M., Kalejs, N. I., Leonhardt, B. S., Cannon, D., Höök, T. O., & Collingsworth, P. D. (2022). Widespread prevalence of hypoxia and the classification of hypoxic conditions in the Laurentian Great Lakes. Journal of Great Lakes Research, 48(1), 13–23. https://doi.org/10.1016/j.jglr.2021.11.004

Thellman, A., Jankowski, K. J., Hayden, B., Yang, X., Dolan, W., Smits, A. P., & O'Sullivan, A. M. (2021). The Ecology of River Ice. Journal of Geophysical Research: Biogeosciences, 126(9), e2021JG006275. https://doi.org/10.1029/2021JG006275

Theuerkauf, E., Mattheus, C. R., Braun, K., & Bueno, J. (2021). Patterns and processes of beach and foredune geomorphic change along a Great Lakes shoreline: Insights from a year-long drone mapping study along Lake Michigan. Shore & Beach, 46–55. https://doi.org/10.34237/1008926

Titze, D. J., & Austin, J. A. (2014). Winter thermal structure of Lake Superior. Limnology and Oceanography, 59(4), 1336–1348. https://doi.org/10.4319/lo.2014.59.4.1336

Titze, D., & Austin, J. (2016). Novel, direct observations of ice on Lake Superior during the high ice coverage of winter 2013–2014. Journal of Great Lakes Research, 42(5), 997–1006. https://doi.org/10.1016/j.jglr.2016.07.026

Twiss, M. R., McKay, R. M. L., Bourbonniere, R. A., Bullerjahn, G. S., Carrick, H. J., Smith, R. E. H., Winter, J. G., D'souza, N. A., Furey, P. C., Lashaway, A. R., Saxton, M. A., & Wilhelm, S. W. (2012). Diatoms abound in ice-covered Lake Erie: An investigation of offshore winter limnology in Lake Erie over the period 2007 to 2010. Journal of Great Lakes Research, 38(1), 18–30. https://doi.org/10.1016/j.jglr.2011.12.008

Twiss, M.R., Smith, D.E., Cafferty, E.M. and Carrick, H.J. (2014). Phytoplankton growth dynamics in offshore Lake Erie during mid-winter. Journal of Great Lakes Research, 40(2), pp. 449-454.

Tye, S. P., Siepielski, A. M., Bray, A., Rypel, A. L., Phelps, N. B. D., & Fey, S. B. (2022). Climate warming amplifies the frequency of fish mass mortality events across north temperate lakes. Limnology and Oceanography Letters, n/a(n/a). https://doi.org/10.1002/lol2.10274

Wallen, D. G. (1977). Production Processes Under the Ice in Lake St. Clair: 1. Irradiation and Temperature1. JAWRA Journal of the American Water Resources Association, 13(2), 299–308. https://doi.org/10.1111/j.1752-1688.1977.tb02025.x

Wilhelm, S. W., LeCleir, G. R., Bullerjahn, G. S., McKay, R. M., Saxton, M. A., Twiss, M. R., & Bourbonniere, R. A. (2014). Seasonal changes in microbial community structure and activity imply winter production is linked to summer hypoxia in a large lake. FEMS Microbiology Ecology, 87(2), 475–485. https://doi.org/10.1111/1574-6941.12238

Winter Limnology in a Changing World. (2022). JGR: Biogeosciences. https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2169-8961.WINTERLIMNO

Wolf, P. (2022). Acoustic Telemetry Provides New Insights into the Ecology of Smallmouth Bass in Eastern Lake Ontario [Thesis]. https://qspace.library.queensu.ca/handle/1974/30293

Woolway, R. I., Anderson, E. J., & Albergel, C. (2021). Rapidly expanding lake heatwaves under climate change. Environmental Research Letters, 16(9), 094013. https://doi.org/10.1088/1748-9326/ac1a3a

Wright, R. T. (1964). Dynamics of a Phytoplankton Community in an Ice-Covered Lake. Limnology and Oceanography, 9(2), 163–178. https://doi.org/10.4319/lo.1964.9.2.0163

Xu, S., Frey, S. K., Erler, A. R., Khader, O., Berg, S. J., Hwang, H. T., Callaghan, M. V., Davison, J. H., & Sudicky, E. A. (2021). Investigating groundwater-lake interactions in the Laurentian Great Lakes with a fully-integrated surface water-groundwater model. Journal of Hydrology, 594, 125911. https://doi.org/10.1016/j.jhydrol.2020.125911

Xu, X., Frey, S. K., & Ma, D. (2022). Hydrological performance of ERA5 and MERRA-2 precipitation products over the Great Lakes Basin. Journal of Hydrology: Regional Studies, 39, 100982. https://doi.org/10.1016/j.ejrh.2021.100982

Xue, P., Ye, X., Pal, J. S., Chu, P. Y., Kayastha, M. B., & Huang, C. (2022). Climate projections over the Great Lakes Region: Using two-way coupling of a regional climate model with a 3-D lake model. Geoscientific Model Development, 15(11), 4425–4446. https://doi.org/10.5194/gmd-15-4425-2022

Ye, X., Anderson, E. J., Chu, P. Y., Huang, C., & Xue, P. (2019). Impact of Water Mixing and Ice Formation on the Warming of Lake Superior: A Model-guided Mechanism Study. Limnology and Oceanography, 64(2), 558–574. https://doi.org/10.1002/lno.11059

Zepernick, B. N., Chase, E. E., Denison, E. R., Gilbert, N. E., Truchon, A. R., Frenken, T., Cody, W. R., Martin, R. M., Chaffin, J. D., Bullerjahn, G. S., McKay, R. M. L., & Wilhelm, S. W. (2024). Declines in ice cover are accompanied by light limitation responses and community change in freshwater diatoms. The ISME Journal, 18(1). https://doi.org/10.1093/ismejo/wrad015

Appendix A: References Added to Literature Review

Balcer, M.D., N.L., Korda, and S.I., Dodson. (1984). Zooplankton of the Great Lakes: A Guide to the Identification and Ecology of the Common Crustacean Species. University of Wisconsin Press, Ltd, 188. https://api.semanticscholar.org/CorpusID:82627809

Banning, J. (2022). Breaking up: ice loss is changing one Anishinaabe fisherman's relationship with Lake Superior. https://thenarwhal.ca/lake-superior-ice-fishing/

Berge, J., Cottier, F., Varpe, Ø., Renaud, P.E., Falk-Petersen, S., Kwasniewski, S., Griffiths, C., Søreide, J.E., Johnsen, G., Aubert, A., Bjærke, O., Hovinen, J., Jung-Madsen, S., Tveit, M., Majaneva, S. (2014). Arctic complexity: a case study on diel vertical migration of zooplankton. *Journal of Plankton Research*, 36(5), 1279–1297. https://doi.org/10.1093/plankt/fbu059

Bolsenga S.J., Evans, M., Vanderploeg, H., Norton, D.G. (1996). Par Transmittance Through Thick, Clear Fresh-Water Ice. Hydrobiologia, 330(3), 227-230. 10.1007/BF00024210

Bramburger, A.J., Ozersky, T., Silsbe, G.M., Crawford, C.J., Olmanson, L.G., & Shchapov, K. (2022). The not-so-dead of winter: underwater light climate and primary productivity under snow and ice cover in inland lakes. Inland Waters, 13(1), 1-12. https://doi.org/10.1080/20442041.2022.2102870.

Brown, T.A., Rudstam, L.G., Sethi, S.A., Ripple, P., Smith, J.B., Treska, T.J., Hessell, C., Olsen, E., He, J.X., Jonas, J.L., Rook, B.J., Blankenheim, J.E., Beech, S.J.H., Brown, E., Berglund, E.K., Cook, H.A., Dunlop, E.S., James, S., Pothoven, S.A., Amidon, Z.J., Sweka, J.A., Carl, DD., Hansen, S.P., Bunnell, D.B., Weidel, B.C., Honsey, A.E. (2024). Reconstructing half a century of coregonine recruitment reveals species-specific dynamics and synchrony across the Laurentian Great Lakes. ICES Journal of Marine Science, fsae160. https://doi.org/10.1093/icesjms/fsae160

Brown, T.A., Sethi, S.A., Rudstam, L.G., Holden, J.P., Connerton, M.J., Gorsky, D., Karboski, C.T., Chalupnicki, M.A., Sard, N.M., Roseman, E.F., Prindle, S.E., Sanderson, M.J., Evans, T.M., Cooper, A., Reinhart, D.J., Davis, C., Weidel, B.C. (2022). Contemporary spatial extent and environmental drivers of larval coregonine distributions across Lake Ontario. Journal of Great Lakes Research, 48(2), 359-370, ISSN 0380-1330. https://doi.org/10.1016/j.jglr.2021.07.009

Culpepper, J., Jakobsson, E., Weyhenmeyer, G.A., Hampton, S.E., Obertegger, U., Shchapov, K., Woolway, R.I. and Sharma, S. (2024). Lake ice quality in a warming world. Nature Reviews Earth & Environment, 671-685. https://doi.org/10.1038/s43017-024-00590-6

Denison, E.R., Zepernick, B.N., McKay, R.M.L. and Wilhelm, S.W. (2024). Metatranscriptomic analysis reveals dissimilarity in viral community activity between an ice-free and ice-covered winter in Lake Erie. mSystems, 9:e00753-24. https://doi.org/10.1128/msystems.00753-24

Dodge, S.E., L.K. Zoet, J.E. Rawling, E.J. Theuerkauf, D.D. Hansen. (2022). Transport properties of fast ice within the nearshore. Coastal Engineering, Volume 177, 104176, ISSN 0378-3839. https://doi.org/10.1016/j.coastaleng.2022.104176

Dodge, S.E., L.K. Zoet, J.E. Rawling, N. Morgan-Witts, E.J. Theuerkauf. (2024). The effects of beach energy on sediment entrainment within the nearshore ice complex. Journal of Great Lakes Research,102379, ISSN 0380-1330. https://doi.org/10.1016/j.jglr.2024.102379

Farmer, T., Marschall, E., Dabrowski, K., & Ludsin, S.A. (2015). Short winters threaten temperate fish populations. Nature Communications, 6, 7724. https://doi.org/10.1038/ncomms8724

Fernandez, J.M., Townsend-Small, A., Zastepa, A., Watson, S.B. and Brandes, J.A. (2020). Methane and nitrous oxide measured throughout Lake Erie over all seasons indicate highest emissions from the eutrophic Western Basin. Journal of Great Lakes Research, 46(6), 1604-1614, ISSN 0380-1330. https://doi.org/10.1016/j.jglr.2020.09.011

García-Carreras, B., & Reuman, D. C. (2011). An empirical link between the spectral colour of climate and the spectral colour of field populations in the context of climate change. Journal of Animal Ecology. https://doi.org/10.1111/j.1365-2656.2011.01833.x

Hampton, S.E., Galloway, A.W., Powers, S.M., Ozersky, T., Woo, K.H., Batt, R.D., Labou, S.G., O'Reilly, C.M., Sharma, S., Lottig, N.R., Stanley, E.H., North, R.L., Stockwell, J.D., Adrian, R., Weyhenmeyer, G.A., Arvola, L., Baulch, H.M., Bertani, I., Bowman, L.L. Jr., Carey, C.C., Catalan, J., Colom-Montero, W., Domine, L.M., Felip, M., Granados, I., Gries, C., Grossart, H.P., Haberman, J., Haldna, M., Hayden, B., Higgins, S.N., Jolley, J.C., Kahilainen, K.K., Kaup, E., Kehoe, M.J., MacIntyre, S., Mackay, A.W., Mariash, H.L., McKay, R.M., Nixdorf, B., Nõges, P., Nõges, T., Palmer, M., Pierson, D.C., Post, D.M., Pruett, M.J., Rautio, M., Read, J.S., Roberts, S.L., Rücker, J., Sadro, S., Silow, E.A., Smith, D.E., Sterner, R.W., Swann, G.E., Timofeyev, M.A., Toro, M., Twiss, M.R., Vogt, R.J., Watson, S.B., Whiteford, E.J., Xenopoulos, M.A. (2017). Ecology under lake ice. Ecology Letters, 20(1):98-111. 10.1111/ele.12699

Hampton, S.E., Powers, S.M., Dugan, H.A., Knoll, L.B., McMeans, B.C., Meyer, M.F., O'Reilly, C.M., Ozersky, T., Sharma, S., Barrett, D.C., & Chandra, S. (2024). Environmental and societal consequences of winter ice loss from lakes. Science, 386, eadl3211. 10.1126/science.adl321

Kerfoot, W.C., Yousef, F., Green, S.A., Budd, J.W., Schwab, D.J., Vanderploeg, H.A. (2010). Approaching storm: Disappearing winter bloom in Lake Michigan. Journal of Great Lakes Research, (36)(s3), 30-41, ISSN 0380-1330. https://doi.org/10.1016/j.jglr.2010.04.010

McKindles, K., Seto, K., Nguyen, D.Q., James, T.Y., McKay, R.M. (2024). Climate-driven abiotic stressors enhance chytrid infections on a psychrotrophic diatom and shape seasonal phytoplankton succession in Lake Erie. Limnology and Oceanography.

Núñez-Riboni, I., Chelton, D.B., Marconi, V. (2023). The spectral color of natural and anthropogenic time series and its impact on the statistical significance of cross correlation. Science of The Total Environment. Volume 860,160219, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2022.160219

Oldham, R.C., and Kraus, R.T. (2023). Bottom dissolved oxygen measurements from Lake Erie's Central Basin, 2021-2022: U.S. Geological Survey data release, https://doi.org/10.5066/P9FFZWNI

Parent, S. (2024). The heartbreaking decline of Great Lakes ice cover. https://canadiangeographic.ca/articles/the-heartbreaking-decline-of-great-lakes-ice-cover/

Pu, G., Shchapov, K., Pearce, N.J., Bowen, K., Bramburger, A., Camilleri, A., Carrick, H., Chaffin, J.D., Cody, W., Coleman, M.L. and Currie, W.J. (2024). The Great Lakes Winter Grab: Limnological data from a multi-institutional winter sampling campaign on the Laurentian Great Lakes. Limnology and Oceanography Letters. https://doi.org/10.1002/lol2.10447

Shchapov, K., & Ozersky, T. (2023). Opening the black box of winter: Full-year dynamics of crustacean zooplankton along a nearshore depth gradient in a large lake. Limnology and Oceanography, *68*(7), 1438-1451. https://doi.org/10.1002/lno.12355

Seto K., Simmons, D.R., Quandt, C.A., Frenken,T., Dirks, A.C., Clemons, R.A., McKindles, K.M., McKay, R.M.L. , James, T.Y. (2023). A combined microscopy and single-cell sequencing approach reveals the ecology, morphology, and phylogeny of uncultured lineages of zoosporic fungi. *mBio*, 14**:** e01313-23. https://doi.org/10.1128/mbio.01313-23

Stow, C.A., Godwin, C.M., McKay, R.M., Collingsworth, P.D., Foley, C.J., Hinchey, E.K., Wortman, S.R., May, J.C., Yang, E. and Winslow, C. (2023). Introduction to the special section: Status and approaches to assess Lake Erie Central Basin hypoxia. Journal of Great Lakes Research, 49(5), 949-952, ISSN 0380-1330. https://doi.org/10.1016/j.jglr.2023.08.005

Stewart, T.R., Karjalainen, J., Zucchetta, M., Goulon, C., Anneville, O., Vinson, M.R., Wanzenböck, J., & Stockwell, J.D. (2024). Winter is not coming: evaluating impacts of changing winter conditions on coregonine reproductive phenology. International Journal of Limnology. 60, 17. https://doi.org/10.1051/limn/2024014

Taylor, W.W., Smale, M.A., & Freeberg, M.H. (1987). Biotic and Abiotic Determinants of Lake Whitefish (Coregonus ciupeaformis) Recruitment in Northeastern Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences. 44(S2): s313-s323. https://doi.org/10.1139/f87-333

Tellier, J.M., Kalejs, N.I., Leonhardt, B.S., Cannon, D., Höök, T.O., Collingsworth, P.D. (2022). Widespread prevalence of hypoxia and the classification of hypoxic conditions in the Laurentian Great Lakes. Journal of Great Lakes Research, 48(1), 13-23, ISSN 0380-1330, https://doi.org/10.1016/j.jglr.2021.11.004

Vasseur, D. A., J. P. DeLong, B. Gilbert, et al. (2014). Increased Temperature Variation Poses a Greater Risk to Species Than Climate Warming. Proceedings of the Royal Society B: Biological Sciences 281: 20132612. https://doi.org/10.1098/rspb.2013.2612

Wuebbles et al. (2019). An Assessment of the Impacts of Climate Change on the Great Lakes. Environmental Law & Policy Center and University of Chicago, 74. https://elpc.org/wp-content/uploads/2020/04/2019-ELPCPublication-Great-Lakes-Climate-Change-Report.pdf

Wilhelm, S.W., LeCleir, G.R., Bullerjahn, G.S., McKay, R.M., Saxton, M.A., Twiss, M.R. & Bourbonniere, R.A. (2014). Seasonal changes in microbial community structure and activity imply winter production is linked to summer hypoxia in a large lake. FEMS microbiology ecology, 87(2), 475-485. https://doi.org/10.1111/1574-6941.12238

Zepernick, B.N., Denison, E.R., Chaffin, J.D., Bullerjahn, G.S., Pennacchio, C.P., Frenken, T., Peck, D.H., Anderson, J.T., Niles, D., Zastepa, A. and McKay, R.M.L., Wilhelm, S.W. (2022). Metatranscriptomic sequencing of winter and spring planktonic communities from Lake Erie, a Laurentian Great Lake. Microbiology Resource Announcements, *11*(7), e00351-22. https://doi.org/10.1128/mra.00351-22

Zepernick, B.N., McKay, R.M.L., Martin, R.M., Bullerjahn, G.S., Paerl, H.W., Wilhelm,S.W. (2024). A tale of two blooms: do ecological paradigms for algal bloom success and succession require revisiting? Journal of Great Lakes Research. 50(3), 102336. ISSN 0380-1330. https://doi.org/10.1016/j.jglr.2024.102336

Zhang, W., Furtado, K., Wu, P., et al. (2021). Increasing precipitation variability on daily-to-multiyear time scales in a warmer world. Science advances 7: eabf8021. DOI: 10.1126/sciadv.abf8

Appendix B: Great Lakes Winter Science Databases

Table B-1: Great Lakes winter science databases.

Name/Title	Link	Responsible Agency	Description
Ice Cover			
Great Lakes Data Support Files	https://usicecenter.gov/Products/GreatLakesData	U.S. National Ice Center (USNIC)	Ice charts, data files (shapefile, KMZ, ASCII, GRIB) and outlooks available for download. Outlook data includes 30-day forecast, seasonal outlook/summary, and Great Lakes NAVTEX, which provides a daily text description of current and near-term ice conditions in the Great Lakes.
NSIDC Data Search for "Great Lakes"	https://nsidc.org/data/search#keywords=Great+Lakes/sortKeys=score,,desc/facetFilters=%257B%257D/pageNumber=1/itemsPerPage=25	National Snow and Ice Data Center (NSIDC)	Search resulted in 11 datasets, including Great Lakes ice charts, ice thickness data, ice concentrations from 1973 onward, air temperature reports, aerial photos of ice conditions, etc.
Daily ice charts	https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions/products-guides/chart-descriptions.html#daily_ice	Government of Canada	Links to daily ice charts for regions in Canada, including the Great Lakes. Charts represent best estimates of ice conditions based on data from satellite, ship, and aircraft observations.
Product Search - Ice Products	https://iceweb1.cis.ec.gc.ca/Prod/page2.xhtml?CanID=11080&lang=en	Canadian Ice Service	Search resulted in 18 ice applications/data products from the Government of Canada, including daily and weekly regional ice charts, 30-day ice forecasts, historical ice data, etc.
Current Ice Cover Conditions and Historical Ice Cover	https://www.glerl.noaa.gov/data/ice/#currentConditions	NOAA Great Lakes Environmental Research Laboratory (GLERL)	Description and link to CoastWatch and GLSEA (the Great Lakes Surface Environmental Analysis) which provides a current digital map of surface water temperature and ice cover (temperature provided by NOAA satellite imagery and ice cover data provided by the National Ice Center). Provides links to related resources. Historical ice cover data and plots since 1973 are also available.
NOAA CoastWatch Great Lakes Node	https://coastwatch.glerl.noaa.gov/	NOAA	Homepage for CoastWatch. GLERL hosts the Great Lakes CoastWatch Node for NOAA's National Environmental Satellite and Data Information Service (NESDIS). From the homepage the user can navigate to other pages, such as Sea Surface Temperature Imagery, Great Lakes Surface Environmental Analysis, Ice Data, Surface Temperature Contour Maps, etc. Contact information is provided on this page.
Satellite Data Services	https://www.ssec.wisc.edu/datacenter/	University of Wisconsin-Madison Space Science and Engineering Center	Homepage for the Satellite Data Services group out of the University of Wisconsin-Madison Space Science and Engineering Center. Page provides links to real-time data information, archived information, and related sites, as well describing the mission of the Center (to provide access, maintenance, and distribution of real-time and archive weather satellite data).

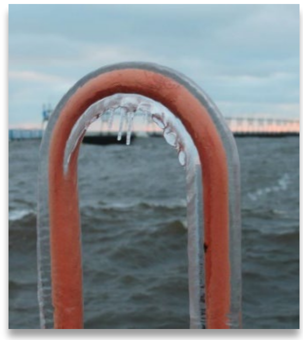
Name/Title	Link	Responsible Agency	Description
Great Lakes Adaptation Data Suite (GLADS)	https://glisa.umich.edu/glads-interface/	Great Lakes Adaptation Data Suite	GLADS provides climate data from several public data sources. From the homepage the user can read about the background of GLADS, or select point-based data sets, spatially aggregated data sets, or gridded data sets for download by request. The page indicates that at a later date the data will be available to download through a user interface, but at this time an email request is required.
USCG End of Season Ice Reports	https://www.atlanticarea.uscg.mil/Portals/7/Ninth%20District/Documents/D9_Ice_Reports/2017-2018%20End%20of%20Season%20Ice%20Report%20(combined).pdf?ver=fmAXzKwRMfm1IiYzDyEpng%3D%3D	US Coast Guard	Reports of Great Lakes ice coverage and winter performance measures
Precipitation			
MQTBrowser - Snowfall Observation Site (NWS Marquette, Michigan)	https://www.ssec.wisc.edu/lake_effect/mqt/	University of Wisconsin-Madison Space Science and Engineering Center	Charts for reflectivity, fall speed, particle size, and particle density (of snow). The user can view the available data for a selected day.
ECCC Data Catalogue search results for "Snow"	https://catalogue.ec.gc.ca/geonetwork/srv/search?keyword=Snow	Environment and Climate Change Canada (ECCC)	Search resulted in 17 records, including databases for specific regions in Canada or specific experiments, as well as general Canadian snow data such as snow depth and snow cover.
Homepage - no title	https://www.cocorahs.org/	Community Collaborative Rain, Hail & Snow Network (CoCoRaHs)	Homepage for CoCoRaHs, which is a volunteer-driven network that measures and maps precipitation in the U.S. Homepage shows an interactive, timestamped U.S. map of 24-hour precipitation.
Water			
Winter grab database	https://doi.org/10.6073/pasta/25b45064d0e2fd8578aad055609c0ca3	N/A - Multi-Organization Effort	Data Package for the 2022 Great Lakes Winter Grab that contains the results from a multi-institutional winter limnology sampling campaign on the Laurentian Great Lakes. Researchers from 19 institutions sampled 49 locations in all five of the Great Lakes over a period of 24 days in February-March 2022. This dataset contains information on diverse physical, chemical, and biological parameters.
Great Lakes Water Level Data > Monthly mean lakewide average water levels	https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/	U.S. Army Corps of Engineers (USACE)	Charts showing daily average and monthly mean water levels by individual Great Lake.
Great Lakes Connecting Channels Monitoring and Surveillance Data	https://data-donnees.az.ec.gc.ca/data/substances/monitor/great-lakes-water-quality-monitoring-and-aquatic-ecosystem-	Environment and Climate Change Canada (ECCC)	Year-round water quality data for 7 sites located within the Huron-Erie corridor, Niagara River, and St. Lawrence River.

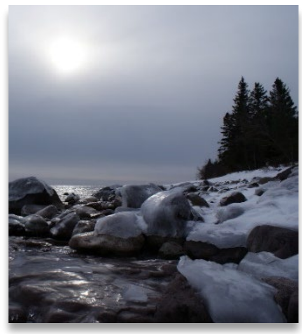
Name/Title	Link	Responsible Agency	Description
	health-data/great-lakes-connecting-channels-monitoring-and-surveillance-data/		
NOAA-GLERL Data > Water Temperature and Ice Data	https://www.glerl.noaa.gov/data/#watertemp	NOAA GLERL	Links to water temperature data collected from buoys and people deploying instruments from research vessels. GLERL also predicts Great Lakes water temperatures using NOAA scientific models.
NOAA-GLERL Data > Biological and Water Quality Data	https://www.glerl.noaa.gov/data/#biological	NOAA GLERL	Links to GLERL datasets for water quality and biological resources, including benthos & invasive species, biological identification (Great Lakes Water Life), long-term ecological research (Muskegon Transect), water quality, and zooplankton.
NOAA CoastWatch Great Lakes Node	https://coastwatch.glerl.noaa.gov/	NOAA	Homepage for CoastWatch, the NOAA program within which GLERL operates. From the homepage the user can navigate to other pages, such as Sea Surface Temperature Imagery, Great Lakes Surface Environmental Analysis, Ice Data, Surface Temperature Contour Maps, etc. Contact information is provided on this page.
USGS Water Data for the Nation	https://nwis.waterdata.usgs.gov/nwis	U.S. Geological Survey (USGS)	Links to water-resources data collected across the U.S., including data on surface water, groundwater, water quality, and water use.
Bottom dissolved oxygen measurements from Lake Erie's Central Basin, 2021-2022	https://data.usgs.gov/datacatalog/data/USGS:64834dfbd34ef77fcafcd657	U.S. Geological Survey (USGS)	Holds data for dissolved oxygen sensors coupled to GLATOS receivers in Lake Erie.
Provincial (Stream) Water Quality Monitoring Network	https://data.ontario.ca/dataset/provincial-stream-water-quality-monitoring-network	Ministry of the Environment, Conservation and Parks Environmental Monitoring and Reporting Branch	Links to spreadsheets with stream water quality monitoring data for a number of parameters, including total and dissolved nutrients, metals, and chloride, for rivers and streams across Ontario. Available datasets date from 1964 through the end of 2021.
Safe Drinking Water Information System	https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/200	U.S. EPA	Federal Data Warehouse of all public water systems, violation information, and enforcement information.
Lake water quality at drinking water intakes	https://data.ontario.ca/dataset/lake-water-quality-at-drinking-water-intakes	Ministry of the Environment, Conservation and Parks	Links to spreadsheets with sampling locations, water chemistry, and chlorophyll collected at 18 locations in the Great Lakes-St. Lawrence River and 4 locations in Lake Simcoe. Available datasets date from 1976-2019.
Lake water quality at drinking water intakes – All Ontario Great Lakes	https://files.ontario.ca/moe_mapping/downloads/2Water/GLIP/All_Lakes_GLIP.csv	The Great Lakes Intake Program	Great Lakes and Lake Simcoe water chemistry and chlorophyll data since 1976.

Name/Title	Link	Responsible Agency	Description
2022 Drinking Water Quality for Charter Township of Michigan	https://cms2.revize.com/revize/washingtonmi/DPW/2023_DPW/2022%20CCR.pdf	Charter Township of Washington	Water Quality Report highlights the performance of GLWA and the Charter Township of Washington (Lake Huron water intake).
Great Lakes DataStream	https://greatlakesdatastream.ca/en/	The Gordon Foundation	An open access platform for sharing information on freshwater health. It brings together water quality datasets collected by monitoring groups throughout the Great Lakes and Saint Lawrence Basin.
The R/V Lake Guardian	https://www.epa.gov/great-lakes-monitoring/lake-guardian	USEPA	The Lake Guardian is the largest research vessel operating on the Great Lakes and is owned by the USEPA Great Lakes National Program Office (GLNPO). Conducts annual surveys that sample water and biological life at designated locations in all five Great Lakes during both the spring (late March, after ice break-up) and summer (August) seasons. These monitoring surveys have been ongoing since 1983. Links to 2018 Annual Report and Lake Erie Dissolved Oxygen Monitoring Program Technical Reports.
Lake Superior moored temperature and currents, Sep 2005-May 2015	https://conservancy.umn.edu/handle/11299/222317	University of Minnesota Duluth, Large Lakes Observatory	Temperature data is presented in two different forms. First, individual, raw temperature records are presented in directories corresponding to individual mooring deployments. In addition, a separate directory includes hourly, gridded data from each individual mooring deployment, which are likely of more interest to investigators. Acoustic Doppler Current Profiler (ADCP) data is presented in raw form. All data is presented in MATLAB format.
Lake Superior moored temperature and currents, Spring 2015 to Spring 2021	https://conservancy.umn.edu/handle/11299/226963	University of Minnesota Duluth, Large Lakes Observatory	Temperature data is presented in two different forms. First, individual, raw temperature records are presented in directories corresponding to individual mooring deployments. In addition, a separate directory includes hourly, gridded data from each individual mooring deployment, which are likely of more interest to investigators. Acoustic Doppler Current Profiler (ADCP) data is presented in raw form. All data is presented in MATLAB format.
Seagull	https://glos.org/priorities/seagull/	Great Lakes Observing System (GLOS)	Platform used to connect people to data collected by GLOS, which supports real-time, historical, and predictive observing data from the five Great Lakes and the watershed. GLOS supports physical data (i.e., wind, waves, underwater environment, etc.), biogeochemical data (i.e., chlorophyll, oxygen, toxins, etc.), and biological data (i.e., fish, algae, etc.).
BCO-DMO	https://www.bco-dmo.org/	Biological and Chemical Oceanography Data Management Office	Query ‘winter’ and ‘great lakes’ and users will come across datasets featuring water quality data (including ice, nutrients, chlorophyll biomass and some phytoplankton) related to US NSF projects between 2012-2024

Name/Title	Link	Responsible Agency	Description
Ontario water and weather monitoring stations	https://data.ontario.ca/dataset/ontario-water-and-weather-monitoring-stations	Government of Ontario	Point locations of water and weather monitoring stations used by the Surface Water Monitoring Centre to assess flood and drought conditions across Ontario.
Other			
National Survey of Fishing, Hunting, & Wildlife - Associated Recreation (FHWAR): 2016	https://www.census.gov/library/publications/2018/demo/fhw-16-nat.html	United States Census Bureau	The National Survey of FHWAR collects data from U.S. residents about fishing, hunting, and wildlife watching. The link provided is for the 2016 report, but trend information is also available by comparing against earlier survey reports using similar methodologies.
GLATOS	https://glatos.glos.us/	Great Lakes Acoustic Telemetry Observation System (GLATOS)	Homepage for GLATOS, which tracks fish movement in the Great Lakes through implanted transmitters. From the homepage the user can view maps, publications, recent projects, and photos.
The North American CORDEX Program	https://na-cordex.org/	World Climate Research Programme (WCRP)	Homepage for the WCRP North American CORDEX (Coordinated Regional Downscaling Experiment) Program, which provides global coordination of regional climate downscaling for improved climate change adaptation and impact assessment. The user can download data from the CORDEX search page.
Audubon Christmas Bird Count	https://netapp.audubon.org/cbcobservation/	Audubon	Audubon's Christmas Bird Count website allows the user to view historical counts and current year results either by species or by count.
Waterborne Commerce Statistics Center (WCSC)	https://www.iwr.usace.army.mil/About/Technical-Centers/WCSC-Waterborne-Commerce-Statistics-Center-2/	USACE	Information on vessels, tonnage, commodity, origin, and destination from vessel operating companies.
Provincial Groundwater Monitoring Network	https://www.ontario.ca/page/map-provincial-groundwater-monitoring-network	Government of Ontario	Groundwater level and chemistry data from monitoring wells that are part of the Provincial Groundwater Monitoring Network (PGMN) Program. Precipitation data (rain) is also available for some PGMN sites.
Environmental Response Management Application	https://response.restoration.noaa.gov/esi_download#GreatLakes	NOAA	web-based Geographic Information System (GIS) tool that assists both emergency responders and environmental resource managers in dealing with incidents that may adversely impact the environment. ERMA integrates and synthesizes various real-time and static datasets into a single interactive map
TRCA Open Data Portal: Aquatic Monitoring and Management	https://data.trca.ca/	TRCA	This dataset contains the species fish caught using boat electrofishing along the TRCA Lake Ontario shoreline from 2000 to 2018.
limno.io	https://limno.io/	LimnoTech	Links to real-time monitoring stations in Lake Michigan, Lake Huron, and Lake Erie.

Appendix C: Workshop #1 Report



Great Lakes Winter Science Workshop #1
May 1-2, 2023

Final Report

August 25, 2023

Prepared for:

International Joint Commission

Science Advisory Board

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1
Background and Workshop Summary

Background

The International Joint Commission (IJC) is conducting a project seeking to document the state of winter science in the Great Lakes and develop recommendations to address research priorities that will help understand the impacts of climate change on winter and on the chemical, physical, and biological integrity of the waters of the Great Lakes. Climate change has been identified as one of the most important problems facing humanity today. The 2021 Intergovernmental Panel on Climate Change report emphasized the importance of limiting global temperature increases below 1.5 degrees Celsius (° C) within the next decade to reduce catastrophic impacts on ecosystems and human health. Responses of lakes to climate change are well documented with increases in water temperature, loss of ice cover, alterations in distribution of freshwater fishes, and decrease in deep-water oxygen concentrations. The largest lakes in the world are most vulnerable to losing ice cover and are warming at the fastest rates, in some cases as much as 1°C per decade.

The IJC Science Advisory Board (SAB) recognizes that winter is an overlooked season across the Great Lakes-St. Lawrence River system, even though it is the season that is altered the most due to climate change across the basin. This is partly due to the challenge of winter observations and the requirements for specialized equipment, highly qualified personnel, and coordinated approaches. As a result, management decisions are often based on data and models derived from ice-free observations. The topic of winter science in the Great Lakes-St. Lawrence River system involves many Annexes of the Great Lakes Water Quality Agreement (GLWQA), but winter is not currently incorporated into any of the Annexes.

The SAB has undertaken this project to better inform the IJC about the gaps that exist in our understanding of winter in the Great Lakes and the impacts of climate change; to document research priorities and proposed solutions to improve winter science; and to provide recommendations on meeting these winter science needs and priorities. Activities conducted to date under the project include:

- A literature review (completed March 2023) to uncover new knowledge published since the completion of other recent literature reviews and workshops, and identify persistent knowledge gaps pertaining to winter science as it impacts the Laurentian Great Lakes;
- A survey of publicly available databases containing information relevant to winter and winter science in the Great Lakes (completed March 2023); and
- Interviews with stakeholders and rights holders, including agency personnel, academic researchers, and members of shipping and other industries in the Great Lakes (completed April 2023).

The project also includes three workshops to identify winter science gaps, needs, and science priorities; identify, describe, and assess research needs related to infrastructure, training, inter-agency coordination, and meeting science priorities; and winter science priorities with existing and future capacities and to develop recommendations for sustainably meeting winter science needs. Workshop #1 was completed in May 2023, and the proceedings and outcomes are described in this report.

Workshop Summary

Workshop #1, focused on winter science gaps, needs, and science priorities, was held virtually over two half-days on May 1st and 2nd, 2023 (see Appendix A for workshop agenda). In addition to IJC staff and the support contractor team, 21 experts participated in the workshop (see Appendix B for a list of workshop participants). The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group had the opportunity to speak and present their points of view. Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations.

High-level observations and recommendations from workshop general discussions and breakout sessions are included in the list below:

- Any advancement in Great Lakes winter science is likely to have a high impact on the field, as few low-impact gaps or needs were identified by workshop participants.
- Lake access in winter is a key barrier to filling research gaps, as evidenced by the fact that this theme appeared in some form in almost every discussion topic. Lake access is further restricted by an overall lack of resources for winter science including funding, training, staff, ships, sensors, and data platforms.
- Interdisciplinary efforts are essential to understand complex research questions, including crossing disciplinary data collection and analysis and integrating social science, economics, and traditional knowledge.
- Opportunities exist to improve coordination and collaboration, including leveraging and formalizing existing collaborations to improve winter sampling and developing central platforms for winter science. Examples include:
    - Equipping Coast Guard vessels for sample collection and storage,
    - Expanding the use of autonomous vehicles and other unmanned systems (e.g., buoys) for winter data collection, and
    - Better utilization/expansion of water intake monitoring for year-round data collection.

2
Workshop Presentation and Discussion Summary

Day 1 of the workshop began with welcome and introductory comments by the hosts, organizers, and facilitators. The workshop team, composed of contractors, IJC staff, and the IJC SAB Co-chairs, outlined the objectives and approach and reviewed materials sent to the group in advance. This included a synthesis report describing the results of a Great Lakes-focused winter science literature review, a list of public databases with data relevant to winter in the Great Lakes, and a summary of interviews with Great Lakes stakeholders and rights holders. Background information on project progress to date was provided by the contractor team, followed by a round of breakout group discussions on specified topics (fisheries and biology, economy and culture, drinking water, and methodologies) related to winter science.

Day 2 of the workshop began with a recap of Day 1 activities and a review of workshop objectives. The opening session was followed by another round of breakout group discussions (shorelines/offshores, shoulder seasons, disciplinary needs, and lake-by-lake and connecting water differences). Additional supporting material is available in report appendices.

DAY 1

Introductory Sessions

The SAB Co-chairs (see agenda in Appendix A for names) shared thoughts and perspectives on the need for better understanding winter in the Great Lakes, including the effects of climate change. They also provided an overview of the GLWQA, the IJC's advisory role, and how the present project fits within that role, including any recommendations that may ultimately be developed. Their remarks served to stimulate thought and frame discussion during the subsequent breakout groups. Introductory session slides are included in Appendix C.

As part of the Co-chair's introductory presentation, attendees were prompted with the following question: "What keeps you up at night regarding winter science?" Attendee responses are summarized in Table 1 below.

Table 1. Summary of Attendee Concerns Regarding Winter in the Great Lakes

Capacity and General Concerns
Lack of winter research platforms; How to do winter science well; Lack of under ice observations; The unknown unknowns related to winter impacts on the Great Lakes; Lack of knowledge about winter processes; So much to be done at every level; Lack of continuity and a systems approach in addressing problems; Lack of sampling capabilities
Emerging or Understudied Issues
Chloride/road salt; Ecological mismatches as seasons change; Phenology; Wellbeing of fish and wildlife that use the lakes not knowing what's coming or not be able to adapt; Concerns about permanent stratification and what that means for the ecosystem; Effects on the recruitment of fish due to the changes
Perceptions and Beliefs
That the public is welcoming warmer winters in our region; The misconception that nothing much happens in winter (esp. for fish) - translated partly as 'I don't want to work in winter, it's cold and

dangerous on lakes' - leading to disinterest in winter work; Loss of our identity as hearty ice-adept Northerners (we will get soft, or "slushy")
Culture and Recreation
Inability of fishers to fish due to lack of ice or too much wind over the open waters; Not being able to finally catch a fish ice-fishing - not about me but the impact that has on many, many others is profound
Infrastructure
Rapid rate of erosion along Lake Huron shoreline where my in-laws home site is precariously perched; The big rainstorm in January that will knock out my water treatment plant; Lack of federal investment based on the belief ice seasons will end on the lakes

Following the SAB Co-chairs' presentation, the contractor team provided a summary of background information compiled under this project to date. This included the results of the literature review, database summary, and stakeholder/rights holder interviews. Key points of the contractor team presentation on Day 1 included:

- The literature review looked at 149 papers to understand the current state of winter science and organized information across five categories: physical properties, chemistry and biogeochemical cycles, biology, modeling and forecasting, and socio-economic and cultural services.
    - Recent scientific literature reaffirms that water quality and the environmental patterns that govern it are changing, especially in winter.
    - While progress is being made on understanding the functioning of aquatic ecosystems in winter, more data are needed on the ecological chain of reactions to changing winter conditions.
- These overarching themes were also reflected in stakeholder and rights holder interviews, which included the following findings:
    - Interviewees highlighted the lack of collective winter science research objectives and the lack of consistent funding and resources for winter research and data collection.
    - There is a need for longer term and continuous data to better understand spatial and temporal changes, including increasing interannual variability.
    - Reliability of ice forecasts was identified as a concern.
    - In general, the relative lack of winter data across disciplines (physical, chemical, ecological) was cited by many researchers.
    - Changes in winter conditions can affect drinking water treatment systems, and there is need for more research on their effects on spring and summer phenomena (e.g., phytoplankton and zooplankton populations, algal blooms, and fish spawning).

Day 1 Breakout Session

Following the introductions, workshop participants were divided into four breakout groups (numbered A through D). Each group was assigned one of four topics and was asked to consider winter science needs and gaps related to that topic and further, to rank them as high or low effort and high or low impact. Each group was given approximately 20 minutes and then the groups switched topics. This way, over the course of the breakout session, each group had the opportunity to consider each topic and contribute their perspectives to the overall discussion.

The four topics assigned to the groups were fisheries and biology, economy and culture, drinking water, and methodologies. Priorities and key themes identified for each group topic are listed below, along with high impact research topics related to winter science. The breakout groups used Mural to document their ideas and discussion. Screenshots of the Mural workspaces can be found in Appendix D.

Fisheries and Biology

- High impact, high effort initiatives (major projects) include:
    - Study of under-ice food web ecology, bioenergetics, resource availability, and timing.
    - Improved winter monitoring of microbes, phytoplankton, zooplankton, and fish; metabolism; and lake thermal structure.
- High impact, low effort initiatives (quick wins) include:
    - Collaboration with fishing community (commercial and recreational).
    - Utilization of existing technology to improve year-round fish and biochemical observations.
    - Characterizing impacts of changing winter conditions on fish spawning success.

Key research gaps identified from fisheries and biology discussions include the need for increased under-ice observations including, microbes, phytoplankton, zooplankton, and fish; population composition and distribution; metabolic changes (primary productivity and net ecosystem production); and lake thermal structure. Additionally, food web ecology, including connections and changing trophic relationships, and resource use, availability, and timing mismatches were identified as research needs, specifically as they relate to fish spawning. Lastly, workshop participants highlighted the need to better leverage existing technology and collaborations to fill the above identified research gaps by collecting year-round samples and improving sample resolution.

Economy and Culture

- High impact, high effort initiatives (major projects) include:
    - Studying the impacts of increased winter shipping.
    - Studying the impacts of changing winter seasons on Indigenous language, ceremonies, and priorities.
    - Quantifying economic impacts of changing winter, including:
        - Productivity/economics of key fisheries.
        - Coastal erosion.
        - Increasing winter flooding and storms.
        - Lakefront infrastructure and property.

- High impact, low effort initiatives (quick wins) include:
    - Economic impacts on winter recreation.
    - Establishing winter baseline data for communities and economies.
    - Leverage social science to better characterize impacts of ice loss on communities.

Key economy and culture research gaps identified focused mainly on winter shipping and boating, fishing, and local impacts of the changing winter season. Workshop participants highlighted a need to better understand the true costs and benefits of lengthening the winter shipping season. Further, understanding the impacts of climate change on the ability to conduct winter recreation and subsistence fishing, as well as economic impacts of changing fisheries were identified as research needs. Lastly, the need to characterize social and cultural impacts of changes in winter was highlighted, including the need to establish baselines, leverage social science to understand impacts to communities, understand impacts to Indigenous language and ceremonies, and identify concrete examples of the economic value of winter activities such as ice fishing, ice-based transportation, and winter-specific tourism to coastal communities.

Methodology

- High impact, high effort initiatives (major projects) include:
    - Pie in the sky: dedicated winter science-equipped ice breakers.
    - More winter-durable tools, technologies, and under-ice sensing platforms.
    - Standardized protocols for winter sampling.
- High impact, low effort initiatives (quick wins) include:
    - Improved awareness/visibility of existing under-ice platforms and datasets.
    - Resource and knowledge sharing with communities who have year-round fishing and navigation abilities.
    - Formalizing contract agreements with those already out on the water in winter to increase sample collection.
    - Remote sensing and big data algorithms and analyses method development.

Key themes identified by workshop participants pertaining to winter methodology included the need for resources to conduct sound winter research, specifically, consistent funding for winter research, icebreakers, autonomous underwater vehicles (AUVs), and maximizing existing and emerging technologies. The need to establish standardized sampling protocols was also discussed. Pertaining to modeling, a key theme that arose was the need to update modeling methods and designs for the purpose of addressing winter science problems. Identified points of research included linking models with event-based water quality monitoring to better predict extreme hydrological events, generating predictive models of winter abiotic conditions and biotic processes, improving flood risk models associated with increased winter runoff volume and changing timing, improving big-data analysis, and improving model biases to increase scientific credibility of modeled outputs. The need for improved coordination was discussed, including improved knowledge, data, resource sharing. Lastly, the need for more training on winter science methods as well as an evolution of winter science training was identified as participants discussed how the ice on which research is conducted is no longer solid, but rather unstable ice that is actively deteriorating or very cold but unfrozen water, highlighting the need for a "different safe way" to conduct winter research than has been used in the past.

Drinking Water

- High impact, high effort initiatives (major projects) include:
    - Effects of changing winter on groundwater.
    - Effects of hydrological changes on source water quality and treatment plants:
        - Increased turbidity.
        - Oxygen.
        - Alkalinity and hardness.
        - Nitrogen and phosphorus.
        - Chloride loading.
        - Increased contaminants.
        - Increased summer harmful algal blooms (HABs) resulting from winter changes.
- High impact, low effort initiatives (quick wins) include:
    - Better utilization/expansion of water intake monitoring for year-round data collection.
    - Understanding impacts of snowpack melt and timing on water supply.

Key themes identified by workshop participants pertaining to drinking water included better characterization of changing source water timing, quality, and implications for treatment strategies, as well as improved spatial coverage and temporal resolution of water intake quality monitoring.

DAY 2

Opening Discussion

Day 2 began with a review of workshop activities and outcomes on Day 1, followed by a refresher of the tools and techniques to be used. Key takeaways from Day 1 included:

- Any advancement in winter science is likely to have a high impact on the field.
- Many opportunities exist to improve our understanding of winter in the Great Lakes that could be realized with improved coordination and collaboration:
    - Leveraging and formalizing existing collaborations to improve winter sampling by, for example:
        - Equipping Coast Guard vessels for sample collection and storage.
        - Contracting with fishing community in increase volume and location of samples.
        - Better utilization/expansion of water intake monitoring for year-round data collection.
    - Developing central platforms for winter science to promote the following:
        - Better utilization of existing technologies.
        - Coordinating sampling efforts and resources.
        - Data sharing, socialization, and analysis development.
        - Knowledge and training resource sharing.

Day 2 Breakout Session

Like Day 1, after the introductory session, workshop participants were divided into four breakout groups (numbered A through D) and were asked to rotate through four topics, identifying winter science needs and gaps related to that topic and further, to rank them as high or low effort and high or low impact. Each group was given approximately 20 minutes per topic.

The four topics assigned to the groups on Day 2 were shorelines/offshore, shoulder seasons, disciplinary needs, and lake-by-lake/connecting water differences. Priorities and key themes identified for each group topic are listed below, along with high impact research topics related to winter science. Screenshots of the Day 2 Mural workspaces can be found in Appendix C.

Shorelines/Offshore

- High impact, high effort initiatives (major projects) include:
    - Impacts of ice cover loss and increased wind energy on:
        - Sediment resuspension.
        - Water column mixing and lake circulation.
        - Nearshore to offshore nutrient dynamics.
        - Shoreline erosion.
        - Littoral vs offshore productivity.
        - Contaminant distribution (mining waste).
    - Nearshore to offshore connections:
        - Biota succession gradients and drivers.
        - Food web coupling.
- High impact, low effort initiatives (quick wins) include:
    - Hovercrafts for nearshore winter sampling.
    - Impacts of ice scour on littoral benthic community structure.
    - Nearshore to offshore nutrient transport models.

Key themes of shoreline to offshore research gaps discussed included the connectivity between nearshore and offshore systems, such as biota succession gradients and drivers, food web coupling, nutrient transport, thermal bar formation, timing, and persistence, and how increasing shoreline erosion impacts offshore sediment load. Furthermore, impacts of ice cover loss and increasing winter wind energy on sediment resuspension and nutrient loading, water column mixing and lake circulation, nearshore to offshore nutrient transport and sediment consolidation, shoreline erosion, littoral vs offshore productivity, contaminant distribution such as mining waste, and littoral benthic community structure were identified as research needs. Lastly, impacts of changing catchment hydrology and increasing freeze/thaw events on tributary loads were discussed as a need.

Shoulder Seasons

- High impact, high effort initiatives (major projects) include:
    - Resources for more shoulder season observations, including:

    - Sensing tools.
    - Transportation.
  - Changes to lake inputs during shoulder season.
- High impact, low effort initiatives (quick wins) include:
  - Shoulder season influence on food web dynamics:
    - Overall lake primary production.
    - Planktonic community composition.
  - Fisheries production and persistence.

Key shoulder season themes and research gaps included changing lake inputs, such as variability, timing, and magnitude of storm events, freshet magnitude and timing, and nutrient inputs and cycling. Pertaining to fish, shoulder season concerns included changes to migration patterns, spawning and hatch, species vulnerability to changing ice on/off timing, and the temporal mismatch of food resource availability and fish spawning/hatch. More broadly, the influence of changing shoulder season characteristics on food web dynamics was discussed, specifically for overall lake primary production, overwintering of fall planktonic communities, and impacts of warmer winters on spring phyto/zooplankton bloom composition. Lastly, the resources for making shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles) were discussed.

Disciplinary Needs

- High impact, high effort initiatives (major projects) include:
  - Resources for winter research.
  - Better integration across fields.
  - Continuous lake and climate measurements.
- High impact, low effort initiatives (quick wins) include:
  - Inter-agency collaborations.
  - Traditional knowledge integration to better characterize seasonal changes.
  - Education and awareness of the importance of winter in the Great Lakes.

Key themes and research gaps for disciplinary needs included continuous measurements of lake currents, temperature profiles, water quality, meteorology and climate measurements, and lower food web surveys and productivity. Pertaining to resources, winter and shoulder season-specific funding, staff capacity, vessels and appropriate work platforms, and centralized, cross-disciplinary databases, data integration, and data sharing were all identified as needs. Themes related to cross-field integration included remote sensing, ice phenology observations, and modeling, lake physics and biology, and socioeconomic analysis. Lastly, the need to better leverage social resources, including inter-agency collaborations, traditional knowledge integration to better characterize seasonal changes, utilization of lessons learned in marine science, were identified to improve the education and awareness of the importance of winter in the Great Lakes region.

Lake-by-Lake / Connecting Water Differences

- High impact, high effort initiatives (major projects) include:

- Lake Superior coregonine community spawning biology to inform restoration.
- Lack of sampling on Lakes Superior and Ontario after locks close.
- Characterizing variations in ice cover and productivity between lakes.
- Recognition that connecting channels are not rivers.

- High impact, low effort initiatives (quick wins) include:
  - Understanding impacts of ice breaking and extended shipping season.
  - Winter fish movement through connecting channels.
  - Standardized/comparable methods across all five lakes.

Key themes and research gaps identified across Great Lakes connecting waters focused on the connecting channels, specifically ice jams, leveraging channel infrastructure to sample upstream water column, better recognition that the channels function differently than river ecosystems, and utilization of the channels by fish for movement in winter. Across-lake gaps highlighted by participants included variations in ice cover and planktonic productivity, understanding impacts of ice breaking and extended shipping season, and the implementation of standardized/comparable methods across all five lakes. Lastly, lake-specific research needs identified included Lake Superior coregonine community spawning biology to inform restoration actions, the lack of sampling on Lakes Superior and Ontario after the locks close for the winter, and the significant lack of research and information for Lakes Michigan and Huron.

Overarching Workshop Themes

The following themes emerged as overarching concerns expressed by participants. They were brought up multiple times during the workshop in various contexts.

- Any advancement in winter science has high impact on the field:
  - Few to no low-impact gaps or needs identified through both sessions.
- Lake access in winter is a key barrier to filling research gaps:
  - Theme appeared in some form in almost every discussion topic.
  - Access is regulated by an overall lack of resources for winter science.
  - Funding, training, staff, ships, sensors, data platforms.
- Interdisciplinary efforts are essential to understand complex research questions:
  - Crossing disciplinary data collection and analysis.
  - Modeling: linking disciplinary data streams, such as climate, flood risk, abiotic conditions, and biotic processes, through models to address winter science-specific problems and lower the bias associated with existing models.
  - Integration of social science, economics, and traditional knowledge.
- Many opportunities exist that could be realized with improved coordination and collaboration:
  - Leveraging and formalizing existing collaborations to improve winter sampling.
    - Equipping Coast Guard vessels for sample collection and storage.
    - Encouraging the increased use of autonomous vehicles, buoys, and other unmanned systems for winter data collection.

- Inter-agency collaborations.
- Contracting with fishing community in increase volume and location of samples.
- Better utilization/expansion of water intake monitoring for year-round data collection.

- Developing central platforms for winter science:
  - Better utilization of existing technologies.
  - Coordinating sampling efforts and resources.
  - Data sharing, socialization, and analysis development.
  - Knowledge and training resource sharing.

At the conclusion of workshop activities, all participants were prompted with the following question: "What are the hope spots regarding winter science?" Table 2 summarizes the responses received.

Table 2. Summary of Hope Spots Regarding Winter Science in the Great Lakes

Prioritization and Awareness
General agreement about main priorities; People are noticing, and they are very concerned; Increasing consolidation of prioritization; Second on awareness and AUVs *[in reference to comment under Technology, below, re: under-ice unmanned capabilities]*
Collaboration
I love the opportunity that we have to network and work together; Collaborative projects using the limited ice-capable vessels, especially for water properties and lower trophic measures - making best use of a limited resource.
Technology
Development of affordable in-situ biogeochemical sensors; Technological improvements in sensors and capacity for long deployments; Increasingly finer scales of remote sensing data on ice and water quality parameters to help us understand changes in big landscapes; Under ice, unmanned capabilities to monitor biotic and abiotic variables

Appendix A: Agenda

International Joint Commission (IJC)

Great Lakes Winter Science Workshop #1 – Winter Science Priorities

May 1 and 2, 2023, 1pm – 4:30pm

Draft Agenda

Virtual meeting link: Zoom

IJC Contact: Matthew Child, matthew.child@ijc.org
Li Wang, lizhu.wang@ijc.org

Workgroup Co-Chairs: Maggie Xenopoulos, Trent University, mxenopoulos@trentu.ca
Michael Twiss, Algoma University, michael.twiss@algomau.ca

Support Contractors: Samir Qadir, Potomac-Hudson Engineering, Inc., samir.qadir@phe.com
John Bratton, LimnoTech, jbratton@limno.com
Michelle Platz, LimnoTech, mplatz@limno.com

Objective: Identify winter science gaps, needs, and science priorities.

Approach: Workshop preparatory materials include:

- Summary of literature review describing the current state of Great Lakes winter science and identified knowledge gaps,
- Summary of publicly accessible data related to Great Lakes Winter Science, and
- Summaries of the identified needs of stakeholders and rights holders based on semi-structured interviews, as they relate to Great Lakes winter science.

Workshop participants are expected to have reviewed the materials provided and come prepared to discuss their understanding of science needs and priorities.

Prioritization will take place through group discussions and consensus and/or by polling of workshop attendees to rank priorities.

Outcomes: List of science priorities, as ranked by workshop participants

Day 1

Time	Topic	Presenter
1:00 – 1:15 pm	**Opening and welcoming remarks** Introductions Project and workshop objectives	IJC staff and co-chairs
1:15 – 1:45 pm	**Background and workshop approach** Discuss project activities completed to date Present identified science needs and gaps Discuss workshop approach Introduce the workshop tools/technology	Contractor Team
1:45 – 2:30 pm	**Breakout Rounds 1-2** • Fisheries and biology • Economy and culture • Drinking water • Methodology Groups to rotate through each of the 4 topics/themes, spending 15-20 minutes on each	Contractor Team and Co-chairs
2:30 – 2:45 pm	**Break**	
2:45 – 3:30 pm	**Breakout Rounds 3-4** • Fisheries and biology • Economy and culture • Drinking water • Methodology Groups to rotate through each of the 4 topics/themes, spending 15-20 minutes on each	Contractor Team and Co-chairs
3:30 – 4:30 pm	**Review and Synthesis** Entire group to review and reconcile prioritization results	Contractor Team
4:30 pm	**Day 1 Wrap-Up**	

Day 2

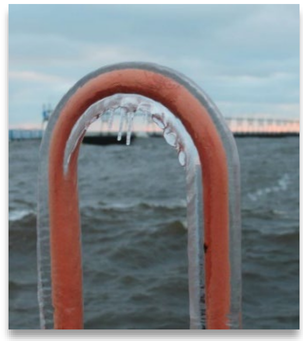
Time	Topic	Presenter
1:00 – 1:30 pm	**Opening remarks** Recap of Day 1 activities Refresher on workshop objectives, approach, and tools	IJC staff and co-chairs
1:30 – 3:15 pm	**Breakout Rounds 1-4** • Shorelines / offshore • Shoulder seasons • Disciplinary needs • Lake-by-lake and connecting water differences Groups to rotate through each of the 4 topics/themes, spending 15-20 minutes on each	Contractor Team and Co-Chairs
3:15 – 3:30	**Break**	
3:30 – 4:00	**Review and Synthesis** Entire group to review and reconcile prioritization results	Contractor Team
4:00 – 4:30	**Workshop summary** Recap of workshop activities Review and confirm draft prioritization	IJC Staff and Co-chairs
4:30	**Day 2 Wrap-Up**	

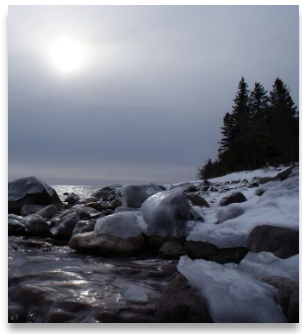
Appendix B: Workshop Participants

Below is a list of the participants who attended all or part of the workshop, including 21 experts and Work Group members, 2 IJC staff, and 4 contractors.

Attendee	Organization
Maggie Xenopoulos	Trent University (co-chair)
Michael Twiss	Algoma University (co-chair)
Andy Bramburger	Environment and Climate Change Canada
Bill Mattes	Great Lakes Indian Fish and Wildlife Commission
Dallas Linley	Fisheries and Oceans Canada
Ed Rutherford	National Oceanic and Atmospheric Administration
Eric Peace	Lake Carriers Association
Georgina Kaltenecker	Ontario Ministry of Environment, Conservation and Parks
Ian Harding	Red Cliff Band of Lake Superior Chippewa
Jay Austin	University of Minnesota
Kathy Jo Jankowski	U.S. Geological Survey
Kelly Bowen	Fisheries and Oceans Canada
Lars Rudstam	Cornell University
Mark Fitzpatrick	Fisheries and Oceans Canada
Mike McKay	University of Windsor
Rachel Eveleth	Oberlin College
Richard B Rood	University of Michigan
Scott Higgins	International Institute of Sustainable Development
Steve Ruberg	National Oceanic and Atmospheric Administration
Ted Ozersky	Univ. of Minnesota
Warren Currie	Fisheries and Oceans Canada
Matthew Child	*International Joint Commission*
Lizhu Wang	*International Joint Commission*
Chris Rua	*Potomac-Hudson Engineering, Inc. (Contractor)*
John Bratton	*LimnoTech (contractor)*
Michelle Platz	*LimnoTech (contractor)*
Kathryn Meyer	*LimnoTech (contractor)*

Appendix D: Workshop #2 Report





Great Lakes Winter Science Workshop #2
Sep 5-6, 2023

Revised Draft Report

December 5, 2023

Prepared for:

International Joint Commission

Science Advisory Board

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Great Lakes Winter Science Workshop #2
Sep 5-6, 2023

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Prepared for:

International Joint Commission

Science Advisory Board

Prepared By:

PHE

Potomac-Hudson Engineering, Inc.

Rockville, MD

LimnoTech

Water | Scientists
Environment | Engineers

LimnoTech

Ann Arbor, MI

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1 Background and Project Summary to Date

Project Objectives

The International Joint Commission (IJC) is conducting a project seeking to document the state of winter science in the Great Lakes and develop recommendations to address research priorities that will help understand the impacts of climate change on winter and on the chemical, physical, and biological integrity of the waters of the Great Lakes. Climate change has been identified as one of the most important problems facing humanity today. The 2021 Intergovernmental Panel on Climate Change report emphasized the importance of limiting global temperature increases below 1.5 degrees Celsius (°C) within the next decade to reduce catastrophic impacts on ecosystems and human health. Impacts to lakes resulting from climate change have already been well documented, including increases in water temperature, loss of ice cover, alterations in distribution of freshwater fishes, and decreases in deep-water oxygen concentrations. The largest lakes in the world are most vulnerable to losing ice cover and are warming at the fastest rates, in some cases as much as 1°C per decade.

The IJC Science Advisory Board (SAB) recognizes that winter is an overlooked season across the Great Lakes-St. Lawrence River system, even though it is the season that is altered the most due to climate change across the basin. This is partly due to the challenge of winter observations and the requirements for specialized equipment, highly qualified personnel, and coordinated approaches. As a result, management decisions are often based on data and models derived from ice-free observations. The topic of winter science in the Great Lakes-St. Lawrence River system involves many Annexes of the Great Lakes Water Quality Agreement (GLWQA), but winter is not currently incorporated into any of the Annexes. The SAB has undertaken this project to better inform the IJC about the gaps that exist in our understanding of winter in the Great Lakes and the impacts of climate change; to document research priorities and proposed solutions to improve winter science; and to provide recommendations on meeting these winter science needs and priorities.

Project Activities

Activities conducted to date under the project include:

- A literature review (completed March 2023) to uncover new knowledge published since the completion of other recent literature reviews and workshops, and identify persistent knowledge gaps pertaining to winter science as it impacts the Laurentian Great Lakes;
- A survey of publicly available databases containing information relevant to winter and winter science in the Great Lakes (completed March 2023); and
- Interviews with stakeholders and rights holders, including agency personnel, academic researchers, and members of shipping and other industries in the Great Lakes (completed April 2023).

The project also includes three workshops to identify winter science gaps, needs, and science priorities; identify, describe, and assess research needs related to infrastructure, training, inter-agency coordination, and meeting science priorities; and winter science priorities with existing and future capacities and to develop recommendations for sustainably meeting winter science needs.

PHE LimnoTech Water Environment | Scientists Engineers

Workshop 1 Summary

Workshop 1, focused on winter science gaps, needs, and science priorities, was held virtually over two half-days on May 1st and 2nd, 2023. In addition to IJC staff and the support contractor team, 21 experts participated in the workshop. The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group had the opportunity to speak and present their points of view. Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations.

High-level observations and recommendations from workshop general discussions and breakout sessions are included in the list below:

- Any advancement in Great Lakes winter science is likely to have a high impact on the field, as few low-impact gaps or needs were identified by workshop participants.
- Lake access in winter is a key barrier to filling research gaps, as evidenced by the fact that this theme appeared in some form in almost every discussion topic. Lake access is further restricted by an overall lack of resources for winter science including funding, training, staff, ships, sensors, and data platforms.
- Interdisciplinary efforts are essential to understand complex research questions, including crossing disciplinary data collection and analysis and integrating social science, economics, and traditional knowledge.
- Opportunities exist to improve coordination and collaboration, including leveraging and formalizing existing collaborations to improve winter sampling and developing central platforms for winter science. Examples include:
    - Equipping Coast Guard vessels for sample collection and storge, and
    - Better utilization/expansion of water intake monitoring for year-round data collection.

2 Workshop 2 Presentation and Discussion Summary

The objective of Workshop 2 was to identify agency needs and recommended actions related to winter science. The target workshop outcome was a list of management agency needs and actions. The workshop was held virtually over two half days on September 5th and 6th, 2023. The workshop agenda is provided in Appendix A. The workshop included over 40 participants, including IJC staff and contractor support. A list of participants is included in Appendix B.

The workshop began with an introductory session that described activities completed to date under this project and discussed the goals for the workshop. This was followed by a series of breakout group discussions in which participants were divided into smaller groups to explore a series of topics. Each breakout session was approximately 45 minutes in duration and was followed by a whole-group discussion where the breakout groups reported back, and all participants had the opportunity to ask questions and engage with the topic. Appendix C includes the list of breakout discussion topics and the questions that were asked during each breakout session to prompt participants.

Overarching Workshop Themes

The following themes emerged as overarching concerns expressed by participants. They were brought up multiple times during the workshop in various contexts.

- Funding for conducting winter science, including funding for expanded monitoring, data sharing, and interdisciplinary collaboration is a critical need.
- Need for winter science resources includes, but is not limited to, ice-hardened vessels, ice-capable autonomous underwater vehicles (AUVs), hovercrafts, mooring, and ice-capable buoys.
- Centralized, cross-disciplinary databases, data integration, and data sharing pipelines are needed to support advancements in the field. Some participants suggested that data sharing may need to be a topic for a separate workshop.
- Better leveraging of available resources is needed including inter-agency collaborations, incorporating traditional knowledge to better characterize seasonal changes, and utilization of lessons learned in marine science.
- Increasing education and awareness among the public is needed regarding the importance of winter science and the consequences if key knowledge gaps are not filled. A focused and consistent message needs to be developed on this topic.

Day 1

Introductory Session

Day 1 of Workshop 2 began with welcome and introductory comments by the hosts, organizers, and facilitators. The workshop team, composed of contractors, IJC staff, and the IJC SAB Co-chairs, outlined the objectives and approach and reviewed materials sent to the group in advance. This included a high-level overview of a Great Lakes-focused winter science literature review, a list of public databases with data relevant to winter in the Great Lakes, a summary of interviews with Great Lakes stakeholders and rights holders, and key takeaways from Workshop 1.

Breakout Session 1: Identify Organizational Mandates and Needs

Following an overview of introductory material, the workshop participants were divided into five groups based on agency/organization type to identify the mandates and needs related to winter science for each organization. The groups and their identified needs, topics of interest, and/or mandates are summarized below.

- **Canadian Federal Agencies and Indigenous Nations**
  - Needs included improved spatial and temporal scales, standardized monitoring approaches, and investments in observational platforms. Topics of interest included primary productivity, algal blooms, improving models, fisheries and fish harvest as a shared interest, economic implications (e.g., reduced ice and shipping), and the importance of shoulder seasons.
- **Canadian Provinces/Municipalities**
  - Needs discussed largely focused on expanding monitoring both spatially and temporally. Topics of interest included overlaps with nearshore water quality monitoring, including data available and that which is still needed. Mandates listed included tributary monitoring, watershed modeling, continuous water quality monitoring, and source water protection and monitoring (raw and finished), as well as public communication regarding taste, odor, and algae. Many groups have shoreline erosion science priorities, including flooding and from wind (e.g., Essex) and wetland erosion, including breaching of barrier beaches.
- **Canadian Academics**
  - Limited participation from this group; no separate breakout group.
- **U.S. Federal Agencies and Indigenous Nations**
  - Needs discussed by this group largely focused on higher resolution data on winter and shoulder season physical, biological, and chemical status and trends of the lakes. Additionally, improved modeling and forecasting capabilities, and considering climate change impacts within those models was also highlighted.
- **U.S. Academics**
  - Needs discussed by this group included an increase in continuous data gathering on currents, temperature, water quality, thermal structure, and nutrients. The need for more under ice observations was also discussed, as well as possible opportunities for collaboration that leverages feedback and data from other organizations.

A more-detailed overview of all the organizational mandates and needs discussed for each of these groups can be found in Appendix D.

Breakout Session 2: Identify Infrastructure and Training Resources and Actions

Breakout session 2 focused on identifying actions or resources needed to meet the priorities identified in Workshop 1, focusing specifically on infrastructure and training. Once again, participants were divided into five groups. The most frequently mentioned need across all five breakout groups was funding for conducting winter science. Related to this need for funding was also the need for winter science resources, including but not limited to, ice-hardened vessels, ice-capable AUVs, hovercrafts, mooring, and ice-capable buoys. The need for standardized sampling protocols for collecting winter samples and making observations, as well as winter sampling method development, was also mentioned frequently. There was a general notion to focus on elevating/maximizing the technology that has already been proven to work in winter rather than waiting for new technology to become available. Better utilization of existing resources such as the GLATOS network for improving data gaps was mentioned, as well as a more organized/centralized inventory of the winter vessels and resources available to maximize their utilization. This inventory also was suggested to include ice-hardened vessels not traditionally used for science, such as winter fishing vessels.

Another key infrastructure need discussed was centralized, cross-disciplinary databases, data integration, and data sharing pipelines. Overall better leveraging of social resources was also mentioned, including inter-agency collaborations, traditional knowledge integration to better characterize seasonal changes, utilization of lessons learned in marine science, and increasing education and awareness surrounding changes occurring in winter throughout this region. In addition to training on standardized sampling protocols, improved/updated winter science safety training was also a commonly mentioned training need, recognizing that ice is increasingly less predictable and poses new safety risks than have been historically present. The need for more qualified staff/students working on winter science was discussed, as well as more formalized contract vehicles with non-scientists or Indigenous groups who are working out on the lakes in the winter. A more-detailed overview of all the infrastructure and training needs discussed for each of these groups can be found in Appendix E.

Day 2

Opening Discussion

Day 2 of the workshop began with a recap of Day 1 activities and a brief review of workshop objectives for Day 2. The opening session was followed by two more rounds of breakout group discussions.

Breakout Session 3: Coordination and Resource/Data Sharing

Breakout session 3 focused on identifying actions to increase inter-agency coordination and resource/data sharing to maximize the use of existing resources. Discussion also examined what has worked well in the past, what has not, roadblocks to coordination, and ideas of how the IJC could help overcome these challenges.

A key topic discussed was the need to better use existing data. Participants suggested that data sharing in support of winter science may need to be a topic for a separate workshop. Another key step would be to engage with individuals and groups who will be responsible for providing as well as using the data. Organizations such as the Great Lakes Observing System (GLOS) may need to be designated as responsible for data management and updates. Improving management of and access to past data was also discussed, including funding for mining data that only exists in paper form or in offline repositories. Establishing a directory of available data, including key metadata and contact information for the data owners, may be an easier alternative to publishing full datasets.

Another key idea brought up by participants was the need to increase vessel access for in-lake monitoring and sampling in the winter. The lack of dedicated ice-hardened vessels for winter research was identified as a key roadblock. However, there is room to improve coordination between researchers and federal agencies regarding workplans for existing vessels. Other ways to expand winter sampling could be through the use of cabled, moored, or autonomous systems. Finally, while formal programs are important, ad-hoc groups can also be established to address specific research questions.

Participants also identified the need for adequate lab capacity to support winter science, including expanded monitoring in the winter and shoulder seasons. Also discussed was the need to expand sampling and monitoring at municipal drinking water intakes (and hydro dams), especially through coordination with municipalities to identify areas where the expanded sampling and monitoring can meet shared needs of researchers and intake operators (or dam operators). Finally, the idea of citizen science and coordinating with groups such as recreational ice fishermen and nearshore residents to expand data collection was mentioned by multiple groups.

Coordination and collaboration with other agencies in the region were also discussed. IJC should facilitate collaboration by setting with a team with Coast Guard, Army Corps, and managers and researchers from other agencies and organizations. Collaboration with the Great Lakes Fisheries Commission and member agencies was also highlighted. Finally, the need to form partnerships with groups outside the Great Lakes (e.g., with international lake researchers) was mentioned.

Participants provided **examples of what has worked in the past**, including:

- CSMI approach for winter science (e.g., Winter Science Cooperative Monitoring Initiative).
- Lean on SMART Great Lakes Initiative and lessons learned from other organizations (e.g., GLOS) and big data platforms.
- Cruise of opportunity with Canadian and US Coast Guard, as well as training for science with US Coast Guard (e.g., work done by Mike McKay). This requires coordination and a focus on areas where ice-breaking operations are occurring (i.e., central and western Lake Erie).
- Working with commercial fisherman, including contracting on a short term and off-fishing season basis.
- Volunteer-based, inter-institutional collaboration and coordination centered around a specific system/objective (Winter Grab, UM-led).
- Developing consistent methods for collaborative sampling (e.g., CSMI).
- Small grants to support data management from CSMI.
- Coordination across agencies/groups for sample collection, then send to other groups for processing/analysis. For example, collection of water samples for phyto analysis from water intakes and by groups out on the lakes for extended field season.
- Data management systems making QA/QC'd, publicly accessible data available in real-time or as close as possible. Data archiving systems for long-term data storage (e.g., NCEI).
- Geographically limited research vessels working in winter (University of Wisconsin - Milwaukee, GLERL).
- Requesting infrastructure access through agency channels (e.g., icebreakers).
- Use of small aircraft for summer hyperspectral imaging in Great Lakes both in the US (GLERL) and Canada (HNRSI).

Participants also provided **examples of what has not worked** well, including:

- Non-linked databases as well as lack of a central database.
- Lack of commitment for data management following completion of research project.
- Limited capacity of a single database to include multiple kinds of data (point, continuous, social science, Indigenous knowledge).
- Ownership of databases or models by a single funding-depending entity can affect updates, maintenance, etc.
- Limited ability of non-government entities to participate in CSMI sampling.
- Lack of standardized protocol leads to lack of information (sensor depth/height, time of day, latitude/longitude, etc.).
- Lack of communication amongst various organizations.
- Relying on contracting commercial fishers for entire projects lasting more than a few weeks or overlap with open fishing seasons.
- Lack of multiple transport options lined up to respond to changing conditions (e.g., snowmobile vs. air boat).
- Unreliable or untested instruments. Most instruments are designed to function in warm waters, and reliability needs to be tested for winter conditions.
- Poor attempts to involve Indigenous organizations into science projects.
- Limited collaboration involving only "insiders", as well as insufficient accountability.
- Overly specific budgets that restrict spending into narrow categories.

Finally, participants discussed how IJC can help advance winter research. Suggestions included funding with focus on binational collaborations, as well as funding to encourage collaboration with tribes and First Nations. Other areas where IJC can assist include coordination between winter limnology workgroup and federal workplans/vessel access and enabling conversations between IJC and GLFC at the technical committee level.

Breakout Session 4: Interdisciplinary Efforts and Communication

Breakout session 4 focused on how to better integrate science, social science, economics, and traditional knowledge to generate new insights, as well as how to improve communication on research findings to both the public and to decision makers.

Integrating Disciplines

Participants brought up several ideas related to this topic. One common theme was to look for increased funding and resources specifically aimed at bringing cross-disciplinary perspectives into agency staff and research programs. Other ideas included preparing joint proposals across disciplines and making interdisciplinary collaboration a priority in agency funding to universities and industry partners. Agencies can promote interdisciplinary engagement within their staff and make this a priority when hiring new staff and when planning work. Agencies can also require or prioritize multi-disciplinary proposals for funding. For example, USGS CASC proposals require clear management relevance that automatically inspires multi-disciplinary approaches. In Canada, having some dedicated funding initiatives run through SSHRC can reinforce the importance of multidisciplinary collaboration.

Another focus of the discussion was increasing engagement and communication with collaborators and increasing equity between collaborators. Attending new conferences is one way to bring in new collaborators. Collaborative publications that cross traditional disciplinary boundaries should be prioritized, and other disciplines should be engaged by formulating winter science questions that encourage collaboration. A related idea was to promote engagement early by setting up internship opportunities for high school and college students. Finally, participants emphasized the need for additional structured, formal opportunities for interaction such as conferences focusing on winter.

Other ideas included setting up pilot projects around interdisciplinary collaboration and setting up a "business incubator"-style initiative focused around winter science. In terms of engaging with a broader audience around winter science, participants mentioned the need to engage with other winter "users" of the lakes (such as ice fishermen, winter sports participants, drinking water intake managers, etc.) to understand their needs and priorities.

Participants also noted that it is important to engage with Indigenous communities and visit them to hear their stories about the natural world and understand how they can inform science. It was also pointed out that Indigenous organizations should be supported financially to self-direct their own research based on their priorities, rather than simply engaging them in support of existing research programs. Finally, some participants noted that traditional knowledge is a separate knowledge system and worldview from Western thinking, so integration with Western science may be challenging.

Finally, workshop participants highlighted the need for additional public forums and events focused around Great Lakes winter science. One idea was to host workshops and panel discussions with a range of participants other than academic researchers and management agencies. Another idea was to host a "Great Lakes Winter Science Forum" similar to a "Mississippi River Science Forum" recently hosted by USGS that invited stakeholders from across the basin to give talks on science gaps and needs for the basin. Additionally, participants noted the need to highlight winter science needs at conferences outside typical Great Lakes and aquatic limnology meetings to engage new collaborators. It is also important to support participation in bi-national and federal forums under the GLWQA that bring together diverse groups, to support cross cutting aspects of winter science.

Communicating Research Findings

A key point highlighted by workshop participants was the need to avoid a “one size fits all” approach. Instead, researchers should consider the target audience and adjust the way that research findings are communicated. For example, publications (e.g., journals) are aimed at the academic community, open data for modelers and statisticians, incorporation into Indigenous ceremonies (water ceremonies), infographics and other public friendly documents for broad engagement, and social media products to engage younger audiences. Finally, participants noted that a strong "why" or common mission statement is needed to justify the effort to support winter science. This may mean better articulation of the implications if science questions are left unanswered.

In terms of efforts to make the public more aware of winter science, participants noted that winter science needs to be highlighted in the news and media. One way could be to organize events (e.g., sled dog or snowmobile races) or science activities (e.g., Winter Grab) and publicize them. There may also be a benefit in hiring professional communications firms and developing a communications strategy with a clear message about the importance of winter science. Other options could be celebrity endorsements, synchronizing winter science announcements with related trending topics, and building relationships with reporters and social media influencers. Examples of different types of communications products mentioned by participants include a user-friendly interface (website) for the public to “play” with the data (e.g., different timescales, different regions/locales), report cards providing a snapshot of winter conditions, and videos. Involving artists could be another way to publicize winter science, as well as students who are good at social media. A key point raised here (and elsewhere in the workshop) was the need to go to community events and not expect them to come to winter science meetings.

Participants also discussed other ways to engage the public. One idea was to find community groups with an interest in winter science and connect with them (e.g., by setting up a table at an ice fishing expo, giving talks at local events, etc.). Other ideas discussed included hosting journalists on a winter science expedition and funding a winter science journalism fellowship. Additional options include partnering with organizations specializing in science communication (e.g., SeaGrant) or organizing K-12 and college teacher trainings. Other options could include holding science cafes or happy hours, connecting with citizen science groups, and inviting public participation in winter science events (such as monthly Great Lakes winter group meetings held the first Friday of each month).

Participants also talked about the need for greater engagement on winter science within the research community and management agencies, and with tribes and First Nations. One step could be to create informal working groups (agency-academic-municipal-tribes/First Nations) on specific winter-related topics and produce white paper(s) designed for communicating the issue, with clear identification of risks and outcomes, to relevant agencies. Emphasizing how research can be applied to management problem solving would be key in any such communications. Encouraging greater participation in the Great Lakes winter group was also mentioned. Encouraging greater involvement in conferences and publications could be important, by removing barriers (e.g., cost) through travel grants and by subsidizing open access costs for publications.

Finally, participants mentioned some examples of other initiatives that could serve as models. These include GLATOS, which works well for scientific community and the public; GLANSIS which has a website for invasive species in the Great Lakes; IAGLR and AGU Ocean Sciences winter research sessions; and NOAA GLERL CoastWatch and modeling/ forecasting group ice classification and ice cover.

Wrap-Up and Next Steps

The workshop concluded following the final breakout session, after the IJC SAB workgroup co-chairs thanked participants for sharing their time and expertise. Next steps discussed included preparing a workshop summary report, as well as starting planning and coordination for a third, in-person winter science workshop to generate prioritized recommendations related to winter science, for action by IJC and other agencies in the Great Lakes.

Appendix A: Agenda

International Joint Commission (IJC)
Great Lakes Winter Science Workshop #2 – Winter Science Priorities
Sep 5-6, 2023, 1pm – 4:30pm
Workshop Agenda

Virtual meeting link:
https://us06web.zoom.us/j/84187933735?pwd=YWJLb1ZDRUF2Y3BVZzc3L3pTZ2xZZz09

IJC Contact: Matthew Child, matthew.child@ijc.org
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Workgroup Co-Chairs: Maggie Xenopoulos, Trent University, mxenopoulos@trentu.ca
Michael Twiss, Algoma University, michael.twiss@algomau.ca

Support Contractors: Samir Qadir, Potomac-Hudson Engineering, Inc., samir.qadir@phe.com
John Bratton, LimnoTech, jbratton@limno.com
Michelle Platz, LimnoTech, mplatz@limno.com

Objective: Identify, assess, and describe needs related to infrastructure, training, and coordination amongst management agencies to meet the science priorities identified in workshop #1.

Approach: Workshop preparatory materials include:

- Summary of Workshop #1 activities and outcomes.
- Summary of literature review describing the current state of Great Lakes winter science and identified knowledge gaps.
- Summary of publicly accessible data related to Great Lakes Winter Science.
- Summaries of the identified needs of stakeholders and rights holders based on semi-structured interviews, as they relate to Great Lakes winter science.

Workshop participants are expected to have reviewed the materials provided and come prepared to discuss their understanding of science needs and priorities.

Workshop attendees are asked to identify training, infrastructure and coordination needs to meet the science priorities identified in workshop #1. Participants will be asked to think of these needs through different "lenses" in four separate breakout sessions:

- **Understanding agency mandates and data needs:** What mandates do agencies currently have with respect to winter in the Great Lakes, both in terms of data collection and management decision (data needs)? What data are they collecting?
- **Supporting science priorities and interdisciplinary efforts:** Where are there gaps in data, especially with respect to workshop #1 priorities including economic and cultural impacts? What steps can agencies take to help close these gaps (e.g., new vessels, buoy-mounted sensors, remote sensing, training, etc.)?
- **Increase inter-agency coordination:** What opportunities exist to increase coordination and resource sharing among agencies, keeping in mind data gaps and actions identified on day 1 and workshop 1 science priorities?
- **Improve data sharing and communication:** How can agencies improve data sharing to support winter science, and better communicate research findings between scientists and agencies and to the public? This could include, for example, the use of central platforms to host and share data and communicate results.

Outcomes: List of management agency needs, as identified by workshop participants

Day 1

Time	Topic	Presenter
1:00 – 1:15 pm	**Opening and welcoming remarks** Introductions Project and workshop objectives	IJC staff and co-chairs
1:15 – 1:35 pm	**Background and workshop approach** Summarize findings from Workshop 1, literature review, and interviews. Discuss workshop approach. Introduce Mural.	Contractor Team
1:35 – 2:20 pm	**Breakout Round 1 – Agency mandates**	Contractor Team and Co-chairs
2:20 – 2:50 pm	**Breakout 1 Review and Synthesis** Breakout groups report out to full group.	Contractor Team
2:50 – 3:10 pm	**Break**	
3:10 – 3:55 pm	**Breakout Round 2 – Supporting science priorities**	Contractor Team and Co-chairs
3:55 – 4:30 pm	**Breakout 2 Review and Synthesis** Breakout groups report out to full group.	Contractor Team
4:30 pm	**Day 1 Wrap-Up**	

Day 2

Time	Topic	Presenter
1:00 – 1:30 pm	**Opening remarks** Recap of Day 1 activities. Refresher on workshop objectives, approach, and tools.	IJC staff and co-chairs
1:30 – 2:15 pm	**Breakout Round 3 – Inter-agency collaboration**	Contractor Team and Co-Chairs
2:15 – 2:45 pm	**Review and Synthesis** Breakout groups report out to full group.	Contractor Team
2:45 – 3:00	**Break**	
3:00 – 3:45	**Breakout Round 4 – Improve data sharing and communication** How can agencies maximize the use of existing data and improve communication of winter science research findings, both within research and management communities and to the public?	Contractor Team and Co-Chairs
3:45 – 4:15	**Review and Synthesis** Breakout groups report out to full group.	Contractor Team
4:15 – 4:30	**Workshop summary** Recap of workshop activities.	IJC Staff and Co-chairs
4:30	**Day 2 Wrap-Up**	

Appendix B: Workshop Participants

Below is a list of the participants who attended all or part of the workshop. Aside from co-chairs, IJC staff, and contractors, there were 40 participants from both the US and Canada across a range of fields including research agencies and academics, federal, state, and provincial agencies, native tribes, and municipalities.

Attendee	Organization
Maggie Xenopoulos	*Trent University (co-chair)*
Michael Twiss	*Algoma University (co-chair)*
Matthew Child	*International Joint Commission*
Lizhu Wang	*International Joint Commission*
Samir Qadir	*Potomac-Hudson Engineering, Inc. (Contractor)*
Kate Kopp	*Potomac-Hudson Engineering, Inc. (Contractor)*
John Bratton	*LimnoTech (contractor)*
Michelle Platz	*LimnoTech (contractor)*
Dennis Donahue	NOAA/GLERL
Liza Ballantyne	City of Toronto
Lynn Bouvier	Fisheries and Oceans Canada (DFO)
Michael Friis	Wisconsin Coastal Program
Ana Sirviente	GLOS
Andy Bramburger	Environment and Climate Change Canada
Angela Wallace	TRCA
Annie Scofield	EPA GLNPO
Arthur Zastepa	ECCC
Ashley Brettell	Region of Durham
Ashley Elgin	NOAA
Ayumi Manome	CIGLR
Bill Mattes	GLIFWC
Casey Godwin	University of Michigan
Chris Massey	USACE
Daryl McGoldrick	Environment and Climate Change Canada
Tracie Greenberg	Environment and Climate Change Canada
David Depew	Environment and Climate Change Canada
Deborah Balika	Conservation Ontario Drinking Water Source Protection
Dennis Donahue	NOAA Great Lakes Environmental Research Laboratory (GLERL)
Andrew Gronewold	University of Michigan
Ed Rutherford	NOAA Great Lakes Environmental Research Laboratory (GLERL)

Ian Harding	Red Cliff Band of Lake Superior Chippewa; Treaty Natural Resources
James Watkins	Cornell University
Jay Austin	University of Minnesota Duluth
Jia Wang	NOAA Great Lakes Environmental Research Laboratory (GLERL)
Kathy Jo Jankowski	U.S. Geological Survey
Katie Stammler	Essex Region Conservation Authority
Ngan Diep	Ministry of the Environment, Conservation and Parks; Ontario
Nicole Zacharda	Great Lakes Commission
Rebecca Smart	Water/Wastewater Technical Specialist, Region of Peel
Reza Valipour	Environment and Climate Change Canada
Richard Kraus	USGS Great Lakes Science Center
Rick Ferguson	Fisheries and Oceans Canada (DFO)
Silvia Newell	Michigan Sea Grant
Steve Ruberg	NOAA
Therese Estephan	Region of Peel
Todd Howell	Ontario Ministry of the Environment and Climate Change
Warren Currie	Fisheries and Oceans Canada (DFO)
Yingming Zhao	Ontario Ministry of Natural Resources and Forestry

Appendix C:
Breakout Group Discussion Topics

Day 1 Breakout Group Discussion Topics

Breakout 1: Agency missions and mandates

- What are their agency mandates, priorities and data needs related to winter?
- What agencies are present in the room?
- What management decisions are they responsible for and how do they relate to (or are affected by) winter?
- Do agency priorities/needs correlate with science priorities identified through IJC Workshop 1? See notes to the right.
- What data related to winter are they currently collecting?
- Are their additional (unmet) data needs?

Breakout 2: Agency infrastructure and training priorities

- What actions or resources would help to meet the identified needs and priorities?

Day 2 Breakout Group Discussion Topics

Breakout 3 - Inter-agency Collaboration and Data Sharing

- What opportunities exist to increase collaboration and resource sharing among agencies?
    - What has/ has not worked in the past?
- How can we maximize the use of existing winter-related data and resources? (e.g., coordinating on vessel/platform availability, central repositories for data, etc.)
- Are there groups that we can collaborate with to advance winter science? Think also of groups outside the traditional scientific and government agency communities.
- Are there any roadblocks to coordination/collaboration?
- How can the IJC help?

Breakout 4 - Interdisciplinary Work and Communication

- How can we better integrate science, social science, economics, and TEK into a fuller understanding of the impacts of changing winter conditions?
- Who should we be communicating with about our research and findings?
    - Within the research and management communities to share findings, generate new research questions
    - Public – create public awareness of the issues
    - Decision makers – get more support for winter science
- How can we improve communication of winter science research?

Appendix D: Breakout 1 Summary Tables

Canadian Feds, Indigenous Groups

Agency	Management Decisions	Science Priorities	Data Collected	Additional Data Needs
Region of Peel	Source water quality monitoring and implications for treatment. Improved spatial and temporal resolution of water intake quality monitoring. Continuous measurements of lake currents, temperature profiles, water quality, meteorology and climate measurements, and lower food web surveys and productivity.	Social and cultural impacts of changes in winter.	Shoulder season water quality and GW levels. Remote and routine drinking water quality samples.	Continuous seasonal data for water quality and level parameters to better understand seasonal fluxes (ie. Salt, temperature, etc.) Social and cultural impacts of changes in winter.
Environment and Climate Change Canada (WSTD Monitoring AND Research)	Winter and shoulder season-specific funding, staff capacity, vessels, appropriate work platforms, and resources for winter research including icebreakers, AUVs, and standardized/ comparable sampling protocols. Training on winter science methods as well as an evolution of winter science training and safety. Leverage existing technology and collaborations by collecting year-round samples and improving sample resolution. Limiting cHABs, nutrient reductions, improved oxygen. Update modeling methods and design for the purpose of addressing winter science problems. Impacts of climate change on winter recreation and subsistence fishing.	Lake-by-lake variations in ice cover and planktonic productivity. Drivers and phenology of cHABs. Lake thermal structure. Improved coordination and data/resource sharing. Increased under ice observations. Metabolic changes (primary productivity and net ecosystem production). Changing variability, timing, and magnitude of storm events, freshet magnitude and timing, and nutrient inputs and cycling.	Opportunistic Winter WQ sampling from CCG vessels. Year round trib loading and connecting channel inter-lake flows. Opportunistic winter sampling of cHABs and other WQ parameters, fragmented.	Continuous, connected seasonal sampling throughout the year to understand phyto/cHAB phenology, WQ. Connectivity.
Environment and Climate Change Canada – Canadian Ice Service	Safety of navigation/marine operations. Joint production of products (ice charts) with USNIC for Great Lakes (under NAIS, North American Ice Service). Detection of oil spills in open water (ISTOP).	Impacts of ice breaking and extended shipping season. Update modeling methods and design for the purpose of addressing winter science problems. Remote sensing, ice phenology observations, and modeling, (but not: lake physics and biology, and socioeconomic analysis).	Satellite remote sensing data (RADARSAT Constellation Mission) + secondary sources. Helicopter and ship-based (CCG) ice observations. Historical ice datasets, WMO mandated 30-year climatology (ice climate normals).	Ice observations from ships? Validation of ice thickness. Continuity of satellite missions.

Agency	Management Decisions	Science Priorities	Data Collected	Additional Data Needs
		Support for Lake Erie ice boom (end of season). Shoulder season observations, sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for autonomous vehicles). Improved coordination and data resource sharing.	Ice/Open water classification using ML/DL.	
DFO Great Lakes Laboratory for Fisheries and Aquatic Sciences	Populations, Species at Risk. Aquatic invasive species – climate impacts to survival, establishment. Changes to fish productivity and food availability (e.g., plankton productivity). Areas of Concern. Aquaculture. Protection of Aquatic Ecosystems.	Other economic impacts of changing fisheries. Impact of cHABs, nutrient reductions, improved oxygen. Connectivity between nearshore and offshore systems (biota succession gradients and drivers, food web coupling, nutrient transport, thermal bar formation, timing, and persistence).	Food web ecology, changing trophic relationships and timing mismatches. Metabolic changes (primary productivity and net ecosystem production). fish channel utilization in winter. Lake ecosystems long-term monitoring.	Changes to fish migration patterns, spawning and hatch, species vulnerability to hanging ice on/off timing, and temporal mismatch of food availability and fish hatch. Influence of changing shoulder seasons on food web dynamics, including overall lake primary production, overwintering of fall planktonic communities, and impacts of warmer winters on spring phyto/zooplankton bloom composition. Lake-by-lake variations in ice cover and planktonic productivity. Improved coordination and data/resource sharing. Lake-specific research needs: Lake Superior coregonine community spawning biology, lack of sampling on Superior and Ontario after the locks close for the winter, and lack of research and information for Michigan and Huron.
Fisheries and Oceans Canada (DFO) including Canadian Coast Guard	Ice jams in connecting channels. Remote sensing. Impacts of ice breaking and extended shipping season. Safe navigable waterways.	Cost and benefits of lengthening the winter shipping seasons.	Remote sensing data.	

Canadian Provincial/Municipalities

Agency	Management Decisions	Science Priorities	Data Collected	Additional Data Needs
Ontario Ministry of Environment, Conservation and Parks	Ensure environmental protection and restoration (policies, programs and legislation). Lake Ontario extend seasonal coverage of water quality monitoring into and within the lake to better understand extremes and events that occur on algae growth.	Connectivity between nearshore and offshore systems (biota succession gradients and drivers, food web coupling, nutrient transport, thermal bar formation, timing, and persistence, and impact of increasing shoreline erosion on offshore sediment load). Changing lake inputs, such as variability, timing, and magnitude of storm events, freshet magnitude and timing, and nutrient inputs and cycling. Continue to monitor chloride in water to advance understanding of conditions, trends, and impacts to Great Lakes water quality and ecosystem health. Better understanding of how winter dynamics complicate/confound/influence nutrient load estimates.	Impacts of ice cover loss and increasing winter wind energy on sediment resuspension and nutrient loading, water column mixing and lake circulation, nearshore to offshore nutrient transport and sediments consolidation, shoreline erosion, littoral vs offshore productivity, contaminant distribution, and littoral benthic community structure. Impacts of changing catchment hydrology and increasing freeze/thaw events on tributary loads. Year-round event-based monitoring of river discharge water quality at 13 rivers near lake output to Lake Ontario. Continuous measurements of lake currents, temperature profiles, water quality, meteorology.	Shoulder season observations, such as sensing tools (e.g., extended sensor deployments cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles). Traditional knowledge integration to better characterize seasonal changes. Development of tools to allow for prediction of unusual water quality conditions to respond in advance rather than the current more reactive approach. Remote sensing, ice phenology observations, and modeling, lake physics and biology, and socioeconomic analysis.
Conservation Ontario	Providing messaging for public if there is a water quality impact affecting broader population such as taste and odor aesthetics issues. Providing technical advice to plant operations staff for managing unusual water quality conditions (treatment adjustments). CAs carry out legislative duties for Clean Water Act & Natural Hazards Ensure environmental protection and restoration (policies, programs and legislation).	Yes, all drinking water priorities are in alignment.	CAs collect specific monitoring program data (topic of interest/smaller or larger scale). CA's have long term monitoring data (MNRF/MECP? Snow survey, PWQMN and flood forecasting).	February to April, broad based water quality monitoring of the nearshore (shoulder season focus) at the time that the intensity lake-land interactions is near maximal. Leverage existing technology and collaborations by collecting year-round samples and improving sample resolution. Lake thermal structure. Fate of sediment bound-P delivered during winter and low light periods of the years and role as a contributor to nuisance algae during the summer. Improved warnings for wind and wave events. Invasive macrophyte behaviors under ice. Improved spatial coverage and temporal resolution of water

Agency	Management Decisions	Science Priorities	Data Collected	Additional Data Needs
				intake quality monitoring.
Essex Region Source Protection Authority	Essex Region is greatly affected by shoreline erosion on Lake Erie and Lake St. Clair and flooding particularly in winter/spring.	Linking models with event-based water quality monitoring to improve predictive capabilities. Improved spatial coverage and temporal resolution of water intake quality monitoring. Many priorities align! Characterization of changing source water quality. Impacts of changing catchment hydrology and increasing freeze/thaw events on tributary loads. Impacts of ice cover loss and increasing winter wind energy on sediment resuspension and nutrient loading, water column mixing and lake circulation, nearshore to offshore nutrient transport and sediments consolidation, shoreline erosion, littoral vs offshore productivity, containment distribution, and littoral benthic community structure.	We do tributary monitoring year-round. Winter/spring runoff is highest. ERCA collects data from tributaries year round – nutrients, e.coli and chloride. ERCA had a network of climate stations throughout the region, including wind sensors.	Better coordination of drinking source water data. Consistent funding support for year-round event-based sampling.
Region of Durham	Source protection function for Durham including lake current monitoring system and modeling of spill movement during an emergency. Providing technical advice to plant operations staff for managing unusual water quality conditions (treatment adjustments). Changing source water and potential impacts for treatment.	Providing messaging for public if there is a water quality impact affecting broader population such as taste and odor aesthetics issues.	Water quality samples collected from drinking water plant intakes year round (within plants). ADCPs in lake will collect parameters such as: Current Speed/Direction Temp. Turbidity, Phycocyanin, Conductivity. Characterization of changing source water quality through years of raw water sampling at drinking water intakes.	Adequate funding resources to increase capacity.
City of Toronto (lack of resources)	Spills Management. Source protection function for Toronto water including lake current monitoring system and modeling of spilled movement during an emergency.	Working collaboratively/linking to all aspects of drinking water from source to tap (science to policy to implementation).	City of Toronto- We have multiple years are raw water quality (Lake Ontario) at the intakes via our SCADA system (online instrumentation such as temperature and turbidity) as well as lab data such as algae. We also commissioned a lake current monitoring	Centralized, cross-disciplinary databases, data integration and data sharing.

Agency	Management Decisions	Science Priorities	Data Collected	Additional Data Needs
	Inter-agency collaboration, data sharing.		system in the spring of 2023 which now collects further information near our water treatment plant intakes such as turbidity, conductivity, temperature, chlorophyl-a, phycocyanin, current speed and direction.	
Toronto and Region Conservation Authority (Fisheries agency is not represented)	Advice re: urban water quality issues – e.g., road salt/chloride. See Conservation Ontario. Characterization of WQ for watershed management.	Watershed modelling for watershed management (e.g., future watershed scenarios – more urbanization).	Monthly grab water quality samples (including through winter months) at mouths of river and throughout watershed (combination PWQMN/TRCA sampling). Automated WQ samplers that can be triggered remotely. Mainly at mouths of rivers but also throughout the city of Toronto (partnership with Toronto/MECP others). Lake Ontario Nearshore and watershed fisheries monitoring (mostly summer but research projects in winter). Continuous WQ at mouths of rivers (partnership with MECP/Toronto/others).	Discussions/communications re: how to do winter science field work better -often we have to figure things out ourselves, but we know others have probably done it before.

Canadian Academic Institutions (no representation in attendance)

US Federal Agencies and Indigenous Groups

Agency	Management Decisions	Related Science Priorities	Data Currently Collected	Additional Data Needs
National Park Service	Winter recreation - ice caves.	Is the ice safe for people to walk on or snowmobile on.	??	How early or late can people kayak? Lake-by-lake variations in ice cover and planktonic productivity. Fleet of autonomous vehicles and operators for them. So have some years of overlap data. Getting more difficult to sample all seasons due to wind.
Red Cliff Band of Lake Superior Chippewa Treaty Natural Resources Division, Great	Recommending sustainable fish harvest rates.	Fish recruitment (trends and mechanisms).	Fisheries independent and Fishery Dependent data primarily for cisco, lake trout, and lake whitefish.	Basic life history during winter and shoulder seasons (habitats occupied,

Agency	**Management Decisions**	**Related Science Priorities**	**Data Currently Collected**	**Additional Data Needs**
Lakes Indian Fish & Wildlife Commission	Liaison with other agencies on environmental priorities, fisheries management goals. Rehab of depleted fish populations (e.g., Lake Sturgeon, Coasters, Walleye). Water quality on and adjacent to Reservation.	Adult abundance and biomass, historical trends and forecasting.	Assessment of lake sturgeon, brook trout, and sea lamprey.	diet, mortality, etc.). How biotic and abiotic conditions affect mortality at early life stages especially during shoulder seasons and winter. Of native, non-native, and invasive species. Resources to assess current ice conditions. Food web ecology, including changing trophic relationships and timing mismatches. Increased under ice observations. Leverage existing technology and collaborations by collecting year-round samples and improving sample resolution. Impacts of climate change on winter recreation and subsistence fishing.
United States Geological Survey	Joint strategic plan priorities / GLFRAA; DOI Trust Species.	Fisheries and Bio. Native fish restoration; invasive species. Harmful algal blooms, nutrient loading, restoration (e.g., coastal wetlands). Linking models with event-based water quality monitoring to improve predictive capabilities.	Water quality and quantity in tributaries. Fisheries Surveys; water quality; acoustics; lower trophic level. Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles). Impacts of changing catchment hydrology and increasing freeze/ thaw events on tributary loads. Nearshore (e.g., tributary mouths) nutrient dynamics, food web, benthic communities. (Work during growing season on) ... on nearshore to offshore nutrient transport and sediments consolidation, shoreline erosion, littoral vs offshore productivity,	More spatially distributed monitoring in tributary basins (more gages in less impacted, northern basins where ice changing rapidly). Little-to-no data during ice-on.

Agency	Management Decisions	Related Science Priorities	Data Currently Collected	Additional Data Needs
			contaminant distribution, and littoral benthic community structure. Implementation of standardized/comparable methods. Centralized, cross-disciplinary databases, data integration, and data sharing. Training on winter science methods as well as an evolution of winter science training and safety - (e.g., Upper Mississippi River monitoring program out of UMESC has been sampling through the winter in the river for 30 years, so knowledge to share from that).	
NOAA/NOAA Lake Michigan Field Station	Winter and shoulder season-specific funding, staff capacity, vessels and appropriate work platforms. Training on winter science methods as well as an evolution of winter science training and safety. Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles). Cost and benefits of lengthening the winter sampling seasons. Build a climate-ready nation: Through upgraded climate information, improved weather forecasts and enhanced infrastructure, NOAA will build a Climate Ready Nation, resilient and prepared for future climate change.	Food web ecology, including changing trophic relationships and timing mismatches. Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles). Training on winter science methods as well as an evolution of winter science training and safety. Linking models with event-based water quality monitoring to improve predictive capabilities. Update modeling methods and design for the purpose of addressing winter science problems.	Winter ecosystem physical, biological, chemical data in specific locations. Winter physical data such as temperature / climate / lake evaporation Great Lakes wide. Winter satellite and airborne remote sensing data Great Lakes wide (ice, temperature, CHL, TSM, DOC, CDOM, PP). Overwintering moorings with temperature and chlorophyll sensors, as well as caged dreissenid mussels. Funded projects to deploy sensors and AUVs in western and central Lake Erie in winter with Coast Guard support.	Connectivity between nearshore and offshore systems (biota succession gradients and drivers, food web coupling, nutrient transport, thermal bar formation, timing, and persistence, and impact of increasing shoreline erosion on offshore sediment load). Impacts of ice cover loss and increasing winter wind energy on sediment resuspension and nutrient loading, water column mixing and lake circulation, nearshore to offshore nutrient transport and sediments consolidation, shoreline erosion, littoral vs offshore productivity, contaminant distribution, and littoral benthic community structure.

Agency	Management Decisions	Related Science Priorities	Data Currently Collected	Additional Data Needs
US Army Corps of Engineers	Winter navigation and associated infrastructure; coastal resilience to ice/snow/waves.			
US EPA	LAMP development and implementation - how changing winter conditions may impact priorities for management actions, restoration projects, etc. For example, changing habitat & overwinter conditions on native species restoration efforts. Impact of changing winter conditions on invasive species (established and/or potential new invaders). Logistical challenges, resources available for extending the field season, adding surveys, vessel operations, etc. CSMI implementation - how winter science priorities may factor into future CSMI priorities and projects, are there important topics that could be addressed in CSMI framework? Training on winter science methods as well as an evolution of winter science training and safety.	Impacts of ice cover loss and increasing winter wind energy on sediment resuspension and nutrient loading, water column mixing and lake circulation, nearshore to offshore nutrient transport and sediments consolidation, shoreline erosion, littoral vs offshore productivity, contaminant distribution, and littoral benthic community structure. Resources for winter research, including icebreakers, AUVs, and standardized sampling protocols. Connectivity between nearshore and offshore systems (biota succession gradients and drivers, food web coupling, nutrient transport, thermal bar formation, timing, and persistence, and impact of increasing shoreline erosion on offshore sediment load). Impacts of changing catchment hydrology and increasing freeze/ thaw events on tributary loads. Lake-by-lake variations in ice cover and planktonic productivity. Lake Erie & embayments/areas impacted by HABs: --> Linking changing winter conditions with factors impacting summer HABs development- changes to nutrient cycling, early season phyto communities, etc. Lake Erie central basin --> Linking changing winter conditions with factors impacting	Limited winter data collections (logistical constraints, not part of long-term monitoring programs); Some limited phytoplankton collections started (collaboration with UMD NRRI, NOAA CIGLR, Canadian partners). Even when data aren't collected by EPA directly, interest and need to coordinate with other agencies to generate data. Work through GLRI to support data collection by other groups. Interest in additional shoulder season sampling, gliders/AUVs, technology-based approaches, remote sensing, etc. How can we partner with other agencies to collect data to complement our in-situ monitoring programs (doing some of this already but could do more).	Comparisons of conditions under ice vs. open water in same year and/or between low and high ice years. How do changing ice conditions impact lake productivity and base of food web, and what does that mean in the context of oligotrophication and/or eutrophication of GL waters. How do changing winter conditions impact nutrient loading & cycling? Lake-by-lake variations in ice cover and planktonic productivity. How does changing seasonality & lower food web productivity impact larval fish bottlenecks, impacts on native fish populations.

Agency	Management Decisions	Related Science Priorities	Data Currently Collected	Additional Data Needs
		summer Hypoxia development, intensity, duration. Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles). Changes to fish migration patterns, spawning and hatch, species vulnerability to hanging ice on/off timing, and temporal mismatch of food availability and fish hatch. Changing lake inputs, such as variability, timing, and magnitude of storm events, freshet magnitude and timing, and nutrient inputs and cycling. Influence of changing shoulder seasons on food web dynamics, including overall lake primary production, overwintering of fall planktonic communities, and impacts of warmer winters on spring phyto/zooplankton bloom composition.		

US Academic Institutions

Agency	**Management Decisions**	**Related Science Priorities**	**Data Currently Collected**	**Additional Data Needs**
Michigan Sea Grant	Sustainable fisheries, healthy coastal ecosystems. Winter and shoulder season-specific funding, staff capacity, vessels and appropriate work platforms.	Winter Limnology. Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles).	Leverage existing technology and collaborations by collecting year-round samples and improving sample resolution. Increased under ice observations.	Increased under ice observations. * Impacts of climate change on winter recreation and subsistence fishing. Population composition and distribution. Other economic impacts of changing fisheries. Continuous measurements of lake currents, temperature profiles, water quality, meteorology and climate measurements, and lower food web surveys and productivity.

Agency	**Management Decisions**	**Related Science Priorities**	**Data Currently Collected**	**Additional Data Needs**
				Food web ecology, including changing trophic relationships and timing mismatches. Resources for winter research, including icebreakers, AUVs, and standardized sampling protocols. Economic value of winter activities such as ice fishing, ice-based transportation. Better leverage social resources, including inter-agency collaborations, traditional knowledge integration to better characterize seasonal changes, utilization of lessons learned in marine science, and education and awareness. For MISG, many of the priorities identified here fit under healthy coastal ecosystems and sustainable fisheries (our mandate).
Cooperative Institute for Great Lakes Research (CIGLR)	Advance Prediction via Modeling (CIGLR). Fundamental physical, chemical, biological, ecological, and social science to support NOAA's Great Lakes Lab.	Linking models with event-based water quality monitoring to improve predictive capabilities. Resources for winter research, including icebreakers, AUVs, and standardized sampling protocols. Update modeling methods and design for the purpose of addressing winter science problems. Training on winter science methods as well as an evolution of winter science training and safety. Coordinating sample and data collection across organizations. Consequences of winter processes for the other seasons and the reverse. *	Remote sensing, ice phenology observations, and modeling, lake physics and biology. ** Water samples from municipal intakes, irregular grab samples through ice. Population composition and distribution. Lake thermal structure. *	Ice jams in connecting channels. Continuous measurements of lake currents, temperature profiles, water quality, meteorology and climate measurements, and lower food web surveys and productivity. * Social and cultural impacts of changes in winter. Ice biogeochemistry modeling (e.g., under-ice algae). Lake thermal structure.
Wisconsin Coastal Program	Adaptive management - climate change.	Coastal Processes. Erosion rates/deposition.	Bathy/Terrestorial LiDAR.	
NOAA		Climate & fisheries; ecosystem dynamics, AIS, physical modeling and forecasting.	Lower trophic level biomass and dynamics; surface temperature, currents, benthos, ice duration, extent, quality, water levels, AIS, HABs, primary producers, remote sensing, food web dynamics.	Under ice measures of water quality, lower trophic levels, benthos, primary producers, biogeochemistry, how loss of winter affects primary, secondary production and plankton spp composition effects of warming groundwater on fish nursery habitats, growth/survival and migration /spawning phenology.

Agency	**Management Decisions**	**Related Science Priorities**	**Data Currently Collected**	**Additional Data Needs**
Great Lakes Observing System	Support observing platforms that support various stakeholder needs. Centralized, cross-disciplinary databases, data integration, and data sharing.	Linking models with event-based water quality monitoring to improve predictive capabilities. Lake thermal structure. Implementation of standardized/comparable methods.	Characterization of changing source water quality. Some moorings and real-time buoys - mostly physical characteristics.	Economic value of winter activities such as ice fishing, ice-based transportation. Increased under ice observations. Changing lake inputs, such as variability, timing, and magnitude of storm events, freshet magnitude and timing, and nutrient inputs and cycling. Resources for winter research, including icebreakers, AUVs, and standardized sampling protocols. Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles). Long-term physical, biogeochemical data. *
UMD Large Lakes Observatory	Understanding the large lakes of the world.	Winter conditions; climate change both modern and paleo.	Lake thermal structure. Long-term (>18 yrs), year-round, full water column moorings. Lake circulation.	Sustainable model for long-term observations. Technology to expand the scope of observations. Under ice/winter nutrient transformations and rates. * Under-ice oxygen consumption (respiration and nitrification).
UM SEAS/Earth		Impact of winter on nutrient cycling, sedimentation, algal community structure (spring and summer).	Phytoplankton Population composition and distribution. Under-ice nutrient concentrations, algal community, and sedimentation rates.	Improved coordination and data/resource sharing. Remote sensing, ice phenology observations, and modeling, lake physics and biology, and socioeconomic analysis.

Appendix E: Breakout 2 Group Discussion Summaries

Group 1

Infrastructure or Training Needs

- Improved spatial coverage and temporal resolution of water intake quality monitoring. *
- Centralized, cross-disciplinary databases, data integration, and data sharing*.
- Funding resources. **
- Characterization of changing source water quality.
- Centre of Excellence to train scientists, engineers and field operators on the latest technology and approaches to winter science as well as including TEK and ways of knowing. Can include placements across institutions/organizations.
- Skills- succession planning- the history and advancement of data collection and models.
- Tap into academic research/expertise on nearshore water quality.
- Better leverage social resources, including inter-agency collaborations, traditional knowledge integration to better characterize seasonal changes, utilization of lessons learned in marine science, and education and awareness. *
- Linking models with event-based water quality monitoring to improve predictive capabilities.
- Integration of Western science and Indigenous Knowledge Systems.
- Transfer of knowledge from academia research to municipal water treatment plant operators and managers/create a synthesis of information and knowledge.
- Modeling capability for ice biogeochemistry.
- Data sharing.
- Training of modelers for large lakes (coastal ocean + ice + biogeochemistry modelers).

Next Steps

- Improved coordination and leveraging to create opportunities between agencies, organizations and Indigenous groups to undertake the work.
- Communication plan to target decision makers, funders and the public to support enhanced resourcing for winter science work. ***
- Redefine/further examine the 'shoulder seasons' or timing. *
- Shoulder season observations, such as sensing tools (e.g., extended sensor deployments, cabled observation platforms) and transportation (e.g., vessel operations and safety policy for shoulder seasons, autonomous vehicles) include insurance/liability and on ice/safety training. Is there an opportunity for bulk training/insurance.
- Survey existing GL WQ data sources- set standards.
- Include community science opportunities. *
- Annual or bi-annual knowledge sharing (that all can afford to attend- low cost- virtual).
- Leverage existing technology and collaborations by collecting year-round samples and improving sample resolution.
- Better incorporation of source water protection/drinking water in the GLA and reports-metrics.
- Building ice biogeochemistry modeling capability for GL (e.g., under-ice/within ice algae).
- Applying grants for agencies (e.g., NOAA CPO, CEFI).
- Collaboration/coordination between modelers and observation lists to best inform the sampling strategy. *

Group 2

Infrastructure or Training Needs

- Resources for winter research, including icebreakers, AUVs, and standardized sampling protocols. *
- Training on winter science methods as well as an evolution of winter science training and safety. ***
- Taxonomy, species identification.
- Infrastructure - proper flow monitoring and gauging stations. Updated flood forecasting models. *
- Standardized sampling protocols. *
- Funding for database creation and management.
- Training for Database usage and the ability to merge historical data.
- More buoys/monitoring platforms that can stay out under ice. *
- Standardized and coordinated sampling protocols that can be used across agencies.
- Maximize moorings! Coordinate among agencies so that a single mooring platform can serve multiple projects/agencies.
- Winter safety training (including on ice safety).

Next Steps

- Funding.
- Data collection under standard protocols and housed in a common database.
- Identifying infrastructure and data need at targeted or many locations to address data/knowledge gaps to inform a science plant.
- e.g., many tributaries in US and Canada do not have flow monitoring.

Group 3

Infrastructure or Training Needs

- List of vessel/contractor resources currently available. There are ice hardened commercial fishing vessels and fishing guides using amphibious vessels.
- Resource, like a weather app to help staff make decisions on ice safety etc. Largely operating off of word of mouth at the moment.
- Hovercrafts.
- Focus on existing, proven technologies rather than waiting another decade for developing techs. *
- Better equipped vessels for conducting winter sampling.

Next Steps

- Fund work to make fish and lower food web collections under the ice.
- Invest in unmanned craft for collecting acoustic data.
- Integrating agency needs to inform ship designs and retrofits.

Notes

- Million-dollar question - how to fund it.
- Hovercrafts are more expensive to maintain than moorings- limited weather window, can't travel that long.
- Real-time data transmission - is this a cool thing to have or not worth the cost - are there real-time management questions in the winter that require real-time data? maybe only for forecasting - depends on the question you're asking.
- Complete data is more valuable than real time data - need to be realistic about needs vs wants vs abilities.

- Canadian water treatment plants - city of Toronto- are actively installing instrumentation to monitor intakes and track movement of blooms and spills - need research collaboration to identify fluorometer signals and understand their signals - data processing/analysis training needs - real time forecasting of current speed and direction - deterministic model - potential for using AI.
- Method development needed - RFUs for Chl-a - need a better understanding of how indicative these are.
- GLATOS network is underutilized in Lake Superior - need a network of receivers under the ice to learn about winter fish movements - can also add instrumentation too for environmental parameters.
- Leveraging ice-hardened fishing vessels - probably 30+ fishing vessels out in the winter in Lake Superior - a blind spot as we tend to only consider coast guard or shipping - potentially interesting finding mechanism as well! - more sustainable funding approach - add costs to contractor budget - cheaper to contract what's already out there - co benefits.
- Contracting winter research - how far out in the islands can we get - informed by the guiding community and their knowledge - how safely can you get a snow mobile out, ice fishing/sport fishing word of mouth and forums - how to mine these scattered data with tools like AI to improve ice forecasts is an infrastructure/training need.

Group 4

Infrastructure or Training Needs

- Instrumentation for in/under-ice phytos community composition (enumeration).
- Centralized, cross-disciplinary databases, data integration, and data sharing.
- Analyze fish migration patterns, spawning and hatch. Identify species vulnerability to hanging ice on/off timing, and temporal mismatch of food availability and fish hatch.
- Measure food web dynamics during shoulder seasons, including overall lake primary production, overwintering of fall planktonic communities, and impacts of warmer winters on spring phyto/zooplankton bloom composition.
- Leverage existing technology and collaborations by collecting year-round samples and improving sample resolution. *
- Increased under ice observations: Early Life History / Recruitment dynamics for cold water species.
- Ice-hardened ships for science missions.
- Mandated ship time for sampling year-round to collect continuous, connected seasonal data on cHAB/phyto phenology and corresponding WQ.
- Resources for winter research, including Science icebreakers, AUVs, and standardized sampling protocols. *
- Improved ports / harbors to support winter sampling.
- Data science, machine learning / deep learning training for young scientists (re: remote sensing, modeling, forecasting of ice and other variables.
- Continuity of synthetic aperture radar (SAR) satellite missions and datasets.
- Validation data for ice thickness.
- Data analytics and management resources.
- Direct satellite measurement of ice thickness (rather than freeboard).
- Training on winter science methods as well as an evolution of winter science training and safety.
- Training for personnel in sampling during shoulder and winter.
- Changes in timing of primary productivity and food web mismatches.
- Metabolic changes (primary productivity and net ecosystem production).
- Linking models with event-based water quality monitoring to improve predictive capabilities.
- Improved coordination and data/resource sharing.
- Coordination among agencies to share limited resources for completing winter work (vessel time on ice-hardened ships, training workshops, etc.).

- Improved involvement with Indigenous led projects.
- Impacts of climate change on winter recreation and subsistence fishing.
- Social and cultural impacts of changes in winter.
- Cost and benefits of lengthening the winter shipping seasons.
- Lake-specific research needs: Lake Superior coregonine community spawning biology, lack of sampling on Superior and Ontario after the locks close for the winter, and lack of research and information for Michigan and Huron.
- Improved spatial coverage and temporal resolution of water intake quality monitoring.
- Collect samples at intakes for more frequent monitoring of more water quality variables, nutrients phytoplankton, etc. Leverage this infrastructure.
- Continuous measurements of lake currents, temperature profiles, water quality, meteorology and climate measurements, and lower food web surveys and productivity.
- Year-round cabled monitoring stations and autonomous sensors.
- Access to emerging tech such as remote sensing to fill data gaps especially in winter season

Next Steps

- Funding for staffing and expanded monitoring to including winter.
- Need to draw clear connections between winter science priorities and GLWQA General Objectives, Lake Ecosystem Objectives, Substance Objectives --> justification for investment in additional monitoring that is needed inform actions and/or progress on objectives under changing conditions. * Needed to secure additional funding.
- Collaborative partnerships established to leverage funding and project management. (See later breakout on collaboration)
- Tools and sampling to understand physical-biological interactions related to recruitment of cold-water fishes; habitat specific information (priority management areas).
- Solicit proposals for funding planning of centers of excellence.
- Build science-capable icebreakers.
- Improve bandwidth for communications (ability to send more data to ships to support science work and operations, i.e., StarLink).
- "Test drive" AUV technology in summer for deployment under ice.
- Develop/use labs and conduct expts that simulate under ice conditions

Notes

- Leverage existing technology and collaborations.
- Continuous measurements.
- Next steps on connecting to GLWQA.
- Unclear how to access icebreakers for science.
- Lack of purpose-built winter science vessels.
- Discussion of strategies to increase resources.

Group 5

Infrastructure or Training Needs

- Coordinating student support (funding for student and advisor) with access to infrastructure.
- Testing and deployment of low-cost observing platforms/sensors.
- Shared vessel for year-round multiple coordinated deployments/retrievals.
- Standardized methods.

- Increase capacity to operate uncrewed systems especially under ice. *
- Winter capable vessel-- icebreaker or military grade hovercraft ($400K).
- Physical infrastructure for long-term monitoring (20-30 years) of exit water volume and quality at selected major tributaries throughout the Great Lakes basin

Next Steps

- Hope for a generational scale science funding program...
- Determine strategic locations for year-round, long-term deployments of cabled observatories.
- View of resource needs to move from three season to four season for field programs.

Notes

- Ice hardened vessel needed - CG vessels are more available when less ice on the water.
- Year-round, long-term monitoring of water quality/qty entering lakes.
- Lake access - not enough vessels and platform, limited research time.
- Remote platforms - how accurate are these sensors? Need improved methods.
- Need trained operators for uncrewed systems? Shortage of skilled personnel.
- OMECP - success in getting water samples from DW intakes. Collaboration. Limited number of parameters can be analyzed - need sensors, more sophisticated sampling methods. P samples - an example. Resource limitations? May be given an extra push with need for winter sampling. Don't have the staff.

Appendix F: Breakout 3 Group Discussion Summaries

Group 1

Coordination and Data Sharing

- Examine innovative approaches to data sharing and analysis e.g., AI.
- Resolve how data is stored to meet the needs of the user (e.g., summarized data vs raw data) as there will be implications on cost (data storage), efficiency (data processing speeds) and utility (e.g., data for models, trend analysis etc.).
- Ensure data availability for all researchers while respecting intellectual property.
- Determine an efficient mechanism for data sharing and transparency for both the scientific community and the public.
- Ensure the model can be accessed by various groups providing data (e.g., community science, Indigenous nations).
- Academia- field schools- Winter or courses- colleges train the technical staff- e.g., Fleming College, Algonquin College, etc.).
- A common schedule of vessels and assets available for science/monitoring.
- Ensure lab capacity exists to support the enhanced monitoring in the shoulder and winter seasons. *
- Create a process or framework to analyze and interpret the winter science data that is to be collected at minimum. Expand out areas where there are high variability or high impact to communities and biota/ecosystem.
- Shipping Industry (e.g., partnering with NOAA VOS program) https://www.vos.noaa.gov/.
- Determine a reporting schedule (fiscal or calendar year?) where data is summarized and disseminated to provide insights on winter dynamics as it compares to the ice-free season.
- As before, a communication plan to support coordination, engagement for researchers and opportunities for local participation.
- Ensure resources are available to maintain, operate and repair winter assets (e.g., sensors, vessels, platforms).
- Pilot a winter science database with existing data to determine how it can look and can be efficiently utilized before investing in a much larger database structure.
- Explore non-traditional sampling partners e.g., polar dip participants, ice fishers, surfers.
- Safety is an issue and should be addressed.

High Priority

- Engage all user groups/who will inputting/ using data.
- Data sharing needs its own workshop to support winter science.
- Ensure lab capacity exists to support winter science.
  * Note that post-its with a 'star' above were also prioritized.

What has worked in the past?

- Lean on SMART Great Lakes Initiative and lessons learned from other organizations (e.g., GLOS) and big data platforms.
- CSMI approach for winter science e.g., Winter Science Cooperative Monitoring Initiative. *
- High volume of data (e.g., winter weather) from ship obs, even lower quality. Helps physical modeling.
- Local, regional, provincial scale connections/links coordination.
- Strong set of data standard protocols.

- Adequate training.

What has not worked in the past?

- Non-linked databases. *
- Although the ability to participate in CSMI sampling as a non-government entity is irregular.
- Lack of info (sensor depth/height, time of a day, lat/lon, etc.), can be addressed by standardized protocol.
- Lack of communication amongst various organizations.
- One owner of database/model-funding dependent entity-impacts on updates/ maintenance, etc.
- Lack of a central database. The capacity of a single database to include multiple kinds of data (point, continuous, social science, Indigenous knowledge).

Notes

Group discussion at start of breakout included the following:

- Winter science data sharing challenges are a lot like data sharing challenges generally.
- Broader issues of data sharing apply.
- Funding issue applies to data mgmt. and communication too.
- Non-linked databases are a problem!
- CSMI may provide a good model for coordination.
- For data sharing, GLOS SMART GL may provide a model.
- NSF BCO-DMO database website – helps ensure datasets are discoverable and accessible.
- At the very least centralize metadata.
- Realistically an ensemble of approaches may be needed e.g., lots of agencies have their own repositories.
- Point source data ‘easier’ to handle than expeditionary data.
- Costs influenced by degree of data processing that is needed.
- One stop shop for data repository especially needed by some entities; agencies have their own repositories.
- Automatic upload of data? Some approaches exist.
- Winter science data are limited so we may be in a good spot to develop centralized data repositories etc.
- Need to think about who the user groups are, and engage with them, to inform the architecture of our system!!!

Group 2

Coordination and Data Sharing

- ROAD BLOCK: data sovereignty.
- Identify existing overwintering moorings and coordinate among partners to add sensors/experiments.
- Connect with ice fishing communities to know specific ice conditions and potentially get citizen-collected data?
- Collaborate with ice fishing guides that have equipment to access lake during poor ice conditions.
- Purchase research vessel from sherp-amphibio and/or airboat.
- Future collaborations: MPRI (NRCan) Oil Spill in the GL Research Network.
- DNR Winter creel surveys.
- Wisconsin DNR has winter creel survey at ports around the Apostle Island.
- Michigan DNR has a creel in lower Keweenaw Bay and through November at two ports on east side of Keweenaw (maybe other locations too).

High Priority

- Data collection in hydrodams (St Marys River; Upper St. Lawrence): relationships with dam operators.
- Municipal Water Intakes.
- IJC could form a team that includes Coast Guard, Army Corps, and managers and researchers from other agencies/organizations.
- Collaborate with GLFC agencies through CLC/CLFMA.
  * Note that post-its with a 'star' above were also prioritized.

What has worked in the past?

- Cruise of opportunity with Can Coast Guard.
- Work with commercial fisherman.
- Contracting with commercial fishers on a short term and off-fishing season basis.
- Training for science with US Coast Guard (McKay model).
- NYSG funding.

What has not worked in the past?

- NSF funding.
- Relying on contracting commercial fishers for entire projects lasting more than a few weeks or overlap with open fishing seasons.
- Not having multiple transport options lined up to respond to changing conditions. Snowmobile vs. air boat.

Group 3

Coordination and Data Sharing

- CSMI
- Data/File Sharing tools: have to overcome agency firewalls.
- Increase knowledge and linkages between existing open date catalogues expand open data catalogues.
- Better utilize GLASS to make ship resources more accessible.

High Priority

- Coordination between winter limno workgroup and federal workplans / vessels.
- Not having dedicated vessel for winter/ice work.
- Funding with focus on binational collaborations.
  * Note that post-its with a 'star' above were also prioritized.

Medium Priority

- Increase knowledge and linkages between existing open date catalogues expand open data catalogues.

What has worked in the past?

- Opportunistic sampling from ice breakers.
- CSMI.
- WinterGrab.

What has not worked in the past?

- Winter modeling should be expanded in watershed as well.
- Not having dedicated vessel for winter/ice work.

- Most instruments are designed to function in warm waters; and reliability needs to be tested for winter.

How can IJC Help?

- Funding with focus on binational collaborations. *
- Funding to encourage collaboration with First Nations.
- Coordination between winter limno workgroup and federal workplans / vessels.
- Conversations between IJC and GLFC at technical level committees.

Notes

- Identified Opportunities to increase collaboration.
    - GLASS – GL Association of Science ships – model that could be utilized to identify/ catalog ships of opportunity and their capabilities.
    - CSMI – although traditionally has been summer-heavy in scope,
        - Provides fisheries and lower food web folks with a platform for conversations.
        - CSMI-like approach to winter science could be effective to extend these sampling and collaborations to identified winter science priorities.
- Opportunities to increase resource sharing – grappling with ways to share larger datafiles.
    - Tools to work around agency firewalls to improve data and file sharing.
        - Different agencies all have different requirements for file sharing.
        - Often have to go outside DOI to collaborate to work around firewalls.
        - Need a better/safer system than email attachments.
    - Expanding open data catalogues and linkages between existing open data sources.
- Things that worked well in the past:
    - CSMI –
    - Opportunistic sampling from ice breakers
    - Winter Grab
        - Was a very successful grass roots effort.
        - Low funding but needs a champion to organize and students to manage materials coming into labs.
- How IJC can help
    - Bi-national funding mechanisms to support binational collaborations – high priority.
    - Funding to encourage First Nation collaborations.
    - Facilitating coordination between the winter limnology work group, federal work plans, and vessel availability.
        - Identified as a high priority item.
        - As we've discussed, a lack of access to vessels has historically been a pinch point in winter science but there seems to be opportunities to work around this that just need someone to champion the coordination with groups like GLASS and fishing communities.
    - Conversations between IJC and GL Fisheries Commission within technical level committees**.**
- GL Fish Commission - more conversations on knowledge gaps in winter - technical committee draft research priorities.

Group 4

Coordination and Data Sharing

- Leverage/engage central agencies to lead process, e.g., newly formed Canada Water Agency.

- Planning for data management on collaborative cross-agency projects - who manages those data, what repositories do they go to, who's ultimately responsible for management long-term, etc.?
- Citizen collections, e.g., on-ice rec., nearshore residents. Advantage - higher temporal res.
- Find out utility of winter data to highest level of DoE (energy) and DoC (Commerce, not just NOAA).
- Roadblock: everyone is busy running existing programs and may not have capacity (staff, time, and or funding) for development and support of winter projects --> need for winter work to be formalized as part of mission-critical work and/or dedicated staff with expertise to engage in projects.
- Hire personnel as liaison across agencies to seek and find available winter data (bases).
- Do other agencies/ countries have experience with winter science that can be utilized.
- Leveraging ocean science/tech.
- Coordination with Coast Guards; focus on areas where ice-breaking operations are occurring (central, western Lake Erie, Straits, E/W L Superior).
- Involvement of organizations such as Smart Great Lakes.
- Coordinate with agencies with limited ability to get vessels out in winter (U Wisconsin - Milwaukee, GLERL).
- When is winter w/r to CSMI?
- CSMI is many different groups with different data sharing needs.
- Winter science center of excellence, with a data management role as well.

High Priority

- Use of GLOS and similar organizations for Data Management.
- Partnering with international (European) lake groups.
- Resources: absence of ice-hardened research vessels.
- Coordinate on successful winter data collection efforts on moored, cabled, and/or autonomous systems.
- Ad-hoc groups to target specific winter science questions (e.g., WinterGrab)
- Citizen collections, e.g., on-ice rec., nearshore residents. Advantage - higher temporal res.
  * Note that post-its with a 'star' above were also prioritized.

Medium Priority

- Intra-agency collab/coordination when winter vessels available (ECCC-DFO, Lake Erie mostly pre-2017 data).
- Sharing instrumentation and data between agencies.
- Developing consistent methods for collaborative sampling (e.g., CSMI).
- Volunteer-based, inter-institutional collaboration and coordination centered around a specific system/objective (Winter Grab, UM lead).
- Federal agencies (e.g., NOAA-GLERL) serving as repositories for critical long-term foundational data (e.g., coast watch and ice cover); probably need more of this.
- WinterGrab.
- Episodic Events Great Lakes Experiment (EEGLE) succeeded in obtaining winter data due to a couple of mild winters (EPA, NOAA, Universities on Lake Michigan).

Low Priority

- Expecting all partners to be able to acquire funding.
- Competition among research groups and agencies.
- Scheduling and funding cycles, which are often lined up better for the traditional field season (example: CSMI planning timelines tough to plan for winter before field year).
- Overly specific budgets that restrict spending into narrow categories.

What has worked in the past?

- Volunteer-based, inter-institutional collaboration and coordination centered around a specific system/objective (Winter Grab, UM lead).
- Developing consistent methods for collaborative sampling (e.g., CSMI).
- Small grant to support data management from CSMI.
- Coordination across agencies/groups or sample collection, send to other groups for processing/analysis - for example, collection of water samples for phyto analysis from water intakes and by groups out on the lakes for extended field season.
- Data management systems making data available in real-time or as close as possible; QA/QCed, public access.
- Data archiving systems for long-term data storage; NCEI, QA/QCed, public access.
- Coordination with US Coast Guard; focus on areas where ice-breaking operations are occurring (i.e., such Mike McKay on central, western Lake Erie).
- Geographically limited research vessels working in winter (U Wisconsin - Milwaukee, GLERL).
- Requesting infrastructure access through agency channels (e.g., icebreakers).
- Collaborations that include gov't agencies and academia.
- EEGLE.

What has not worked in the past?

- Single PI lead projects with no commitment for data management.
- Lack of involvement from leading oceanographers and scientists from outside the GL community (a new perspective).
- Broad-scale announcements in media and top journals.
- Poor attempts to involve Indigenous organizations into science projects.
- "Insiders" only collaboration.
- Insufficient accountability.
- Overly specific budgets that restrict spending into narrow categories.
- PI silo effect; data on spreadsheets and hard drives with bad file names.

Breakout 3 Facilitator Notes:

- Discussed Winter Grab data management approaches and challenges of constructing a system after the field activities are completed; publication of a data paper is underway, with an eventual DOI.
- Some agencies do a great job and others do not.
- Need a champion for all of this.
- Some history of funding work in Canada with GLRI.
- NOAA exploring doing oil spill research for Canada.
- Canada Water Agency example.
- Transboundary NSF-NSERC match.
- CSMI coordination is decentralized; GLRI provides some funding; winter science would be tricky to integrate.
- Need big projects/orgs to anchor smaller efforts.

Group 5

Coordination and Data Sharing

- Periodic workshops of collectives of shoreline residents groups and coastal focused NGO associations to gather observations on lake conditions during winter and shoulder seasons as more people line year

round on the shores of the Great Lakes. Unfiltered broad observations to be used as early warning and insight from diverse angles of perspective.
- Directory of equipment used/available so others can discuss pros/cons before they start their own projects.
- Collaboration board/email directory to allow others to know when you are conducting winter sampling (e.g., it might be possible to collect samples for someone else).
- Engage merchant marine in sampling/autonomous sensors on board (ferry boxes). Very successful in marine science.

High Priority

- Hyperspectral imaging from small aircraft. Used for summer imaging in Great Lakes both in US (GLERL) and Canada (HNRSI).
- Spend resources on mining old data and make it accessible.
- Roadblock: general) lack of coordinated funding opportunities for US and Canada to work on topics of mutual interest.
- Past poor data management.
- Follow example of partnering with recreational charter boat captains in summer (Lake Erie - Justin Chaffin at OSU Stone Lab) and extend to winter sampling (ice-fishing community).
- Expand the capacity of sample and information collection at water plants based on better communication and agreement on shared issues and benefits of collaboration. Explicit Identification of areas where the extra efforts and information collection meets mutual needs.
- Directory of data available & contacts (not a central data repository/database).
- Designate an agency that will "own" contact information or data repositories, that will keep the information up to date (i.e., center of excellence as mentioned in breakout #2).
  * Note that post-its with a ‘star’ above were also prioritized.

Medium Priority

- Engage merchant marine in sampling/autonomous sensors on board (ferry boxes). Very successful in marine science.
- Roadblock: agencies with strong centralized organization. In many cases, would be much easier to coordinate activities directly with 'boots on the ground' (e.g., Canadian vs US Coast Guard).

Low Priority

- Each year, we typically see one of the ocean-going Canadian icebreakers enter the Great Lakes later in the season - could be excellent opportunity to leverage science but we only find out about these ships being tasked here is once they are here.

What has worked in the past?

- Used small aircraft for summer HS imaging in Great Lakes both in US (GLERL) and Canada (HNRSI).

What has not worked in the past?

- Scheduling - my experience with winter science is you can schedule very little and are at the whim of ship operations/tasking to other duties and/or the weather.

Notes

- List of data/ongoing research/plans/platforms:
  - Need to know who's working on what, not necessarily have access to the actual data.

  - Not having a designate owner means these efforts often run out of steam.
  - List/directory to share experience with using winter sampling equipment.
  - Need someone to own this list/directory. Center of Excellence?

- Utilize citizens to report data on lake conditions - especially with unknowns driven by climate change.
- Resource allocation to studies over 4 seasons, instead of 3?
- Data management - improved procedures/plans, required by funding (e.g., NSF). Need to spend resources on capture old/legacy datasets and make them accessible.

Appendix G: Breakout 4 Group Discussion Summaries

Group 1

N/A – group 1 participants were moved into groups 3, 4, and 5 due to reduced attendance.

Group 2

N/A – group 2 participants were moved into groups 3, 4, and 5 due to reduced attendance.

Group 3

How can agencies integrate other disciplines?

- Funding and resources specifically.
- Create equity between collaborators.
- Program time/funding into the duties/activities; will take work to navigate agency objectives/mission/goals, and communication between leaders mgmt.
- Early engagement with collaborators.
- With who specifically?
- Increase in communication and collaborations.
- Pilot project.
- Resource sharing.

How can agencies improve communication of research findings?

- Subsidize open access costs for pubs.
- Need more winter science in the news and media - people can only care about issues they are aware of, and support for leveraging public funding for winter research needs public support.
- Avoid a 'one size' fits all report/ dissemination.
- Involve in research process at different stages.
- Great Lakes winter group meets every first Friday of the month. Currently chaired by Ted Ozersky but expected to be co-chaired going forward, currently 80+ invitees but open to the public.
- Removing barriers to attendance of conferences/workshops/etc...(travel grants, hybrid options, etc.).
- GLATOS is a good model. Works for scientific community and public.
- Emphasize how researching can be applied to management problem solving.
- Different communication products for sharing (e.g. decision making vs public).
- Multiple communication opportunities formal and informal.
- Marketing?
- Communal support for winter-oriented conferences.
- Currently no publicly available, winter-specific conferences or workshops - could leverage existing angling organizations.
- Happy hour and/or science cafes.

Notes

- Need program time/funding into the duties/activities; will take work to navigate agency objectives/mission/goals, and communication between leaders mgmt.
- Public communication.
- Need more winter science in the media.

- To do this, need a marketing strategy.
- Need to package information differently depending on the audience.
- Science communication is a full-time job.
- Also need publicly available platforms and opportunities to have winter science discussions with the public.
- Conferences/ workshops – can build off existing angling organization meetings.
- Less formal – happy hours and science cafes.
- Help to build relationships and collaborations with some of the organizations whose knowledge we would like to bring in.
- Also need to lower the barriers to entry.
- Subsidizing attendance or registration costs for workshops or conferences.
- Subsidizing open access journals.

Group 4

How can agencies integrate other disciplines?

- Leverage work done by other ogs such as Smart Great Lakes.
- Actively engage interdisciplinary staff in your both internal and collaborative winter science initiatives, from the planning phase (for example, EPA ORD has multiple social scientists working in GL now). *
- Identify funding sources in your own discipline or somebody else's and prepare a joint proposal.
- Funding! ****
- Thru grants to university and industry partners.
- Support (financially) Indigenous organizations to self-direct input (see Indigenous Smart Great Lakes)).
- Require multi-disciplinary proposals for whatever funding is available (e.g., USGS CASC proposals require clear management relevance which automatically inspires multi-disciplinary approaches).
- Get user needs for ice info from ice boaters, fishers, intake managers, CG, etc). **
- A "business reactor"/hackathon etc, but for winter science. **
- Actively support CSMI-winter activity.
- Paid internships for high school and higher ed to foster training.
- Engage the other disciplines by formulating actionable winter science questions to support collaboration and partnerships.
- Workshops and panel discussions with diversity of participants.
- Host a "Great Lakes Winter Science Forum" - USGS held a "Mississippi River Science Forum" and hosted stakeholders from across the basin to give talks on science gaps and needs for the basin - could do something similar for winter science? ****
- Network with and bring in new collaborators on projects (e.g., attend new conferences).
- Highlight winter science needs at conferences outside the typical rotation of Great Lakes and aquatic limnology meetings and network to engage new collaborators.
- Support and encourage collaborative publications that cover a range of disciplines.
- Get other winter-time users on board (fishers, winter sports etc).

How can agencies improve communication of research findings?

- Connect with citizen science activities.
- Figure out community groups with interest in winter science and connect with them (e.g., table at an ice fishing expo, local talks, etc). **
- Hire professional communicators, PR firms.
- Develop a communications strategy incorporating a clear message about Winter Science. **

- Celebrity endorsement. **
- A good way to demonstrate integration of the various disciples/fields to create multiple communication products for the audience(s). Publications (journals etc.) for the academic community, open data for modelers and statisticians, incorporation into Indigenous ceremonies (water ceremonies), infographics and other public friendly documents for broad engagement. Also, social media products to engage the youth. ***
- Build relationships with reporters and social media influencers.
- Create user-friendly interface for the public to 'play' with the data (e.g., different timescales, different regions/locales).
- Have a winter ecology web site, similar to what GLANSIS does for invasive species in the Great Lakes.
- Capitalize on (synchronize with) trending topics (timing).
- Get a mascot.
- Sponsor an over-ice sled dog or snowmobile race.
- Science-based documentaries with celebrity voice overs??
- Connect with winter-related recreation.
- Connect with partners specialized in science communication (such as SeaGrant). *
- Teacher trainings for K-12 teachers and/or college profs / educators (like exist for summer programs).
- Join the GLWiN / Ozersky research group. *
- Involve students interested in a good at social media.
- **Note that Winter Grab got lots of media attention.**
- Host journalists for winter science expedition. **
- Fund a winter science journalism fellowship. *
- IAGLR and AGU Ocean Sciences winter research sessions. *
- NOAA GLERL CoastWatch and modeling/ forecasting group ice classification and ice cover. *
- Report cards? These are easy to understand and give us a snapshot of what winter conditions are like for a particular year.
- Start social media accounts and/or get Lake Superior to tweet for you :)
- Allow for different granularity of reporting. Social media posts can engage and answer the 'so what question' while detailed reports allow for critical review of the findings.
- We need a strong "why" or common mission statement to justifies the effort and expenditure that is necessary to support winter science. This may mean better articulation of the implications.

Group 5

How can agencies integrate other disciplines?

- Agencies need to hire discipline specific personnel. (i.e., do not expect a fisheries biologist to work as an economist). **
- In Canada, having some dedicated funding initiatives run through SSHRC will reinforce importance of true multidisciplinary collaboration. I'm seeing a lot of biomedical initiatives coming through SSHRC.
- I think agencies are starting to broaden their scope and now hiring social scientists (economists, etc.), so this will help.
- TEK is a separate knowledge system from Western thinking, so integration is like fitting a round peg in a square hole.
- Need to visit communities and hear their stories about (TEK) the natural world these can inform science. ***

- Support participation in bi-national and federal forums under the GLWQA agreement that bring together diverse groups of practioners that have broad public and scientific reporting scope; use this vehicle to bring in cross cutting aspects of winter-related questions. *

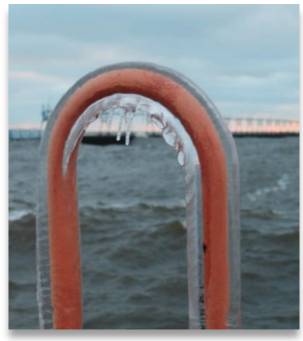
How can agencies improve communication of research findings?

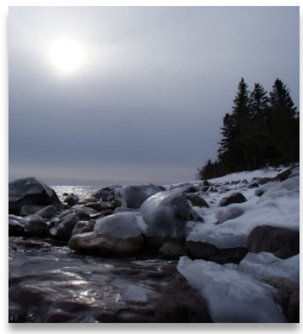
- Create informal working groups (agency-academic-municipal-First Nations) on specific winter-related issues-question topics and have the deliberations produce a white paper designed for communication of the issue, with clear identification of risks and outcomes, to relevant agencies. *
- Something to think about: who is your target audience and does the way you communicate research change. **
- Video (shorter is better).
- Go to small group meetings e.g., sailing clubs (don't always expect people to come to us/our meetings). **
- Virtual meetings. *
- Using art. **
- Listening circles.
- Promote and take ownership role in production of material for coastal-focused NGO groups that have a public outreach and environmental information function. EG. Georgian Bay Biosphere Reserve.
- Advertising, billboards, take a cue from US college football games where they run ads showcasing research at the respective universities to a very large audience. Military does similar showcasing career possibilities - there are some really effective pieces down by joint Coast Guards - these could be run as tv/streaming commercials.

Breakout 4 Facilitator Notes:

- Mandate town halls? Required for IJC, certain other initiatives. Who attends?
- Using art to communicate changes to winter.
- RFP - do they allow communication of winter science to broader audience?
- Listening circles?
- Resources.
- Nutrient loading in Lake Ontario - 45 scientists over two years, produced an in-depth report. Do something similar with winter science - public seminars. Findings of this committee.
- GLWQA drives a lot of agency work.
- Use winter ice to showcase an ice hockey game?
- 30-second ads on winter research?
- Data on backyard rinks.
- Ngan - what does winter mean for Indigenous communities? Use that to depict what changing winter means.
- Changing winter means a loss of something?
- Maggie: Need to get the message out. Use and recapture old data.

Appendix E: Workshop #3 Report





Great Lakes Winter Science Workshop #3
Windsor, Ontario
January 31 - February 1, 2024

Draft Report

April 10th, 2024

Prepared for:

International Joint Commission

Science Advisory Board

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1 Background and Project Summary to Date

Project Objectives

The International Joint Commission (IJC) is conducting a project seeking to document the state of winter science in the Great Lakes and to develop recommendations to address research priorities that will help understand the impacts of climate change on winter and on the chemical, physical, and biological integrity of the waters of the Great Lakes. Climate change has been identified as one of the most important problems facing humanity today. The 2021 Intergovernmental Panel on Climate Change report emphasized the importance of limiting global temperature increases below 1.5 degrees Celsius (°C) within the next decade to reduce catastrophic impacts on ecosystems and human health (reference). Impacts to lakes resulting from climate change have already been well documented, including increases in water temperature, loss of ice cover, alterations in distribution of freshwater fishes, and decreases in deep-water oxygen concentrations. The largest lakes in the world are most vulnerable to losing ice cover and are warming at the fastest rates, in some cases as much as 1°C per decade.

The IJC Science Advisory Board (SAB) recognizes that winter is an overlooked season across the Great Lakes-St. Lawrence River system, even though it is the season that is altered the most due to climate change across the basin. This is partly due to the challenge of winter observations and the requirements for specialized equipment, highly qualified personnel, and coordinated approaches. As a result, management decisions are often based on data and models derived from ice-free observations. The topic of winter science in the Great Lakes-St. Lawrence River system involves many Annexes of the Great Lakes Water Quality Agreement (GLWQA), but winter is not currently explicitly incorporated into any of the Annexes, although there is some mention in documents related to operationalizing Lakewide Management (Annex 2) and Science (Annex 10) activities. The SAB has undertaken this project to better inform the IJC about the gaps that exist in our understanding of winter in the Great Lakes and the impacts of climate change; to document research priorities and proposed solutions to improve winter science; and to provide recommendations on meeting these winter science needs and priorities.

Project Activities

Activities conducted to date under the project include:

- A literature review (completed March 2023) to uncover new knowledge published since the completion of other recent literature reviews and workshops, and identify persistent knowledge gaps pertaining to winter science as it impacts the Laurentian Great Lakes,
- A survey of publicly available databases containing information relevant to winter and winter science in the Great Lakes (completed March 2023), and
- Interviews with stakeholders and rights holders, including agency personnel, academic researchers, and members of shipping and other industries in the Great Lakes (completed April 2023).

The project also includes three workshops to identify winter science gaps, needs, and science priorities; identify, describe, and assess research needs related to infrastructure, training, inter-agency coordination, and meeting science priorities; and winter science priorities with existing and future capacities and to develop recommendations for sustainably meeting winter science needs.

Workshop 1 Summary

Workshop 1, focused on winter science gaps, needs, and science priorities, was held virtually over two half-days on May 1st and 2nd, 2023. In addition to IJC staff and the support contractor team, 21 experts participated in the workshop. The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group had the opportunity to speak and present their points of view. Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations.

The findings of the first workshop were described in a separate workshop report. High-level observations and recommendations from workshop general discussions and breakout sessions are included in the list below:

- Any advancement in Great Lakes winter science is likely to have a high impact on the field, as few low-impact gaps or needs were identified by workshop participants.
- Lake access in winter is a key barrier to filling research gaps, as evidenced by the fact that this theme appeared in some form in almost every discussion topic. Lake access is further restricted by an overall lack of resources for winter science including funding, training, staff, ships, sensors, and data platforms.
- Interdisciplinary efforts are essential to understand complex research questions, including crossing disciplinary data collection and analysis and integrating social science, economics, and traditional knowledge.
- Opportunities exist to improve coordination and collaboration, including leveraging and formalizing existing collaborations to improve winter sampling and developing central platforms for winter science. Examples include:
    - Equipping Coast Guard vessels for sample collection and secure storage, and
    - Better utilization and expansion of shore-based water intake monitoring for year-round data collection.

Workshop 2 Summary

Workshop 2, focused on identifying management agency needs, coordination and recommended actions related to winter science, was held virtually over two half days on September 5th and 6th, 2023. The workshop included over 40 participants, in addition to IJC staff and contractor support. The project team (consisting of IJC and contractor staff) conducted the workshop using small breakout sessions on each day, with a pre-assigned facilitator/rapporteur responsible for moderating the discussion and taking detailed notes. The technique ensured that all members of each breakout group had the opportunity to speak and present their points of view. Augmenting the breakout groups were plenary remarks and whole-group discussions to review and harmonize breakout group findings and recommendations.

The findings of the second workshop were described in a separate workshop report. High-level observations and recommendations from workshop general discussions and breakout sessions are included in the list below:

- Funding for conducting winter science, including funding for expanded monitoring, data sharing, and interdisciplinary collaboration is a critical need.

- Need for winter science resources includes, but is not limited to, ice-hardened vessels, ice-capable autonomous underwater vehicles (AUVs), hovercrafts, mooring, and ice-capable buoys.
- Centralized, cross-disciplinary databases, data integration, and data sharing pipelines are needed to support advancements in the field. Some participants suggested that data sharing may need to be a topic for a separate workshop.
- Better leveraging of available resources is needed including inter-agency collaborations, incorporating traditional knowledge to better characterize seasonal changes, and utilization of lessons learned in marine science.
- Increasing education and awareness among the public is needed regarding the importance of winter science and the consequences if key knowledge gaps are not filled. A focused and consistent message needs to be developed on this topic.

2 Workshop 3 Presentation and Discussion Summary

The objective of Workshop 3 was to develop recommendations to address winter science needs that integrate science priorities with existing and future capacities. The target workshop outcome was to have developed specific, measurable, achievable, relevant, and time-bound (SMART) recommendations for meeting the winter science needs identified through the previous two workshops. The workshop was held in-person over one full day on January 31st and the morning of February 1st, 2024. The workshop agenda is provided in Appendix A. The workshop included 25 participants, including IJC staff and contractor support. A list of participants is included in Appendix B.

Overarching Workshop Themes

The following themes emerged as overarching concerns expressed by participants. They were brought up multiple times during the workshop in various contexts.

- Monitoring is a priority.
- Multiple science needs can be supported by standardized monitoring programs and data management.
- Diverse user community would benefit from enhanced data management.
- Making data usable and findable, possibly using AI to improve data querying and procurement.
- Winter/ice phenology and forecasting.
- Develop/deploy basic monitoring platforms and infrastructure (e.g., buoys, moorings, etc.) with capacity to modularly add sensors or instrumentation from multiple institutions or organizations.
- Better leverage existing monitoring programs (e.g., CSMI).
- Enhance watershed and tributary observations (e.g., flux of solutes and discharge) along with in-lake monitoring.

Day 1

Introductory Session

Day 1 of Workshop 3 began with welcome and introductory comments by the hosts, organizers, and facilitators. The workshop team, composed of contractors, IJC staff, and the IJC SAB Co-chairs, outlined the objectives for Workshop 3 and described activities completed to date under this project.

Breakout Session 1: Work Plan Topic Selection

Following an overview of introductory material, the workshop participants were divided into four groups to develop binational, interdisciplinary, conceptual winter science project work plans. Breakout groups consisted of 4-5 participants and either an IJC staff or contractor team member that acted as a note-taker. Each group appointed a group leader to synthesize discussion and a rapporteur to summarize discussions and report out to the larger group at the end of breakout sessions. Group members selected project idea(s) to advance and began to complete the work plan template, with special consideration of the resources needed to implement such a work plan.

Breakout Session 2: Teams Work on Completing Work Plan Template

Breakout session 2 focused on completing the first several sections of the work plan template, working in any order that the individual team preferred. Appendix C includes the work plan template that was used by each team.

Breakout Session 3: Synthesize Work Plan Highlights and Prepare Report Out

Breakout session 3 focused on completing the latter half of the work plan template and preparing to report out to the whole group. Each group's workplan is summarized below. Appendix D includes the full workplan templates completed by each breakout group.

Group 1

The work plan developed by Group 1 focused on creating a year-round, whole-basin, Great Lakes monitoring network to improve observations at established monitoring sites (such as the CSMI sites) using real-time, sub-surface moorings and seasonal buoys. This network would establish a skeleton monitoring system, whereby the basic infrastructure needed to install monitoring equipment would be put in place at each of these sites to reduce the capital cost of enabling research groups to participate in Great Lakes monitoring. A "pay-to-play" system, coordinated and managed by NOAA-GLERL, would then be put in place whereby organizations can pay a fee to add their complementary monitoring equipment to the monitoring station's buoy or mooring. This work plan suggested using artificial intelligence to filter and clean data from across the 19 different existing Great Lakes data repositories to create a single, unified data system that would be housed at GLOS. This work plan would require $100M of funding for 10 years to support at least 100 buoys and would leverage the use of existing ships (ECCC, NOAA, EPA, USGS) to support installation and maintenance.

Group 2

Group 2's work plan focused on improving short-range and long-range forecasts of changing winter lake conditions, specifically focusing on ice quality forecasts and ecosystem services, to better inform ecosystem management. Ideally, the successful implementation of this plan would result in the development of land-lake management strategies that relate global environmental change and its effect on winter climatology and linked ecosystem processes, such as linkages between low ice cover and early spring diatom blooms. The objectives of this work plan include developing 3-day, 7-day, and long-range ice predictions. Challenges facing this plan include the fact that the linkages between winter forcings and ecosystem services are poorly understood and that model refinement is limited because the data regarding winter conditions are incomplete or insufficient.

Group 3

Group 3's work plan focused on incorporating all disciplines and all the Great Lakes into a study taking place over the course of a decade that captures the temporal variability among winters. By establishing observation platforms and cruise rotations, the study would fill in fundamental data gaps in the Great Lakes and set a foundation for long-term understanding of winter conditions and dynamics. This proposed Great Lakes Winter Science Decade would focus on three primary research thrusts: (1) establishing three master research stations per lake, focusing on offshore sites, to monitor temperature, currents, ice, nutrients, and sediments at a minimum; (2) rotating winter cruises to assess primary production and microbial community composition; and (3) a permanent, nearshore winter grab structure that emphasized university involvement and training to support capacity development within the winter science field. The benefits of this project would include having the research infrastructure and capacity to enable winter observations, the ability to support other binational agencies with data and information needs, and sustained workforce development. Challenges facing this plan include current agency budgets and capacities, a lack of awareness of the importance of winter science, and a lack of complementary social sciences expertise.

Group 4

Group 4's work plan focused on establishing a robust, Great Lakes Basin-wide coordinated network for integrated tributary, nearshore, and offshore monitoring of the Great Lakes to generate reliable, year-round observations and better understand the influence of winter tributary fluxes on the larger Great Lakes biological-physical-chemical dynamics. Specific research questions include understanding the temporal fate, transport, and influences of winter nutrient pulses, as well as improving under-ice phytoplankton and zooplankton sampling. Great Lake monitoring programs exist but are weak on winter and at scales that are not currently informative of winter dynamics, models, and projections. Challenges facing this plan include data provision, oversight and management of a program as large as this one, funding, staff capacity, technology availability, and safety, particularly regarding fieldwork on unstable ice.

Whole Group Report-Outs

Day 1 concluded with a session in which each breakout team presented their proposed work plan's topic and features to the entire workshop. Each work plan "pitch" was followed by a full group discussion of ideas, questions, or general feedback on the proposed work plan.

Day 2

Opening Discussion

Day 2 of the workshop began with a recap of Day 1 activities and a brief review of workshop objectives and the plan for Day 2. The opening session was followed by a breakout group discussion.

Breakout Session 4: Recommendation Development and World Café

Breakout Session 4 began with an hour devoted to each group developing 3-5 winter science recommendations based on the work plans developed during Day 1. Additionally, there was time at the end of the session for a modified "World Café" recommendation review whereby each group rotated to another group's station to discuss and critique that group's recommendations.

Recommendation Report-Outs

Following the World Café session, each group reported their final recommendations to the whole group. After all of the groups presented their recommendations, copies of the recommendations were posted on flipcharts around the room, and workshop participants were given an opportunity to vote on the recommendations. Each participant was given three votes (or dots) that they could assign to one or more recommendations per their preference. The final recommendations, and the votes they received, are summarized below.

Recommendation	Votes
Group 1	
Direct Encourage GLWQA Annex 10 to perform a binational systems analysis to articulate the specific winter data gaps that can be met by monitoring that are limiting policy development and lake management decision making (Annex 2, etc.) - 18 months.	10
Perform an iterative, engineering (enterprise architecture like GLOS) design study to specify year-round monitoring program enhancement components, costs, and operational parameters - 18 months.	5
Develop the business case and operations models (Federal government or private funding, subscriptions to data and modeling outputs?) product suites, dashboard mockups, communication products, and value-added business mapping (like weather industry).	0

Recommendation	Votes
Group 2	

Prioritize improvement of ice models with extensive data validation. Furthermore, short- and long-term forecasting of ice conditions is essential.
• Who?
  - IJC Science Advisory Board
  - Partnerships needed (academics leveraging government agency and vice versa)
• What?
  - Open access, standard model
• We recommend a binational, competitive, and open funding program (5 years) that addresses these priorities on winter science in the Great Lakes.
  - Ice modelling and forecasts.
  - Winter data collection and database development.
  - Watershed linkages.
• NSF-NSERC collaboration program?
• Link with other groups' priorities related to infrastructure/capacity building.
	14

Prioritize collaborative winter data collection with consistent methods submitted to an open-access database based on FAIR (findable, accessible, inter-operable, reproducible) principles. • Contributing Contribute to existing databases (GLOS).	1
Incorporate terrestrial aquatic and watershed linkages to further understand the role of winter on basin-wide ecosystem services.	3
Group 3	
Develop specific funding mechanisms to support the construction, development, and maintenance of winter-first observing platforms over a decade time scale. • Add analysis and evaluation of "value added" of winter science observations. • Target federal governments. • Good to see maintenance included. • Perhaps like GLRI Action Plans or NASA Decadal Survey.	3
The federal government should expand the CSMI to include all seasons starting no later than the date is determined by prioritization in the CSMI cycle, where the sampling year is the calendar year. • Expand to annual cruises? • Fill in gaps between CSMI years	9
Create a bi-national mechanism that dedicates ice-breaking and ice-hardened vessels to science activities on one lake per year in conjunction with CSMI. • One vessel "can't do it all." • Consider sequencing. Need Recommendation #3 fulfilled to accomplish Recommendation #2. • Ice breakers are expensive! Can get more vessel time for your dollar for ice-hardened.	6
Incorporate additional science metrics into the SOGL (State of the Great Lakes) reporting, (e.g. chlorophyll-a and other pigments. • Unclear whether new and self-standing indicators are recommended vs incorporation of winter science into existing industry reports.	2

Recommendation	Votes
• Consider ice thickness, subsurface temps, light penetration.	
Stimulate educational opportunities for teaching the next generation of winter science (where this encompasses STEAM fields) needed for the government and academic workforce. • What level is being targeted? Primary school partnerships? E.g. Sea Grant etc.	3
Group 4	
Include year-round event-based monitoring of water chemistry for major (select) rivers guided by proximity to nearshore areas and lake sub-basins where winter-linked studies of lake limnology are designed to capture climate-related modifiers of watershed connections to lake.	0
A scalable high frequency and grab sampling of physical and biological parameter project that focuses on watersheds, nearshore, and offshore that builds upon current monitoring and enhances to include winter conditions (This program will improve Great Lakes modeling predictions within 5 years).	1
Acquire better understanding of the fate and transport of winter input from wet-weather run-off into the coastal zone. How different are winter mixing conditions in the coastal zone (when the thermal bar is present; just one example of coastal effect) compared to summer conditions?	0
Establish yearly, dedicated meetings among project partners and staff, stakeholders, and rights-holders to standardize methodology, develop a designated data repository and measure progress within the construct of the SOGL process. • Establish a standardized open access database of all Great Lake monitoring programs that are easily queried. - Easy for whom? Taxpayers too?	2
Government bodies should expand budgets for existing monitoring programs to cost/enable year-round coverage of areas of focus within the programs. How do we kick this off? • Likely a Congress-type kick-off • Bring together existing research programs (monitoring, etc.) - EPA-GLNPO; CSMI-all; USGS/NOAA; ECCC; DFO; NSF; NSERC; Sea Grant	3

Full Group Discussion of Recommendations and Next Steps

The voting exercise was followed by a full group discussion of the developed recommendations, their alignment with identified winter science gaps and needs, and prioritizing themes and recommendations developed over the course of the two workshop days. The overarching purpose of this discussion was to prioritize a consolidated list of SMART recommendations. Workshop participants engaged in a wide-ranging discussion about why they voted for certain recommendations over others, and the relative merits of various recommendations (as presented) were discussed. Workshop participants attempted to come to agreement on a concise yet comprehensive set of priorities. A synthesized set of final recommendations based on these discussions is presented in Section 3, below.

Wrap-Up

The workshop concluded following the workshop summary, with the IJC SAB workgroup co-chairs thanking participants for sharing their time and expertise.

3 Synthesized Winter Science Recommendations

The following two recommendations (one short-term and one long-term) have been synthesized from the whole-workshop discussions across all developed recommendations:

Immediate Recommendation:
Within the next 18 months, the IJC Science Advisory Board should encourage the GLWQA Annex 10 (Science) to perform a binational systems analysis to articulate the specific winter data gaps that can be met by monitoring that are limiting policy development and lake management decision making (Annex 2, etc.).

Long-Term Recommendations:
In the next 5 years, the IJC Science Advisory Board should facilitate a process, in partnership with academia and government agencies including NSF, NSERC, Sea Grant, and others as appropriate to establish a bi-national, competitive, and open funding program to address the following priorities:

- **Improve ice modeling and condition forecasting** for both short-term and long-term time horizons through targeted winter data validation.
- **Improve winter data collection** through the establishment and improvement of winter science monitoring infrastructure (both offshore and shore-based) to lower the barriers to winter science monitoring participation and improve the understanding of watershed linkages as well as the role of winter in the basin-wide delivery of ecosystem services.
- **Expand upon existing CSMI sampling** effort and framework to include all seasons and fill the gaps between CSMI sampling years by dedicating ice-breaking and ice-hardened vessels to science activities on one lake per year in conjunction with CSMI priorities.
- **Develop a master, open access, winter science database** that leverages A.I. to consolidate and pull from existing databases and makes collected winter data more F.A.I.R. (findable, accessible, interoperable, and reusable) while ensuring data QA/QC standard are met.
- **Build winter science capacity** by lowering barriers to entry and emphasizing early career training, internships, outreach, and inclusive hiring across many natural science, social science, and engineering disciplines.

Appendix A: Agenda

International Joint Commission (IJC)
Great Lakes Winter Science Workshop #3
Integrating Winter Science Priorities with Existing and Future Capacities:
Recommendations for Meeting Winter Science Needs
Windsor, Ontario
Jan. 31 – Feb. 1, 2024

DoubleTree by Hilton Windsor Hotel
333 Riverside Dr W, Windsor, ON N9A 7C5, Canada

Workshop Contacts

Workgroup Co-Chairs: Maggie Xenopoulos, Trent University, mxenopoulos@trentu.ca
Michael Twiss, Algoma University, michael.twiss@algomau.ca

IJC Contacts: Matthew Child, matthew.child@ijc.org
Li Wang, lizhu.wang@ijc.org

Support Contractors: Samir Qadir, Potomac-Hudson Engineering, Inc., samir.qadir@phe.com
John Bratton, LimnoTech, jbratton@limno.com
Michelle Platz, LimnoTech, mplatz@limno.com

Workshop Agenda

Workshop Objective: Using the preparation of conceptual winter science project work plans, develop recommendations for sustainably meeting winter science needs. Recommendations should SMART (Specific, Measurable, Attainable, Relevant, and Time-Bound).

Approach: Workshop preparatory materials include:

- Summary of Workshops #1 and #2 activities and outcomes.
- Summary of literature review describing the current state of Great Lakes winter science and identified knowledge gaps.
- Summaries of the identified needs of stakeholders and rights holders based on semi-structured interviews, as they relate to Great Lakes winter science.
- Summary of publicly accessible Winter Science databases.
- Work Plan template

Workshop participants are expected to have reviewed the materials provided and come prepared to outline work plans in small groups that are relevant to their disciplines.

Day 1 – January 31

Time	Topic
9:00 – 9:20 am	**Opening and welcoming remarks** • Introductions • Land Acknowledgement • IJC and SAB explanation
9:20 – 9:30 am	**Review project objectives** • Discuss Workshop 3 Objectives and Outcomes
9:30 – 10:00 am	**Ice Breaker – Snowball Exercise**
10:00 – 10:45 am	**Project Background** • Summary of findings from prior project activities **Workshop Approach:** Create bi-national, mock winter science project work plans • Review mock work plan template • Review ground rules • Suggested Work Plan Teams
10:45 – 11:00 am	**Break**
11:00 – 12:00 pm	**Breakout 1** • Form work plan groups • Select a project idea(s) to advance • Begin to complete work plan template, with special consideration of the resources needed
12:00 – 1:00 pm	**Lunch – provided in the hotel**
1:00 – 2:30 pm	**Breakout 2** • Groups continue developing work plan template
2:30 – 2:45 pm	**Break**
2:45 – 3:30 pm	**Breakout 3** • Groups synthesize work plan highlights and prepare to report out to whole group
3:30 – 4:15 pm	**Team report outs** • Teams report out to full group on work plan topics and features • Discuss ideas, questions, or feedback features
4:15 – 4:30 pm	**Day 1 Wrap-Up**

Optional group dinner: 6 p.m.
Loose Goose RestoPub
126 Ouellette Ave, Windsor, ON N9A 1A2, Canada

Day 2– February 1

Revised Agenda

Time	Topic
8:30 – 8:45 am	**Co-chair comments** • Recap of Day 1: summarize group report outs • Refresher on workshop objectives and Day 2 plan • Reallocate team members to account for single day attendance
8:45 – 10:15 am	**Breakout 4** • 8:45-9:45am - Each group develops 3-5 work plan recommendations[1] • 9:45-10:15am – World Café style – each group rotates to next station to discuss and critique that group's recommendations
10:15 – 10:30 am	**Break**
10:30 – 11:00 am	**Report out on Recommendations (Four Groups)**
11:00 – 11:45 am	**Full group discussion on Recommendations** • Is there alignment of recommendation themes? • Prioritize themes or individual recommendations, as appropriate
11:45 – 12:00 pm	**Workshop summary** • Recap of workshop activities and next steps
12:00 pm	**Day 2 Concludes – End of Workshop**

Appendix B: Workshop Participants

Below is a list of the participants who attended all or part of the workshop. Aside from co-chairs, IJC staff, and contractors, there were 18 participants from both the US and Canada across a range of fields including research agencies and academics, federal, state, and provincial agencies, and municipalities.

Attendee	Organization
Maggie Xenopoulos	*Trent University (co-chair)*
Michael Twiss	*Algoma University (co-chair)*
Matthew Child	*International Joint Commission*
Lizhu Wang	*International Joint Commission*
Samir Qadir	*Potomac-Hudson Engineering, Inc. (contractor)*
John Bratton	*LimnoTech (contractor)*
Michelle Platz	*LimnoTech (contractor)*
Carl Platz	USACE
Claire Stevens	Trent University
David Cannon	University of Michigan
Euan Reavie	University of Minnesota-Duluth
Jay Austin	University of Minnesota-Duluth
Joshua Culpepper	York University
Juliane Mai	University of Waterloo
Matthew Wells	University of Toronto at Scarborough
Nandita Basu	University of Waterloo
Nicole Wagner	Oakland University
Olivia Sowa	Oakland University
Scott Sowa	The Nature Conservancy
Silvia Newell	Michigan Sea Grant
Steve Ruberg	NOAA
Ted Ozersky	University of Minnesota-Duluth
Todd Howell	Ontario Ministry of the Environment and Climate Change
Trista Vick-Majors	Michigan Technological University
Warren Currie	Fisheries and Oceans Canada (DFO)

Appendix C: Work Plan Template

Great Lakes Winter Science Project Work Plan Template

All proposed workplans must be interdisciplinary and binational (Canada/U.S.) on winter science topics of relevance to both countries including Indigenous communities, that advances the objectives of the Great Lakes Water Quality Agreement[1]

Develop a workplan considering the following variables:

1. **Spatial Scale; 2. Temporal Scale; 3. Risk; 4. Interdisciplinarity**

Example: large scale

Design a workplan for a large-scale, interdisciplinary research project that addresses a major challenge related to winter science across all the Great Lakes and their catchment, with the potential to realize real and lasting change. The challenge may be fundamental, leading to a scientific breakthrough, or applied, with a social, economic, environmental or health impact.

Example: small scale:

Design a workplan for a smaller-scale, potentially higher risk research project that leverages non-traditional interdisciplinary approaches to formulate a research team with the capacity to explore something new that might fail, but that has the potential for significant impact to tackle a winter science challenge. The project's spatial scope should focus somewhere specific in the Great Lakes, such as a single protected embayment, as well as focus on solving a particular problem.

1. **Project Title:**

2. **Challenge:**

Explain the challenge and or science gap to be addressed, the importance of the topic and the need for new concepts or directions. Describe the current barriers impeding a solution to the challenge and the proposed novel strategy for addressing the issue.

[1] The workplan exercise is intended to elicit insights on high priority winter science needs and approaches to filling them. Although ideas discussed during the IJC workshop may lead to real-life grant applications, this is intended to be a thought exercise and the resulting workplans should not be construed as having IJC endorsement.

Great Lakes Winter Science Project Work Plan Template

3. Intro/Background/Literature Provide brief background of the challenge/question to be addressed.
4. Partnerships a) List all partner organizations participating in the project. For each, describe their core activities and how they align with the project, their need for the proposed project, and their experience related to it, such as efforts to date to address the challenge. b) Describe each partner organization's active role in the project, and how they will collaborate and contribute to the workplan. c) Explain why and how the team and partner organizations are positioned to address the selected challenge.

2

Great Lakes Winter Science Project Work Plan Template

5. Workplan objectives and methods:

Specify the research objectives and expected results. Describe the planned research activities, methodology and experimental design.

6. Impacts and Benefits:

a) Explain how and the extent to which the proposed workplan will meet the Great Lakes Water Quality Agreement objectives, and how it will generate new knowledge in winter sciences.
b) Discuss how the project is novel will lead to new or improved technologies, policies, economic, environmental, and/or other societal benefits.

7. Timeline

Provide approximate timelines for the activities, milestones and deliverables. You may use a Gantt chart, table or diagram.

3

Great Lakes Winter Science Project Work Plan Template

8. Approximate budget range:
9. What shared resources at the lake or regional scale could reduce the project-specific budget?
10. Potential funders:
11. What types of funding sources, programs, or structures don't currently exist but are needed? Are there examples from other regions that could be copied or adapted?

4

Appendix D: Completed Work Plan Templates

Group 1

All proposed workplans must be interdisciplinary and binational (Canada/U.S.) on winter science topics of relevance to both countries including Indigenous communities, that advances the objectives of the Great Lakes Water Quality Agreement **Develop a workplan considering the following variables:** **Spatial Scale; 2. Temporal Scale; 3. Risk; 4. Interdisciplinarity** **Example: large scale** Design a workplan for a large-scale, interdisciplinary research project that addresses a major challenge related to winter science across all the Great Lakes and their catchment, with the potential to realize real and lasting change. The challenge may be fundamental, leading to a scientific breakthrough, or applied, with a social, economic, environmental or health impact. **Example: small scale** Design a workplan for a smaller-scale, potentially higher risk research project that leverages non-traditional interdisciplinary approaches to formulate a research team with the capacity to explore something new that might fail, but that has the potential for significant impact to tackle a winter science challenge. The project's spatial scope should focus somewhere specific in the Great Lakes, such as a single protected embayment, as well as focus on solving a particular problem.
Project Title: **Improving Short-Range and Long-Range Forecasts of Changing Winter Lake Conditions to Inform Ecosystem Service Management (Water Quality, Transportation, Public Safety, Fisheries)**
Challenge: • Linkages between winter forcings (hydrodynamics and hydrology) and ecosystem services (water quality, nutrient cycles, etc.) are poorly understood. • Incomplete/insufficient understanding of winter conditions are unable to provide effective, actionable forecasts of ice cover, ice thickness, ice quality and related biogeochemical parameters, including harmful algal blooms (HABs), nutrient , and fisheries response. • We can't improve models because we don't have data. Specifically, ice thickness, ice quality, spatial variability, etc. Improve ice cover and ice thickness predictions for both long term (i.e. annual, seasonal) and short term (i.e. 3-day, 7-day forecasts)
Intro/Background/Literature *Provide brief background of the challenge/question to be addressed.* How do variable winter conditions affect ecosystem services in the Laurentian Great Lakes and how can land-lake management be used to effectively protect • winters are getting warmer (on average), but there is still a lot of year-to-year variability that makes management difficult   ○ Hard to plan for operations (Army Corp) • Cannon et al. 2023, 2024 (lake climate changes; ODyn, JCli)

- Winter recreation: safety is really important for public
- Ice breakers: when should they be operational
- Over-road transport affected by changes in lake effect snow
- GL Shipping: Potential improvements, but variability might be challenge
- Fisheries: spawning, egg development, early life, habitat
    - potentially
- hypoxia: may change in changing ice conditions- over winter hypoxia in nearshore would be improved, summer hypoxia may be worsened
- HABs: timing of water warming and nutrient delivery could possible worsen.
    - how could this change the food web?
- Hydrology: changes in flashiness of stream flow inputs, lack of snow/ice
- Shoreline/bed erosion: increased erosion from winter waves in absence of ice
- Changes in salinity: increased snow could lead to increased salinity from salt runoff
- Invasive species: more or less susceptible to invasion? Habitat changes (oxy thermal)?
- Lake Memory: how does variability things year-over-year?
- Hampton et al. 2017: changing faster than anticipated, not sure how to catch up research with knowledge gaps.

Partnerships

List all partner organizations participating in the project. For each, describe their core activities and how they align with the project, their need for the proposed project, and their experience related to it, such as efforts to date to address the challenge.

Describe each partner organization's active role in the project, and how they will collaborate and contribute to the workplan.

Explain why and how the team and partner organizations are positioned to address the selected challenge.

Funding, in-kind contributions, partnerships

- USACE
- NOAA
- Fish and Wildlife
- Forest Service
- ECCC
- USDA
- EPA
- DOE
- AAFC
- USNIC
- Coastguard
- GLOS
- SeaGrant orgs (state)
- Great Lakes Commission (inter-governmental collab)

- University partnerships
- Indigenous Group partnerships: translating knowledge to science

Workplan objectives and methods:

Specify the research objectives and expected results. Describe the planned research activities, methodology and experimental design.

Research Objective(s)

Improve, develop, and validate short-range(3-day, 7-day) and long-range (annual, seasonal) ice forecast models (concentration, thickness, quality)

Quantify the role of winter hydrodynamic and hydrologic forcing on ecosystem service provision across the land-lake ecosystem

Develop land-lake management strategies related to global environmental change and its effect on winter climatology and linked ecosystem processes.

Potential Research Ideas

- Identify locations that are potentially more susceptible to variations in winter climatology, with larger impacts on ecosystem services. Focus on spatial heterogeneity of variability to identify "hot spots" and "cold spots."
- Improved parameterization of ice models (i.e. CICE6)
    - Ridging, ice-wave interactions, snow on ice, etc.
        - Improved shoulder season representation
    - stand-alone and coupled ice quality model development
    - data assimilation: ice concentration from USNIC
- How will changing lake conditions affect fish habitat and downstream use by tribal communities, first nations, etc.
- Validation of ice models and remote sensing
    - Ice thickness measurements: core subsurface mooring, sonar sleds
        - spatial variability- how variable is ice thickness on small scales
        - ice ridging - volume of ice contained in ridges and pile-up
        - icebergs?
    - Floe size distributions
    - Sub-surface temperatures- - important for understanding stratification and ice setup
- Lidar measurements to look at total ice surface: point cloud representation to look at spatial variability.
- Under ice turbulence microstructure: nothing available in freshwater…
- Developing seasonal forecast tools using climate indices to predict ice cover, spring HABS, etc.
- Influence of wetlands - - - fluxes of nutrients to lake with and without ice.

Impacts and Benefits:

Explain how and the extent to which the proposed workplan will meet the Great Lakes Water Quality Agreement objectives, and how it will generate new knowledge in winter sciences.

Discuss how the project is novel will lead to new or improved technologies, policies, economic, environmental, and/or other societal benefits.

Timeline

Provide approximate timelines for the activities, milestones and deliverables. You may use a Gantt chart, table or diagram.
Approximate budget range:
What shared resources at the lake or regional scale could reduce the project-specific budget?
Potential funders:
What types of funding sources, programs, or structures don't currently exist but are needed? Are there examples from other regions that could be copied or adapted?

Group 2

All proposed workplans must be interdisciplinary and binational (Canada/U.S.) on winter science topics of relevance to both countries including Indigenous communities, that advances the objectives of the Great Lakes Water Quality Agreement **Develop a workplan considering the following variables:** **Spatial Scale; 2. Temporal Scale; 3. Risk; 4. Interdisciplinarity** **Example: large scale** Design a workplan for a large-scale, interdisciplinary research project that addresses a major challenge related to winter science across all the Great Lakes and their catchment, with the potential to realize real and lasting change. The challenge may be fundamental, leading to a scientific breakthrough, or applied, with a social, economic, environmental or health impact. **Example: small scale** Design a workplan for a smaller-scale, potentially higher risk research project that leverages non-traditional interdisciplinary approaches to formulate a research team with the capacity to explore something new that might fail, but that has the potential for significant impact to tackle a winter science challenge. The project's spatial scope should focus somewhere specific in the Great Lakes, such as a single protected embayment, as well as focus on solving a particular problem.
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How do variable winter conditions affect ecosystem services in the Laurentian Great Lakes and how can land-lake management be used to effectively protect

- winters are getting warmer (on average), but there is still a lot of year-to-year variability that makes management difficult
  - Hard to plan for operations (Army Corp)
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- University partnerships
- Indigenous Group partnerships: translating knowledge to science

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- Under ice turbulence microstructure: nothing available in freshwater…
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Impacts and Benefits:

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Provide approximate timelines for the activities, milestones and deliverables. You may use a Gantt chart, table or diagram.

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Potential funders:

What types of funding sources, programs, or structures don't currently exist but are needed? Are there examples from other regions that could be copied or adapted?

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1. **Spatial Scale; 2. Temporal Scale; 3. Risk; 4. Interdisciplinarity**

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Example: small scale

Design a workplan for a smaller-scale, potentially higher risk research project that leverages non-traditional interdisciplinary approaches to formulate a research team with the capacity to explore something new that might fail, but that has the potential for significant impact to tackle a winter science challenge. The project's spatial scope should focus somewhere specific in the Great Lakes, such as a single protected embayment, as well as focus on solving a particular problem.

1. **Project Title:**

Opportunity to go big on the idea and topic – all disciplines, all lakes e.g., International Biological Program which was a 10 year intensive effort, and Decadal scale Ocean Science program…take that approach in Great Lakes?
Big ideas resonate better with higher level recommendations

Project title: Great Lakes Winter Science Decade

Is a decade enough to capture temporal variability between winters?

- We are so data poor we are not in a good position to assess appropriate duration of study, but…
- 10 years is admittedly quite arbitrary but it may be long enough to fit with ice cycle trends (historically ice min/max is 3-5 year cycles), water level fluctuations (~10 year cycle), practicalities of funding cycle
- 10 years is still longer than most research projects
- 10 years needed to understand variability, and is aligned with two CSMI cycles which provide insights on ice free season (if it is a decade, no matter which year you start you'll capture two CSMI cycles)
- A decade can capture the workforce development cycle of opportunity to train students and students to transition to ECRs

Leverage and extend CSMI to the winter season – the 'year' is the winter and summer that follows to account for ecological memory.

[1] The workplan exercise is intended to elicit insights on high priority winter science needs and approaches to filling them. Although ideas discussed during the IJC workshop may lead to real-life grant applications, this is intended to be a thought exercise and the resulting workplans should not be construed as having IJC endorsement.

In addition, deploy instruments and collect observations above and beyond CSMI to ensure better temporal, spatial and 'parameter' coverage.

The 'program' would guarantee having a decade to build capacity and allow the exploration of various research questions, gaps and needs; it could also leverage other activities and investments.
Need year round monitoring to put any one season into context.

Side discussions:
Can we compress CSMI to, say, each lake every three years?
Reality is it would take dedicated resources
Explanation of CSMI cycle – LAMPs identify priorities, Annex 10 operationalizes priorities, GLRI funds …so extending to winter means that planning and implementation run continuously and concurrently
CSMI core team – six major federal agencies

Community Science angle – recreational, commercial and Indigenous fishers assisting with data collection – some existing examples

M Child aside/thoughts:
Alignment with GL Science Plan – Winter Science as a microcosm
How to ensure agency and academic alignment, coordination, etc.

2. Challenge:
Explain the challenge and or science gap to be addressed, the importance of the topic and the need for new concepts or directions. Describe the current barriers impeding a solution to the challenge and the proposed novel strategy for addressing the issue.

Barriers:
- Current agency budgets, including core agency budgets and capacities (highly qualified personnel).
- If winter science gets prioritized, agencies would have to shift their culture and embrace change etc.
- Federal science funding programs – limited focus on winter science.
- Lack of awareness of importance of winter science in understanding the system for management/policy decision-making, and broader public awareness of how improved winter science affect ecosystem services e.g., fisheries
- Lack of social sciences expertise – can be particularly helpful given cultural and economic importance of seasons including winter
- General lack of applying Indigenous Knowledge as a separate but complementary way of knowing.

Technology is changing rapidly – capitalize on public-private collaborations to maximize development and adoption of technology

3. Intro/Background/Literature
Provide brief background of the challenge/question to be addressed.

Other decadal plans e.g., Ocean Decade programs
Other international collaborations e.g., GLOBEC (Global Ocean Ecosystem Dynamics)
CSMI reports

4. Partnerships

a) List all partner organizations participating in the project. For each, describe their core activities and how they align with the project, their need for the proposed project, and their experience related to it, such as efforts to date to address the challenge.
b) Describe each partner organization's active role in the project, and how they will collaborate and contribute to the workplan.
c) Explain why and how the team and partner organizations are positioned to address the selected challenge.

Evolve existing programs, especially CSMI and Annex 2 and Annex 10 - towards a focus on winter monitoring and winter science.

State and Provincial partners e.g., MNRF, MOECP, State DNR/DEC

Other existing agency science programs and datasets e.g., drinking water intake monitoring

Partnerships needed to help develop workforce capacity e.g., taxonomists. Rely on universities and other training programs. Potential role for Center of Expertise for Taxonomy.

Opportunistic sampling - Coast Guard partnership, commercial/recreational/Indigenous fishers

Indigenous Science organizations – but consider issues of data sovereignty

Existing organizations that are focused on instrumentation, data repository, data representation - GLOS, Canada IOOS, Smart Great Lakes (consider need to sustain the monitoring station long term)

Existing sensor networks – RAEON, UMD-LLO temperature observations, GLATOS, UNOLS (University-National Oceanographic Laboratory System), NERRS (National Estuarine Research Reserves System)

federal funding agencies - NSF, NSERC etc.

GLFC

Community-based science and monitoring

Are there best practices, tech transfer, governance arrangements etc. that we can learn from the Ocean Observatories or Decadal Ocean Science programs e.g., GLOBEC (Global Ocean Ecosystem Dynamics)

5. Workplan objectives and methods:

Specify the research objectives and expected results. Describe the planned research activities, methodology and experimental design.

What we hope to establish:

1. Observation platforms (cabled? uncabled?):

- Observatories – include parameters like temperature, currents/ice presence, DO, light conditions at different depths, chlorophyll and DOM fluorescence, nitrate sensors
- Coupled with autosamplers for microbes etc. & sediment traps
- Station locations TBC - three 'master stations' per lake centered in offshore, with nearshore leveraged by existing DW intake monitoring program and technologies e.g., drones.

2. Cruises:
- Rotation like CSMI – three cruises per winter/shoulder season
- Logistically complex include ice capable vessels
- Multiple parameters and media (water, biota)

3. Permanent winter grab for nearshore environments – university undergraduate program based?

What we hope to accomplish:

Filling fundamental data gaps identified by GL community (e.g., thermal regimes, light measurements; see Ozersky et al., etc.) to set a foundation and capacity for long-term understanding of winter conditions

Establish the dream suite of information for understanding winter: understand the carbon cycle (stoichiometry) to determine the metabolism of the GL through the winter.
…including influence on food web dynamics

We have CSMI, need to leverage that and extend monitoring seasons e.g., algal blooms are being detected in December!

Potential role for a Center of Expertise

Parking lot etc.:

Continuous year-round offshore sensor deployment – in all five lakes – (physical and chemical parameters) - number and location of primary monitoring stations would need to be considered further, and due to scale, basins, etc. would vary between lakes – minimum of three per lake as a starting point, possibly with additional nearshore nodes.

Determine changes e.g.,
physical - ice cover and condition, habitats
biological - change in species composition – microbes to zooplankton at least!

Are there parameters that we can consider as more integrative? Would need to think about this more…

6. Impacts and Benefits:

a) Explain how and the extent to which the proposed workplan will meet the Great Lakes Water Quality Agreement objectives, and how it will generate new knowledge in winter sciences.
b) Discuss how the project is novel will lead to new or improved technologies, policies, economic, environmental, and/or other societal benefits.

Benefits:
- Research infrastructure and capacity to enable winter observations
- Support other binational agencies with data and information needs e.g., GLFC
- Research synergy across science organizations
- Workforce development
- GLWQA linkages – LAMPs routinely flag concerns about lack of winter observations

7. Timeline Provide approximate timelines for the activities, milestones and deliverables. You may use a Gantt chart, table or diagram. Umm, a Decade
8. Approximate budget range: "Buckets of money"
9. What shared resources at the lake or regional scale could reduce the project-specific budget?
10. Potential funders:
11. What types of funding sources, programs, or structures don't currently exist but are needed? Are there examples from other regions that could be copied or adapted?

Group 4

All proposed workplans must be interdisciplinary and binational (Canada/U.S.) on winter science topics of relevance to both countries including Indigenous communities, that advances the objectives of the Great Lakes Water Quality Agreement[2] **Develop a workplan considering the following variables:** **1. Spatial Scale; 2. Temporal Scale; 3. Risk; 4. Interdisciplinarity** **Example: large scale** Design a workplan for a large-scale, interdisciplinary research project that addresses a major challenge related to winter science across all the Great Lakes and their catchment, with the potential to realize real and lasting change. The challenge may be fundamental, leading to a scientific breakthrough, or applied, with a social, economic, environmental or health impact. **Example: small scale** Design a workplan for a smaller-scale, potentially higher risk research project that leverages non-traditional interdisciplinary approaches to formulate a research team with the capacity to explore something new that might fail, but that has the potential for significant impact to tackle a winter science challenge. The project's spatial scope should focus somewhere specific in the Great Lakes, such as a single protected embayment, as well as focus on solving a particular problem.
1. **Project Title:** Waters of the Great Lakes and Tributary Observatory **Lake River Winter Interface** Establishing a coordinated, network/testbed of integrated tributary, nearshore, offshore monitoring of the waters of the Great Lakes

[2] The workplan exercise is intended to elicit insights on high priority winter science needs and approaches to filling them. Although ideas discussed during the IJC workshop may lead to real-life grant applications, this is intended to be a thought exercise and the resulting workplans should not be construed as having IJC endorsement.

2. Challenge:

Explain the challenge and or science gap to be addressed, the importance of the topic and the need for new concepts or directions. Describe the current barriers impeding a solution to the challenge and the proposed novel strategy for addressing the issue.

Challenge: data provision

- Describing the GL condition over time, year-round, including winter (not just April and Aug)
- Understanding the influence of winter tributary fluxes on GL bio/phys/chemical dynamics
- Understanding the temporal fate, transport, and influences of winter nutrient pulses
- Model validation for interactive system models and forecasting
- Under-ice phyto and zoox

Barriers:

- Money
- Staff/workforce
- Technology
- Safety
- Institutional inertia for prioritizing winter data collection (branching from what has always been done in the past) – breaking the attitude barrier
- Networks – more integration
- King/queen – someone coordinated oversite of such a massive program
- Data stewardship

Novelty of this proposal:

- Time and space
- Watershed integration – looking at not just lakes
- New technologies and methods to enable frequency
- Developing an integrated networks through which to perform with **long-term leadership**

3. Intro/Background/Literature

Provide brief background of the challenge/question to be addressed.

Trib → offshore data provisioning

Previous papers

- Some tributary papers exist, but not really for winter time, maybe one for January
- GLNPO /EPA network as example
- CSMI – existing expertise that needs to be built upon and expanded (currently piecemeal)

Challenges: GL monitoring programs exist but are weak on winter and at scales that are not currently informative of winter dynamics/models/projections

4. Partnerships

d) List all partner organizations participating in the project. For each, describe their core activities and how they align with the project, their need for the proposed project, and their experience related to it, such as efforts to date to address the challenge.
e) Describe each partner organization's active role in the project, and how they will collaborate and contribute to the workplan.
f) Explain why and how the team and partner organizations are positioned to address the selected challenge.

- EPA – GLNPO – deep water monitoring
- ECCC, NOAA, GLOS, USGS, etc – collectively institutions – sampling and data analysis
- Water intake facilities – data collection
- Institutional infrastructure
- Coordinate across all the little existing limnology projects – academics and government agencies
    - Need to ID existing/ongoing work – winter science community of practice

- Grassroots winter grab approach – ship out data kits and have them all analyzed in one place –
- Coastal wetland monitoring approach and Cladophora as examples of existing such programs
- Academics
- Environment Canada and NOAA to partner on the leadership – coordination, data management, and quality control – need too ensure accessible, bi-national database
- SeaGrant

5. Workplan objectives and methods:

Specify the research objectives and expected results. Describe the planned research activities, methodology and experimental design.

- Ultimate objective: robust, GL Basin -wide data provision from trib → nearshore → offshore

Methods

- Field sampling: both sensor and grab samples, across trib, water intakes, nearshore, and offshore
- Monthly monitoring across all systems
- Bio/phys/chem parameters
- How realistic is taxonomic data

Hypotheses

- Phosphorus → where is it going and what is it doing? What's diving spring blooms in the lakes outside of LEWB? Does the timing of P delivery in the winter impact productivity of the lake for the rest of the year
- Fundamental differences between winter and summer thermal structures in GL Nearshores
- Nearshore→ offshore phyto-dynamics
- What role does winter play in GL food webs

Questions?

- Is monthly samples enough or too much?
- Currently not including fish – can/should we?
- Who should the king or queen be?

6. Impacts and Benefits:

c) Explain how and the extent to which the proposed workplan will meet the Great Lakes Water Quality Agreement objectives, and how it will generate new knowledge in winter sciences.

d) Discuss how the project is novel will lead to new or improved technologies, policies, economic, environmental, and/or other societal benefits.

7. Timeline

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