APPLICATION OF THE POLARIS METHODOLOGY TO HISTORIC ICE-CLASS SHIP OPERATIONS IN FRESHWATER LAKE ICE

by

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Abstract

The primary objective of this work is to examine ship operations in freshwater versus sea ice in the context of evaluating appropriate regulatory guidelines, through analysis of historic data for the North American (Laurentian) Great Lakes region, a heavily trafficked freshwater waterway that is crucial for the functioning of Canada's industrial heartland.

The first goal of this analysis was to characterize expected ice conditions that could be found within the region through aggregating and sampling data from Canadian Ice Service ice charts over the 10-year study period, which includes the ice seasons from 2010 to 2019. This was followed by an analysis of ship traffic in the region during the same period through the use of historical archived AIS data. Lastly, the POLARIS methodology, an internationally accepted means of guiding ship operators in specific sea ice conditions, was applied to the historic ship operations described by the available AIS data to provide a comparison of historic operator decisions in lake ice to existing guidelines for operations in sea ice of similar thickness and concentration.

The characterization of the regional ice conditions during the studied period was intended to provide additional context for the ship traffic analysis for comparison against typical local ice conditions along shipping routes. As existing reviewed literature previously indicated, this analysis clearly affirmed that there is significant year-to-year variability in the potential severity and duration of a given ice season in the Great Lakes.

Results obtained from the analysis of historic ship traffic in the region and the application of the POLARIS methodology to this data provided valuable insights into the nature of current ship operations in ice in the Great Lakes. Overall, the trends observed suggest that current practices are well aligned with POLARIS guidelines for sea ice (89% of ice operations are in positive RIO

values) and that risk mitigating measures currently used in the Great Lakes (such as icebreaker support and speed reductions when transiting through ice) are compatible with the approaches recommended in POLARIS.

However, it is recommended that a more detailed analysis of the correlation between historical ship operations and icebreaking activity in specific regions be conducted to provide a better understanding of the degree to which ships operate in managed ice conditions. Further exploration of the POLARIS guidelines in the context of adapting mitigating measures into operational guidance for freshwater ice is also recommended, given the known differences in material properties of sea ice versus freshwater ice. Since it is not evident how such differences in ice types would translate into differences between the current POLARIS method and a modified "Freshwater POLARIS", additional research is needed to assess the impact of differences in ice properties in terms of potential for ship damage and appropriate speed limits, as well as assessing the need for possible modification of Risk Index Values for lake ice types.

In summary, the results of this work do suggest that the development of specifically tailored POLARIS-like guidelines presents a promising approach to aid ship operations in lake ice conditions similar to that found within the Laurentian Great Lakes during the studied 10-year period. The potential to codify current best-practices for shipping operations in the Great Lakes into such a modified method would help ensure consistency in the assessment of operational capabilities and limitations for different classes of vessels operating in lake ice. This in turn would provide greater clarity regarding expected mitigating measures and would help support effective decision-making relating to ship operations in ice.

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List of Symbols, Nomenclature or Abbreviations

AIS – Automatic Identification System

CIS – Canadian Ice Service

IACS – International Association of Classification Societies

IMO – International Maritime Organization

POLARIS – Polar Operational Limit Assessment Risk Indexing System

PWOM – Polar Water Operational Manual

RIO – Risk Index Outcome

RIV – Risk Index Value

SIGRID - Sea Ice GeoReferenced Information and Data

WMO – World Meteorological Organization

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Chapter 1:

Introduction

1.1 Background

The motivation for this research is to explore the feasibility of adapting existing guidelines for ship operations in ice, which largely focus on sea ice and glacial ice hazards for ocean-going vessels that operate in Polar Waters, to operations in freshwater lake ice. Within the North American Great Lakes (also known as the Laurentian Great Lakes), a heavily trafficked freshwater waterway that is crucial for the functioning of Canada's industrial heartland, ice is a relevant navigational hazard for a large part of the year, typically from early December to early May. As reported by vessel operators and through media publications, ships transiting the Great Lakes during this time have been known to experience damage due to operations in ice, and cases where ships have become trapped due to unexpectedly severe ice conditions are not uncommon. For some examples, one may see the news articles cited including (Louwagie, 2020) and (Ellison G. , 2015). Measures such as icebreaker assistance are considered essential during the winter months in order to maintain traversable passages through regions that experience the most consistently severe ice conditions (U.S. Army Engineer District Detroit, 1979).

The presence of ice presents a significant and complex hazard for ship operations, primarily due to the potential for both global and localized structural loads that are difficult to predict and can be well above typical design requirements for ships that operate solely in open-water environments. The design and operation of vessels to avoid damage from ship-ice interactions is necessary for several reasons: primarily this includes ensuring the safety of crew and other personnel, but other reasons include preventing potential environmental damage, commercial or reputation losses for ship operators and ensuring the reliability of ship-based transit and supply networks. As such, for operations in any ice environment, it is critical that ship operators have consistent and accurate guidelines regarding ice conditions that can be safely navigated and knowledge of appropriate measures for mitigating the increased risks in these environments. This is essential for ensuring the safety of personnel and the environment during these operations, while also helping reduce the number of ice-related delays and incidents requiring repairs.

To support efficiency in satisfying increased design requirements and to support effective decision-making for ship operations in ice covered waters, ongoing research aims to improve our understanding of the nature of ship-ice interactions in these hazardous environments. Codes and guidelines developed and adopted by national regulatory organizations are intended to provide reliable guidance to ship designers and operators. The research presented in this thesis is intended to support the development of such improved methods.

1.2 Objectives

Contained within the International Maritime Organization's (IMO) Polar Code, the Polar Operational Limit Assessment Risk Indexing System (POLARIS) is a methodology that can be used as a means of providing guidance regarding operational limits in ice for ships operating in polar waters. As an initial study into the feasibility of adapting the POLARIS methodology for ships operating in freshwater ice, the objective of this work is to address the following questions:

1. If the POLARIS methodology were to be applied on the Great Lakes using the closest lake ice equivalents, what range of Risk Index Outcomes are observed?

2. What insights can be gained about the nature of current ship operations in ice in the Great Lakes based on the POLARIS methodology?

3. What additional information and further research would be needed to support the development of a modified POLARIS methodology for the Great Lakes?

Current standards for ice class ships and guidelines for ship operations in ice, such as the Polar Code, focus on sea ice and glacial ice hazards for ocean-going vessels rather than freshwater lake ice. While the impact of differences in material properties between freshwater ice versus sea ice in terms of the potential for damage to a vessel is a highly important consideration, this topic is beyond the scope of the present work.

1.3 Scope

The primary objective of this work is to examine ship operations in freshwater versus sea ice in the context of evaluating appropriate regulatory guidelines. To achieve this, first an analysis was conducted of ice conditions seen within the Great Lakes region during the studied period, which includes the ice seasons of winters 2010 to 2019. This was followed by an analysis of ship traffic in the region during the same period through the use of historical archived AIS data. Lastly, the POLARIS methodology, an internationally accepted means of assessing ship safety and performance in specific sea ice conditions, was applied to the historic ship operations described by the available AIS data. This analysis was expected to provide a comparison of historic operator decisions and risk mitigation measures that were taken while transiting through freshwater ice to POLARIS guidelines for operations in sea ice of similar thickness and concentration.

Many aspects of this analysis break the overall Laurentian Great Lakes region into its composite subregions for more localized analysis. These regions include each of the five Great Lakes, which in descending order of surface area are: Lake Superior, Lake Huron, Lake Michigan, Lake Erie, and Lake Ontario. Additionally, the relatively small waterway between Lakes Huron and Erie (which includes the St. Clair River, Lake St. Clair, and the Detroit River) and the upper St. Lawrence River (to the North-East of Lake Ontario) are defined as their own subregions due to the potentially distinctive river-ice conditions found within those locations. These regions are consistently used throughout this work as outlined below in Figure 1-1.

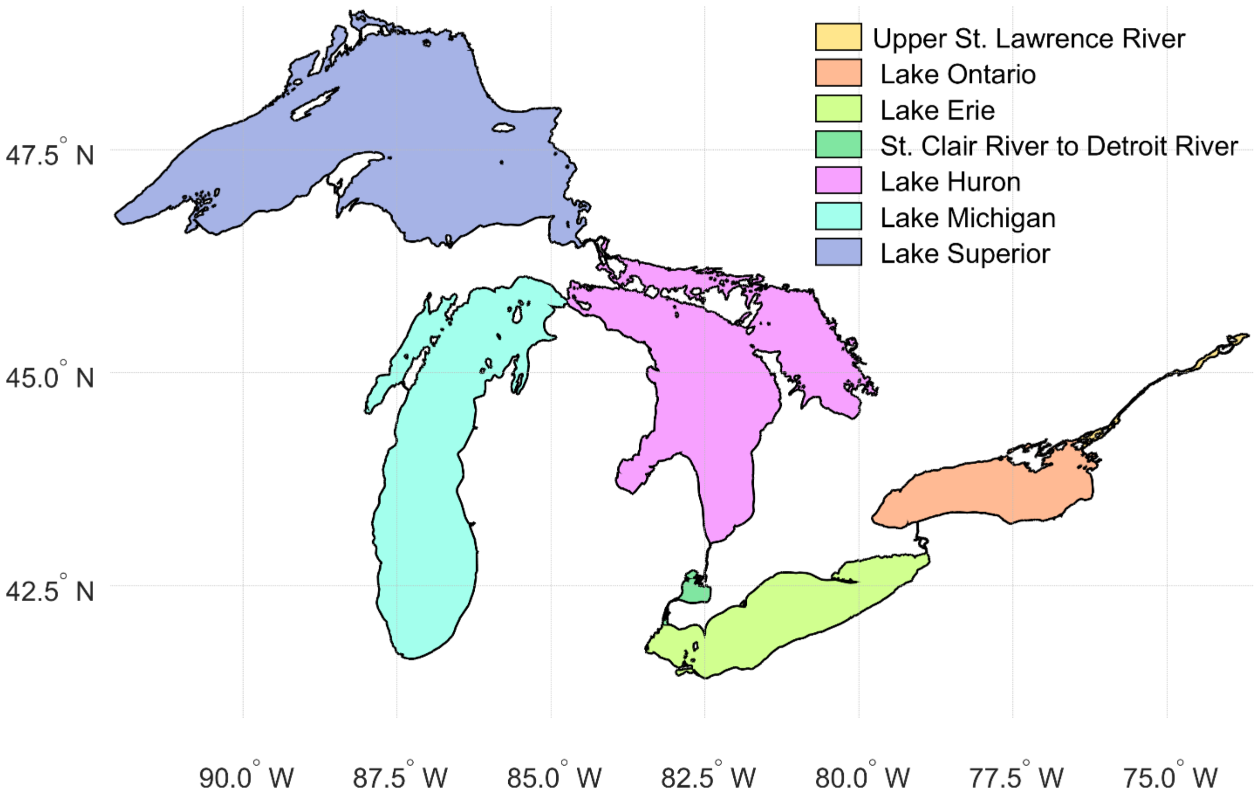

Figure 1-1: Map of the North American (or Laurentian) Great Lakes, colored by the (sub)regions as identified for use in the present research.

Chapter 2:

Literature Review

2.1 Overview

This chapter is primarily intended to provide the necessary background and context required to interpret the research described by this work. The topics reviewed and described in this chapter start with an overview of ship ice classifications and guidelines for ice operations; then followed by an overview of shipping operations within the studied Laurentian (or North American) Great Lakes region, with a brief review of ice climatology research using similar methodology to some analysis presented in Chapter 4. This also includes a review of some relevant scientific literature regarding the material properties of ice that may influence the risk profile for vessel damage when transiting through lake ice versus sea ice of similar thickness. Lastly, included here is a brief description of the technologies and data sources that were used for the technical analyses that are later described in Chapters 4 and 5.

2.2 Classifications and Guidelines for Ship Operations in Ice

2.2.1 Ice Classes and the Polar Code

The primary means used to denote the range of ice conditions a given ship can operate safely within are ice classes. An ice class is a notation that can be assigned to ships within the ship classification systems used by classification societies or national authorities, which specifies design requirements and the level of strengthening that must be met in order to safely navigate particular ice environments. Multiple ice class systems are still used worldwide today, which vary by jurisdiction and classification society, and each system has its own requirements and notation. While some systems are very similar to each other and have clear equivalent ice classes, others have very different requirements or intended operating regimes, with no clear equivalents between systems. However, a ship that operates under multiple jurisdictions may be assigned multiple ice classes under separate systems if it independently meets the requirements for each.

Some examples of ice class systems in use today include the Finnish-Swedish Ice Class Rules used for ships designed to operate in first year ice within the Baltic Sea, the ice class systems used by various classification societies including the American Bureau of Shipping, DNV GL (formerly Det Norske Veritas, who used a separate ice class system prior to its merger with Germanischer Lloyd in 2013), the Russian Maritime Register of Shipping, and ice classes for use in the Canadian Arctic (which include the Arctic Class rules that were used until 2017, and the modern Canadian Arctic Class (CAC) system that has replaced it).

In addition to the ice class systems described above, the International Association of Classification Societies (IACS) has developed the Polar Class requirements to unify the various ice class systems used by different classification societies. These rules began development in the 1990's and were later published within "*Unified Requirements for Polar Class Ships"* in 2007. The Polar Class system was developed in parallel with and was referenced by early guidelines for ship operations in polar waters by the International Maritime Organization (IMO). These IMO guidelines later evolved into the Polar Code (in full: the International Code for Ships Operating in Polar Waters), which IMO adopted in 2014. In 2017, compliance with the Polar Code became mandatory for all ships greater than 500 gross tonnage operating in Arctic or Antarctic waters, not including fishing vessels or those entitled to sovereign immunity. The Polar Code regulations are intended to cover the full range of design, construction, equipment, operational, training, search and rescue and environmental protection matters for ships operating in polar waters.

2.2.2 The POLARIS Methodology

To complement the guidelines outlined within the Polar Code, an index-based methodology was developed to aid with the assessment of operational limits for ships operating in ice-covered polar waters. This methodology, the Polar Operational Limit Assessment Risk Indexing System (POLARIS), was based on operator experiences and established best practices from Canada's Arctic Ice Regime Shipping System, the Russian Ice Certificate, and other existing methodologies. It was first adopted into IMO guidelines with publication of the Polar Code in 2014, following approval by the IMO's Maritime Safety Committee. The Polar Code requires that a ship operating in polar waters should possess a valid Polar Ship Certificate which establishes its operational limitations, as well as a ship-specific Polar Water Operational Manual (PWOM), which identifies procedures to support the decision-making process for operations during both routine and emergency circumstances. Operational limitations recommended through the POLARIS methodology may be referenced by a Polar Ship Certificate, and its guidelines are intended to support the ship-specific information contained within a ship's PWOM (IMO, 2016).

The POLARIS methodology uses a Risk Index Outcome (RIO) value to classify a ship's operational capability in specific ice conditions. The RIO value for a ship in specific ice conditions is calculated by the summation of the concentration (in tenths) of each ice type present multiplied by the ship's corresponding Risk Index Values (RIVs) for those ice types. RIVs are empirically determined values that represent the expected operational impact on safety and performance posed by that ice type for ships of a specific ice class. Any ship with an ice class included in POLARIS guidelines may be assigned a Risk Index that contains a set of Risk Index Values (RIVs) for the different stages of sea ice development defined by the methodology. An alternative set of Risk Indices was developed and may be used for decayed Medium and Thick First Year Ice, which are intended for operations during higher ambient temperatures (such as during late Spring and Summer) in order to reflect an associated reduction in risk. The ice-class based given Risk Indices in POLARIS include the IACS Polar Class ice classes and ice classes assigned equivalence to Finnish-Swedish Ice Class Rules.

Based on the range a RIO falls into, POLARIS recommendations address three operational categories: normal operation, elevated operational risk, and operation subject to special consideration. A RIO equal to or greater than 0 indicates normal operation, with no additional POLARIS guidelines. For Polar Class ships, a RIO equal to or greater than -10 and less than 0 indicates elevated operational risk. POLARIS provides speed limit recommendations ranging from 3 to 11 knots depending on the specific Polar Class for this category. Additional watch keeping or the use of icebreaker support are also suggested measures, as is avoiding areas likely to fall into this category if possible while voyage planning. The remaining category, operation subject to special consideration, applies to Polar Class ships for RIO values less than -10 and for all other vessels (with or without an assigned ice class) for RIO values less than 0. Ice regimes with a RIO identifying operation subject to special consideration merit extreme caution when navigating, and POLARIS recommendations suggest rerouting to avoid such conditions when possible. Otherwise, further reduction in speed is recommended beyond that outlined for elevated operational risk, as well as any other ship-specific risk mitigating special measures that are outlined in its PWOM. In short, the POLARIS methodology provides guidelines that aim to reduce the level of risk of structural damage to a given ship in particular ice conditions (IMO, 2016).

2.3 The North American Great Lakes

2.3.1 Shipping Operations in the Region

The North American Great Lakes are a high-traffic shipping waterway for both Canada and the United States, which is enabled by an extensive system of locks and canals along the Great Lakes-St. Lawrence Seaway. Shipping in the region slows during winter months due to the severe ice conditions seen in the lakes and annual winter shutdown, which limits traffic to essential operations only. The Seaway between Lake Erie and Montreal is closed for an annual winter shutdown from January to mid-March, and the Soo Locks between Lake Superior and the other lakes are typically closed for a slightly shorter duration. It is during this time that the majority of the Seaway's critical infrastructure maintenance is scheduled (Transport Canada et al, 2007).

During the winter lay-up, ships typically still operate within the Great Lakes in reduced numbers. Ice frequently remains in the lakes once shipping has fully resumed, sometimes in significant quantities, beyond the winter season into April and occasionally early May. There is significant year-to-year variability in the length of the ice season as well as the degree of ice coverage seen in the lakes. There is also significant regional variation of ice coverage due to differences in the individual lakes' geography, with contributing factors including water depth and mean ambient air temperature (Assel, 2005).

There have been multiple prior studies into winter navigation in the Great Lakes, largely motivated by efforts of the Canadian and US governments to assess the feasibility of extending shipping operations in the region into the winter months. The most comprehensive of these was conducted by the U.S. Army Engineer District, Detroit, and the report was published in 1979. It provided an assessment of the potential environmental impact of extending the navigation season to winter months, provided detailed plans for implementation and solutions to potential engineering challenges (such as maintenance of the seaway infrastructure), public views and social impacts, a cost/benefit analysis, and an overview of the climatology of the Great Lakes region, which identified problem areas with the most hazardous ice conditions.

In general, prior studies into the feasibility of extending winter operations within the Great Lakes have concluded that the main concerns to be addressed include risks to personnel safety, ship damage, and economic factors such as operating delays. Increased risk for environmental harm due to ice operations (specifically, for reasons such as the potential for fuel or other material spills) was not considered significant over the historically low rates for such incidents in the region. Wuebben (1995) provides a detailed summary of prior works performed to assess the environmental impact of winter ship operations in the Great Lakes. While the studies described by Wuebben are themselves older works, the fundamental risks can be assumed to be similar or further reduced today due to advancements in ship design. One of these studies states that substantial damage must occur for most ships to experience a spill due to design features such as "*double-hulled construction, the presence of a forward cofferdam in the bow, and the aft location of the fuel tanks*." Minor incidents involving ice seem to be common in the lakes, although it is difficult to assess the exact prevalence as this information is only known when voluntarily disclosed by operators. However, the majority of ice-related incidents seem to result only in minor hull damage and operational delays. Another work described by Wuebben concludes that:

"*The probability of a spill during the extended season was quite low in all cases. Generally the probability was an order of magnitude less than the probability of a spill in the normal season, in part due to the lower frequency of shipping. However, it was found that there was an increased risk of a spill per transit during the extended season period of 1.5–3 times the normal season. In*

Lake St. Clair it was found to be five times the normal risk. This increased risk was largely due to operating in ice.”

This aligns with and is supported by information from other sources, as Lake St. Clair is known to experience extremely heavy rubble buildup following spring breakup (U.S. Army Engineer District Detroit, 1979). A more recent study (English et al, 2016) also provides an overview of environmental spills in the region from 2002 to 2011. The summary contained here states that:

“*There were 73 reported releases from vessels in Canadian Great Lakes-Seaway waters and 66 releases in U.S. Great Lakes-Seaway waterways over the period of 2002 to 2011. Incidents were mainly related to relatively small spills of product during loading/unloading operations or minor releases of consumables involving hydraulic fluid, lubricating oil or fuel oils.*”

From the information contained within this study, it appears there were no major spills resulting from collisions with ice during this period, while most spills occurred in port/during transfer operations aside from “*an accident where a vessel lost engine power in strong winds and overrode its anchor*” and “*a fuel release from a bulk-cargo vessel, following a striking event on a river.*” Overall, the study concludes that “*Based on a total number of vessel trips of 69,960 over the 10-year data interval, 99.8% of vessel trips were “incident-free.*” This recent data from English reinforces the conclusions reached by Wuebben and earlier works, where the greatest risk was seen to be posed by transfer operations, followed by grounding and ship-ship collisions.

The overall safety profile of winter operations in the region is best summarized by the following excerpt from Wuebben’s concluding remarks:

“*…the general operational assessment is that spills in winter are unlikely for the following reasons:*

• When vessel traffic continues through an extended season, tracks are established by preceding ships, so the risk of collision or grounding is less.

• Vessels moving through ice are not able to move at high rates of speed; they are not able to move out of their tracks with ease; and when they do start to get out of the track, it is relatively easy to stop them because of the friction effect of ice.

• There are fewer vessels operating and they generally operate with an escort when they are in difficult waters.

• With lake waters covered or largely covered by ice, the effects of wind and waves are considerably reduced, and ice between ships tends to serve as a buffer to keep vessels away from danger."

2.3.2 Ice Climatology

While it is not a primary objective of this research, understanding the seasonal trends and year-to-year variability of ice coverage across the Great Lakes provides important context for interpreting historic ship ice operations in the region. For instance, when considering specific instances of ship operations in heavy ice conditions, it is helpful to know if the operator was anticipating encountering such conditions when route planning or if it was an operational decision to continue through heavier-than-desired conditions. On a broader scale, an understanding of the locations and predictability of problem areas for ice build-up in the lakes provides context for the overall distribution of ship traffic. When comparing the incidence of ship operations in highly negative RIOs to the distributions of ship traffic and ice coverage in the lakes, possible discrepancies could highlight the need for further investigation. This could identify potential gaps in the analysis, such as an inaccurate approximation of historic local ice conditions versus the archived ice chart data, or unconsidered risk mitigating factors such as icebreaker assistance.

Several works are considered here regarding trends for ice coverage within the Great Lakes region, including a number produced by the NOAA Great Lakes Environmental Research Laboratory and affiliated authors. The first of these to be discussed in detail is "*Classification of Annual Great Lakes Ice Cycles: Winters of 1973-2002*" by Raymond Assel, which was published in the Journal of Climate in 2005. Based on the overall progression of daily ice coverage across individual lakes and the entire Great Lakes region, it classifies each yearly ice cycle as mild, typical, or severe over the 30-year period. Overall, it concludes that Lake Erie has the longest typical ice season and greatest mean coverage, followed by Lake Huron and Lake Superior. Lake Erie and Lake Huron's relative severity is largely attributed to their shallow depths compared to the other lakes. In the case of Lake Erie, it also experiences the largest variations in ice cover between mild versus severe ice cycles, which is attributed to increased sensitivity to interannual variability in air temperature due to its especially shallow depth. The second largest variability in ice coverage between mild to severe ice cycles can be seen in Lake Superior. Despite being the deepest of the lakes, is said to usually develop extensive ice cover that can last late into the ice season due to exposure to the lowest winter air temperatures in the region. However, its depth and resulting heat capacity precludes the development of extensive ice cover during milder winters. Lake Ontario and Lake Michigan are of middling mean depth and experience consistently mild winters. As a result, they see both the lowest seasonal averages and lowest variability of ice cover extent. This study also notes that over half of the mild ice cycles seen during the 30-year study were during its last 5 years, between 1998-2002. It projects that in future years, a new "typical" ice cycle would likely match the "mild" ice cycles more closely than the "typical" ice cycles described in the current paper.

The next work, titled "*Temporal and Spatial Variability of Great Lakes Ice Cover, 1973-2010,*" includes an analysis that is of similar scope to Assel's over an expanded timescale. The primary author of this work is Jia Wang, and it was published in the Journal of Climate in 2012. While their methodology is similar to Assel's, its objective is largely shifted from defining the severity ranges for typical ice cycles to characterizing the interannual variability and predictability of ice cycles in the lakes within the context of the driving meteorological factors. Overall, it concludes that all lakes in the region experience similar seasonal variations in ice cover, albeit with timing differences given that ice formation within the shallower lakes (Lake Erie followed by Lake Huron) reaches its maximum earlier in the season than for the other lakes under similar environmental conditions. The overall seasonal variability of ice cover extent in the lakes is very high, leading to poor predictability of the severity of a given season's medium to long term ice conditions. It also notes a significant downward trend in total lake ice cover, reinforcing the earlier predictions by Assel. During the 38-year period, a 71% loss in average ice coverage across the entire region was seen. This loss was strongest in Lakes Ontario, Superior, and Michigan, and was smallest in Lake Erie and the adjacent Lake St. Claire, which have historically produced the most hazardous ice conditions in the region and likely continue to do so into the current studied period.

A number of other works by Assel and Wang (among other colleagues from the NOAA Great Lakes Environmental Research Laboratory) were also reviewed that largely cover the same topics relating to the ice climatology of the Great Lakes region and the classification of ice cycles. Some of these discuss additional year ranges but are otherwise similar in content and findings. Others discuss topics such as driving factors behind the observed trends in ice climatology, which is tangential to the present research.

In addition to the more recent research discussed above, while it is an older work, the 1979 U.S. Army report "*Final Survey Study for Great Lakes and St. Lawrence Seaway Navigation Season Extension*" (that was previously described) provides a highly detailed analysis of the ice conditions found throughout the Great Lakes region and in particular its relevance to ship operations. Volume 2, Appendix A of this report ("Problem Identification") specifically includes a comprehensive description of typical and potential ice conditions that may be seen in various distinct and notable subregions across the lakes. This is especially helpful for interpreting historic ship operations in the region, as its objective is to highlight the potential impact on ship navigation posed by hazardous ice conditions. Although this report is somewhat outdated and may not fully reflect the current climate of the Great Lakes region (given the trend towards less severe winters in recent decades as indicated by Assel and Wang), the level of detail described here is still useful as a means of characterizing "worst-case scenario" ice conditions that still mimic the most severe winters seen in recent years (such as the 2014 and 2015 ice seasons) and potential severe winters in future seasons. It is also useful for identifying problematic subregions within the lakes and provides insight into the underlying processes that produce particularly hazardous ice conditions in certain subregions. Even if the overall severity of winters in the region is decreasing, the factors that produce these hazardous conditions (such as downstream pile-ups of ice during spring break-up) likely remain and will continue to produce the lake's most hazardous ice conditions in upcoming years, and in some cases these factors could even be exacerbated by milder winters.

In addition to the existing works discussed in this section, an original analysis of the ice conditions seen within the Laurentian Great Lakes during the studied period was also performed for this research. This analysis is based on the Canadian Ice Service's digital ice chart archive for the Great Lakes region for ice seasons between 2010 to 2019 using methodologies similar to those used by

Assel and Wang. The Canadian Ice Service yearly summary reports for these ice seasons were also reviewed to provide context for the analysis of this data. The findings of this analysis are detailed in Chapter 4.

2.3.3 Freshwater Lake Ice versus Sea Ice

There are significant differences between sea ice and lake ice that complicate the use of existing methodologies such as POLARIS for freshwater operations in the Great Lakes. It should first be noted that ice is a highly complex natural material and details of the underlying processes that influence its macroscopic material properties during ice-structure interactions are not yet fully understood. Since the failure of ice (at scales relevant to ship operations) is largely governed by difficult-to-predict large-scale flaws and deformities, many of the engineering properties used to predict the behavior of ice have been determined empirically by way of a combination of full-scale field experiments and laboratory testing. Regulations and guidelines for ice-class ship design and ship operations in ice are based on a combination of this empirical data as well as past operator experiences and statistical analysis of historic ship operations in ice. This section is intended to provide a brief overview of some of the underlying processes and micro-mechanical behaviour which are known to influence the differences in properties between freshwater and saline ice. Further description of the complexities involved in these processes is outside the scope of this work, given that it is not directly relevant to existing regulations based primarily on empirical data.

The most apparent difference between the two ice types is the result of a significantly higher presence of salts and other dissolved solids in seawater versus that of freshwater lakes. While pure water freezes completely at 0ºC (at 1atm atmospheric pressure), dissolved salts will reduce its freezing point based on their concentration. Seawater at typical salinities of around 35% will begin freezing at approximately -1.8ºC (at a pressure of 1 atm). However, a given sample of seawater will not freeze completely at this temperature due to the complexities involved in the freezing process of a brine solution. The majority of dissolved salt ions in a brine solution do not get incorporated into the solid crystal structure of ice during initial freezing as water first crystallizes. On a micro-mechanical scale, seed crystals of pure ice first form and grow independently when seawater first approaches its freezing temperature. As these crystals grow, they float and consolidate at the surface as a layer of new ice consisting of frazil ice, grease ice, slush or shuga. During this consolidation, individual ice crystals at different orientations grow and meet each other until they become locked into stable configurations. As freezing continues downward, the dissolved salt ions that are not incorporated into ice's crystal structure become trapped within pockets of increasingly concentrated brine along grain boundaries. Within newly frozen sea ice, the total amount of salts contained within each isolated brine pocket is static. In turn, this results in an equilibrium relationship between brine pocket volume (the porosity of ice) and temperature, as the freezing point of the remaining liquid brine has an inverse relationship with the pocket's brine concentration. It thus follows that brine pockets will continue to freeze around their edges until the increased salt concentration of the remaining brine solution further reduces its freezing point to match its current temperature. If the temperature later changes, the total volume of brine pockets within sea ice will grow or shrink accordingly until their salt concentrations are in equilibrium with their temperature(s).

As a result of this process, the networks of liquid brine pockets within first year sea ice increase its porosity and decrease its mechanical strength compared to solid freshwater ice. Its mechanical properties are also more dependent on ambient temperature than freshwater ice, given the relationship between ice porosity and temperature in the presence of liquid brine pockets. However, as sea ice ages, its trapped salt content decreases due to brine migration out of the ice.

This can be the result of several known mechanisms. For instance, when air temperatures warm and approach or exceed 0ºC, neighbouring brine pockets can connect through melting, thus forming channels that allow liquid brine to flow out of the ice. Additionally, cyclic temperature changes at cooler temperatures can cause individual brine pockets to migrate through the ice. Repeated freeze-thaw cycles will cause this gradual migration as freezing and thawing within brine pockets tends to occur asymmetrically along the direction of the temperature gradient. Due to these processes, multi-year sea ice older than two years is typically assumed to have little to no brine content and is known to be correspondingly stronger than first-year sea ice (Timco & Weeks, 2010). As such, guidelines for ship operations in sea ice are largely based on the potential presence of multi-year ice which would govern the maximum expected loads. For a more detailed description of ice properties and behaviour, one may refer to *Creep and Fracture of Ice* (Schulson & Duval, 2009).

While the aforementioned processes suggest that lake ice may most closely match the properties of multi-year sea ice, and correspondingly that that guidelines for ship operations in ice-covered freshwater environments should reasonably reflect that for ship operations in the presence of multi-year sea ice, other factors further complicate the translation. Sea ice, and specifically multi-year ice that has survived at least one summer, has been known to achieve significantly greater thicknesses than the typical maximum for lake ice (specifically in the Great Lakes region). In addition, multi-year sea ice can include remnants of reconsolidated features of broken ice (such as ridges) that can reach significantly greater thicknesses than that which can be achieved through the natural growth of level, unbroken ice in any environment. As a result, multi-year ice typically fails by crushing rather than flexure and represents a more extreme design condition.

This issue is further compounded when considering how ice thickness is conflated with stage-of-development in WMO nomenclature and the guidelines which use it, such as the POLARIS methodology (U.S. National Ice Center, 2020). For instance, POLARIS includes only two RIV categories for multi-year ice: Heavy Multi Year Ice, and Light Multi Year Ice, less than 2.5m thick (IMO, 2016). Meanwhile, the thickest lake ice stage-of-development used by the Canadian Ice Service (from whom historical ice condition information was obtained for this study) is Very Thick Lake Ice, which includes all lake ice greater than 70cm (Canadian Ice Service, 2016). While the fundamental material properties of lake ice may more closely match multi-year sea ice, the maximum expected loading conditions it can produce is not translatable from multi-year sea ice with such a large difference in thickness.

In addition to the effects of salinity on the porosity of ice, differences in the formation environment can also affect the microstructure of ice and thus its macroscopic properties. Given the significant differences in the environments within which sea and lake ice form, this may be an additional contributing factor and uncertainty surrounding differences between the two ice types. For instance, under ideal conditions, undisturbed ice typically grows in a columnar grain structure. Due to its crystalline geometry, ice crystals have a higher growth rate along their basal planes versus the direction of their crystallographic axes. After the roughly plate-shaped seed crystals of new ice consolidate into a rigid structure, further downward freezing will occur only at grains locked into the solid structure at the exposed lower surface of the ice. Those grains with their crystallographic axis oriented perpendicular to the water's surface will most quickly grow downward. These grains typically grow together and block further downward growth by grains aligned in significantly different orientations. If undisturbed, continued downward growth would occur primarily along continuous columns of these grains. However, disturbances during freezing such as wave action or turbulent ocean conditions can alter or prevent the development of this idealized grain structure. Breakup and reconsolidation could reorient the grain structure of what was initially columnar ice, and environmental conditions such as temperature, air bubbles, or impurities in the water can affect additional factors such as the number and growth rate of initial seed grains, and thus average grain size.

In practice, columnar ice possesses orthotropic properties not seen in granular ice, such as decreased flexural strength around the growth axis but increased compressive strength along it (Timco & Weeks, 2010). It follows that grain structure has a significant effect on the limiting factors which govern the large-scale failure processes of ice, resulting in significantly different peak loading conditions under alternative modes of failure (ie: crushing versus flexural failure and deflection).

On a larger scale, floe size and the form of ice are also affected by the surface conditions beyond this initial formation process. In general, it can be expected that larger undisturbed floe sizes are more likely in calmer environments. While calmer formation conditions are expected freshwater ice, it is difficult to generalize as there are regions within very large bodies of fresh water such as the Great Lakes which more closely mimic ocean surface conditions than typical freshwater environments. As stated above, the most hazardous sea ice features (aside from glacial ice remnants) result from the breakup and reconsolidation of sea-ice rubble. This can produce ridges and other ice features which reach extreme thicknesses that greatly exceed the maximum growth extent possible for undisturbed columnar ice. While multi-year ice does not occur in the Great Lakes, pile-ups and ridges of freshwater ice that appear superficially similar to these sea ice hazards are known to occur, especially in problem areas such as the St. Clair River and Lake Erie during spring break-up (U.S. Army Engineer District Detroit, 1979).

With these considerations in mind, it is very difficult to directly adapt guidelines for operations in sea ice to a freshwater lake environment purely on the basis of the differing material properties between sea and lake ice. Due to the complex mechanical behavior of ice, which is difficult to fully model or to replicate in a lab environment, many guidelines for ice operations are themselves heavily governed by a combination of full-scale data and operator experience. As such, it is reasonable that translating these guidelines to a freshwater environment should start with an overview of the available empirical evidence of historical ship operations in these environments, with additional consideration being given to the known property differences between freshwater and sea ice in future studies.

2.4 Data Sources

2.4.1 Ship Automatic Identification System (AIS)

The primary data source used for the analysis of ship operations in ice was an archive of historic AIS records for ships operating in the North American Great Lakes region for winter seasons between 2010 and 2019. AIS stands for Automatic Identification System, and it is a standardized automatic ship tracking system. It is required by IMO for all international voyaging ships greater than 300 gross tonnage and all passenger ships of any size (IMO, 2015) (IMO, 2003). AIS involves the use of shipboard Very-High-Frequency (VHF) radio transceivers that regularly broadcast information including ship identification (callsign, name, and unique IMO identification number), geographic position, course, speed, and other information. These transmissions are picked up by AIS receivers, which can be installed onboard other ships, by port authorities or other shore-based facilities, and increasingly by satellite. Traditional AIS receivers are limited by the VHF range of approximately 10 to 20 nautical miles (IALA, 2016). In recent years, AIS coverage has been expanding beyond the range of shore-based stations through satellite receivers which use a modified version of the technology.

The intended purpose for AIS is to aid in ship navigation and to supplement marine radar for collision avoidance and route planning. However, several internet-based service providers have emerged which aggregate global AIS data obtained through internet-connected shore-based stations and increasingly by satellite receivers to provide live (and archived) coverage of AIS broadcasting ship traffic. One of these services, Vesselfinder.com, was used to obtain the historical AIS records used for this analysis. While the original intent for shipborne AIS was to aid in navigation and coordination of local ships for increased safety, this data has been increasingly used in the years since its implementation for unanticipated research opportunities involving ship traffic (such as the present analysis) and operational innovations such as live route planning (Fiorini, Capata, & Bloisi, 2016).

During the initial implementation of regulations requiring the use of AIS by IMO, there were some concerns by vessel operators regarding the availability of AIS data online and how its misuse might hamper IMO's original intent for these regulations to improve collision avoidance and thus vessel safety (IMO, 2004). To address these concerns, IMO largely condemned the freely available live broadcasting of AIS data.

The relevant statement quoted below remains on the IMO webpage on AIS transponders at the time of this publication, found at https://www.imo.org/en/OurWork/Safety/Pages/AIS.aspx. As follows:

"At its seventy-ninth session, in December 2004, the Maritime Safety Committee (MSC) agreed that, in relation to the issue of freely available automatic information system (AIS)-generated ship data on the world-wide web, the publication on the world-wide web or elsewhere of AIS data

transmitted by ships could be detrimental to the safety and security of ships and port facilities and was undermining the efforts of the Organization and its Member States to enhance the safety of navigation and security in the international maritime transport sector.

The Committee condemned the regrettable publication on the world-wide web, or elsewhere, of AIS data transmitted by ships and urged Member Governments, subject to the provisions of their national laws, to discourage those who make available AIS data to others for publication on the world-wide web, or elsewhere from doing so."

At first glance, this statement appears to condemn the use of AIS data for research such as this work, and in fact for any purpose that does not directly use it for its intended purpose of aiding navigation. However, further investigation indicated that these concerns were largely motivated by a potential increased risk of piracy involving the live tracking of commercial ships (Ellison B. , 2009). Some secondary concerns may be related to the potential for AIS data to compromise commercial contracts by allowing production and shipping numbers to be inferred through vessel tracking (Riviera Newsletters, 2015). Neither of these motivations seem to preclude the use of historic AIS data for the present research relating to the applicability of IMO sea ice regulations to lake ice within the Great Lakes.

However, these concerns relating to the requirement of AIS broadcasting could have secondary implications on navigational safety (or the use of historic data for research purposes) if it they would motivate ship operators to falsify their broadcasted AIS data. While authors have raised such issues as potential concerns, there is no evidence of any actual such issues with the data, and it can be assumed that all vessel transits across the region are accurately tracked and verified during the vessel's use of locks and canals.

2.4.2 Ice Charts

To publish and archive regional ice condition information, many organizations worldwide today use WMO terminology, and a standardized digital charting format known as SIGRID-3. SIGRID-3 evolved from earlier SIGRID formats (originally an acronym for Sea Ice GeoReferenced Information and Data) and was developed by WMO in cooperation with various organizations that use and publish ice chart information (WMO, 2004). The organizations most involved in the development and use of this format include the Arctic and Antarctic Research Institute, Russia's AARI, the Danish Meteorological Institute (DMI), the U.S. National Ice Center (NIC), and the Canadian Ice Service (CIS), whose digital ice chart archive was used for this work's analysis of ship operations in the Great Lakes.

SIGRID-3 is a vector-based format intended to be suitable for automated processing. It encodes regional ice condition information in a "shapefile" file format which is accompanied by a header file containing metadata such as the map projection. Ice chart information within a shapefile is defined by polygons which represent subregions comprising the total chart area. Each polygon represents a geographic feature and consists of a list of geographic coordinates as vertices defining its outline as well as a set of attributes based on the feature type (classified as either land, ice-containing water, or open water). Ice within ice-containing regions is primarily defined by distinct ice types with their own partial concentrations, stage of development, and form (U.S. National Ice Center, 2020).

This system for defining ice characteristics corresponds to WMO's "egg-code" system commonly used to describe and manually interpret ice charts. An example of an egg-code as used by Canadian Ice Service is shown below in Figure 2-1.

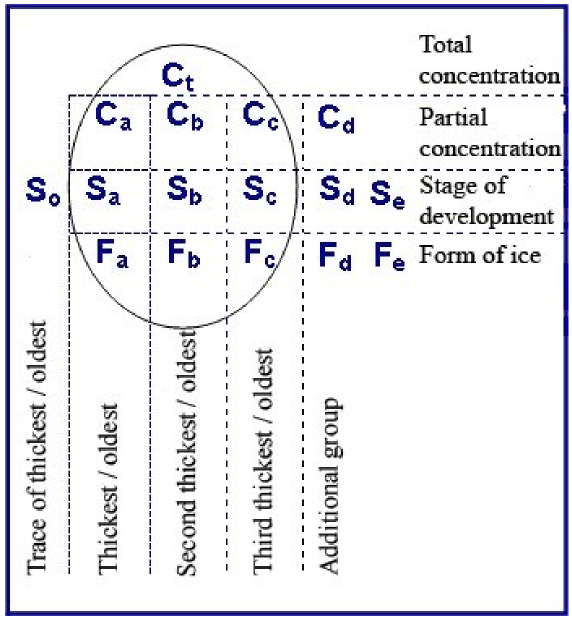

Figure 2-1: Guide to interpret egg codes as used for Canadian Ice Service ice charts (Canadian Ice Service, 2016).

An egg code is used to describe a particular ice-regime using three parameters for each ice type present: Partial Concentration, Stage of Development, and Form. This is because the ice regime contained within the region described by an egg code may contain multiple distinct ice types. These ice types each have their own respective partial concentrations that summate to the total ice concentration in the region. The "total concentration" parameter within egg codes represents the ratio of ice coverage to water in tenths by area. Stage-of-development roughly corresponds to ice of different thickness ranges, ranging from newly formed ice/slush to first year sea ice of increasing thickness to multiyear ice. Form is most frequently used to define average floe sizes. However, it may also be used to describe ice forms such as fast ice or ice of land origin (such as icebergs). Other (local) ice features such as ridges or hummocks are typically not represented in this format.

Chapter 3:

Methodology

3.1 Overview of Data Processing Procedure

This chapter is intended to provide a detailed walkthrough of the procedure and techniques used to perform the presently discussed analysis of historic ice class ship operations in the freshwater North American Great Lakes. Logically, this starts with a brief overview of the main data sources that were used and how the required information was extracted from them.

To reiterate, the primary purpose of this work is to assess the historical operations of these ships operating within the Great Lakes within the context of regulatory guidelines intended for seafaring ships transiting through comparable sea ice conditions (the Polar Code). This was achieved by retroactively applying the Polar Code's POLARIS methodology to verifiable instances of ice class ship operations in the region that involved transits through ice-covered waters. POLARIS is an index-based methodology intended to provide clear guidance to ship operators when transiting through a particular *ice regime* (an ice-covered region within navigable water, which contains relatively uniform ice conditions that can be described using partial concentrations of ice types that fall within particular thickness range categories) (Canadian Ice Service, 2016). This methodology requires two key pieces of information to perform the calculations it uses to assess a ship's operational capability in specific ice conditions: the ship's ice class and a breakdown of the ice regime present in the immediate vicinity of the ship.

The original data sources used to obtain this information include Canadian Ice Service's (CIS) digital ice chart archive and a collection of AIS records for ship traffic in the region from 2010 to 2019 that was obtained from Vesselfinder.com. Aside from some manual filtering and validation, the vast majority of data processing described in this chapter (as well as later analysis of this data in Chapters 4 and 5) was implemented using MATLAB R2020b, of which some excerpts are included in Appendix B.

The first step in data processing was to prepare an index of all available CIS ice charts that were published during the studied period. Using this index, the most suitable ice chart (if any) for a given timestamp could be quickly determined. From here, MATLAB code was written that could extract and parse the CIS reported ice conditions at a set of Lat-Lon coordinates from the most appropriate chart for a provided timestamp.

To perform the ship traffic analysis using the AIS dataset, several rounds of filtering were first necessary. The dataset was initially filtered to remove records that were clearly unsuitable for analysis, such as those outside the geographic bounds of the available ice charts. Following the initial filtering of the dataset, ice conditions were extracted from the CIS ice chart archive corresponding to each individual remaining AIS record's Lat-Lon coordinates and timestamp. This was followed by additional filtering which was primarily based on the presence of ice.

A list of unique ships in the fully filtered dataset was then compiled based on their IMO identification numbers included in the AIS records (to account for potential name and operator changes). Each unique ship found in the dataset was then investigated using a number of online resources to determine whether or not it had a verifiable ice class. For the remaining AIS records of all ships with a confirmed ice class, POLARIS RIO values were calculated using the POLARIS RIVs corresponding to their ice class and the ice conditions for each record as taken from the CIS chart archive. Statistical analysis was performed on the resulting archive of RIO values, which is described in detail in Chapter 5. A flowchart detailing this data processing workflow can be found in Figure 3-1

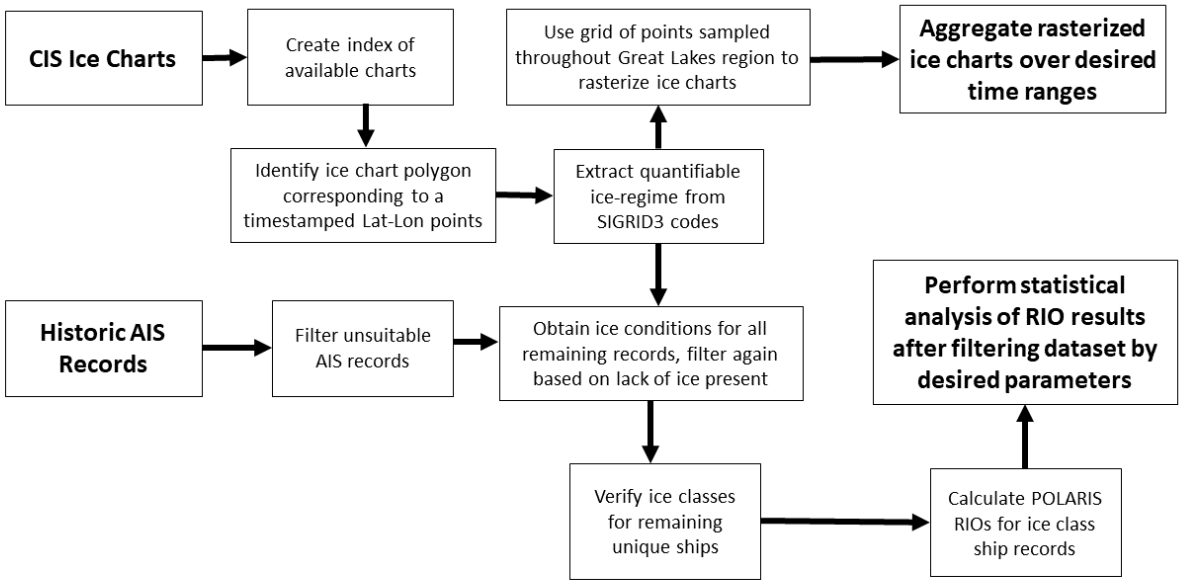

Figure 3-1: Flowchart depicting the data processing workflow.

3.2 Methodology for Estimation of Historic Ice Conditions

3.2.1 Extraction of Ice Conditions from CIS Ice Charts

The ice condition information used for this analysis was extracted from daily ice charts obtained from the Canadian Ice Service (CIS) digital chart archive for the Great Lakes region. These charts are published in the SIGRID-3 Shapefile format using WMO terminology, and within the archive each published chart is saved as a zip file. The data contained within ice chart Shapefile describes a number of polygons that comprise the total chart area. These polygons represent regions that are classified as either *ice*, *open-water*, or *land*.

Each SIGRID-3 polygon describes an ice-chart region that is assumed to have uniform properties. When imported into MATLAB for analysis, it is formatted as a structure with fields that describe the polygon's boundary, area, and various other attributes. The most important of these are two-digit enumerated codes (ranging from 00 to 99) that are used to describe the partial concentration, stage-of-development, and form (ie: floe size) of any ice types present throughout ice-containing regions. These codes typically have egg-code analogues that are used for ice charts published in non-digital graphical formats. The SIGRID-3 enumerated values for ice properties tend to be similar but not identical to their egg-code counterparts. For instance, the digital code '85' corresponds to an egg code of 5 when used to describe stage-of-development, '84' corresponds to 4, and so on. Egg codes for concentration tend to be single digit values in tenths, whereas in SIGRID-3, most concentration enumeration values correspond to a concentration in percent. Some exceptions include the enumerations '92' (for ten-tenths concentration) and '01' (for trace ice, or 0.1 tenths or less). In practice, only whole-number tenths (and occasionally 9.5) are used on CIS digital ice charts, as they mirror the CIS graphical charts that use egg codes to describe ice conditions (WMO, 2010). As this analysis is limited to the available ice chart information, it assumes unbroken level ice, and does not consider degraded ice conditions, rubble buildup or ridging effects, and unreported local variations in ice conditions such as broken-ice shipping lanes or icebreaker escorts.

To obtain ice conditions from a given chart within this dataset, it was necessary to prepare an index of the archive's available ice charts. CIS ice charts are typically published daily, though there are occasional gaps of up to 3 days. For the analysed AIS data, the mean absolute difference between each AIS timestamp and the publication of the nearest ice chart was approximately 0.3 days, with the largest gap being 2.5 days. Presumably due to later revisions, multiple versions of the same chart were published on some days. This required manual review to determine the most appropriate chart and the omission of duplicates or alternate versions from the index.

Using this index, it was possible to write MATLAB code that could extract and parse the CIS reported ice conditions at a set of Lat-Lon coordinates from the most appropriate published chart for a provided timestamp. This code first extracts the ice chart from the zipped archive and loads the extracted SIGRID-3 Shapefile into MATLAB as a *struct*. Not all ice charts within the archive use the same coordinate system to define polygon boundaries: many are saved in a Lat-Lon format, but some use an X-Y coordinate system specific to the ice chart. For these charts, it was necessary to check whether the zipped Shapefile contained a projection file, which would then be used to convert the boundaries of all contained polygons to a standardized Lat-Lon notation. Once all polygons are in a Lat-Lon format, the code would iterate through the *struct* to determine which SIGRID-3 polygon contains the sampled Lat-Lon coordinates. This polygon is then parsed to interpret the SIGRID-3 codes for the relevant ice condition information used for POLARIS (partial concentration for each ice stage-of-development present). This interpreted ice regime is then returned in a more portable custom data structure that could more easily be used for later analysis than the unprocessed Shapefile polygons.

3.2.2 Generation of Regional Ice Condition Distributions

A secondary analysis was conducted to characterize the ice climatology of the region during the studied period. This analysis was intended to provide additional context for the ship traffic analysis and distribution of calculated RIO values.

To do so, ice chart data was extracted using the MATLAB code described above at each location in a dense grid of points sampled throughout the Great Lakes region. The spatial resolution of these points varies by subregion based on manually determined densities that were sufficient characterize potential differences in ice conditions along each subregion's shoreline. Data for these points was taken daily from the nearest published ice chart, up to a maximum difference of three days (which was the maximum gap between chart publications seen within an ice season over this period). Open water was assumed for all points on days when there was no chart published within this timeframe. Similarly, open water was assumed for points contained within "water" polygons on the nearest ice chart, or within "ice" polygons containing only trace amounts of ice (defined by a total ice concentration less than 1/10).

Two parameters were used to generate the distributions illustrated in Chapter 4. The first parameter, "*Probability of Ice Present*", was calculated for each point as the percent ratio of days that a given point contained ice at 1/10 or higher concentration to the total number of days in a specified period. This is intended to be used in conjunction with the second parameter, "*Mean Equivalent Thickness*." This parameter is based on an Equivalent Thickness value which is given by the summation of the partial concentration of each ice type present in an ice regime by the median thickness of the thickness range encompassed by each ice type. This calculation also includes open water using a partial concentration given by 10 – Total Ice Concentration with a thickness of 0 cm. The "*Mean Equivalent Thickness*" for a given point is its daily averaged Equivalent Thickness over the days it contained at least a 1/10 or greater total ice concentration. Combined, these two parameters are intended to convey the probability a ship would encounter ice at a given location and the expected severity of ice conditions at that location should it encounter ice.

Table 3-1: CIS Lake Ice Stages-of-Development and corresponding median thicknesses.

CIS Stage-of-Development for Lake Ice	Thickness Range	Median Thickness
New Lake Ice	< 5 cm	2.5 cm
Thin Lake Ice	5 – 15 cm	10 cm
Medium Lake Ice	15 – 30 cm	22.5 cm
Thick Lake Ice	30 – 70 cm	50 cm
Very Thick Lake Ice	> 70 cm	100 cm*

*Estimated based on available literature (U.S. Army Engineer District Detroit, 1979)

3.3 Methodology for Ship Traffic Analysis

3.3.1 Description of AIS Dataset

In order analyze freshwater ice operations in the region and to assess current operational practices, an archive of historical AIS records for ships operating in the North American Great Lakes region for ice seasons between 2010 and 2019 was obtained from vesselfinder.com. This initial dataset comprised a total of 262,945 individual AIS records.

A limitation that should be noted of the AIS dataset obtained from vesselfinder.com is that it is not necessarily comprehensive of all ship traffic within the defined region and period due to limitations of the technology. Historic AIS records are limited by the historical AIS coverage of the service's archives. During the studied period, AIS coverage by Vesselfinder.com increased significantly in the Great Lakes region, primarily due to the addition of satellite AIS receivers which greatly expanded the coverage beyond that available purely from shore-based facilities. This resulted in an increased number of historic AIS records for recent years versus earlier years in the study, which should not be misinterpreted as increased ship traffic in the region.

While this limitation precludes direct year-to-year comparative analysis of overall ship operations in the region, the dataset is still sufficient to characterize most transits of individual ships across the Great Lakes. The dataset includes a large quantity of records for analysis that each contain timestamped Lat-Lon positions of known ships within the lakes that to that could be cross-referenced with archived historic ice conditions. Additionally, while AIS navigational data is typically broadcast every 2 to 180 seconds, and other voyage data at 6-minute intervals, the archived AIS dataset obtained from Vesselfinder.com contains data that was sampled hourly. While the present analysis only includes ship records within the archive, there is room for later analysis to further characterize specific instances of historic ship-ice interactions by approximation of transit routes through interpolation between archived AIS records. Alternatively, the archive could be expanded with additional AIS records taken at a higher sampling frequency or from alternative AIS record archives.

The original AIS dataset was first filtered to remove records that were clearly unsuitable for analysis. This included records that were outside the geographic bounds of the CIS ice charts, records from dates with no suitable ice chart in the index (typically immediately before or after a year's ice season), and records where ships were stationary (with speeds equal or less than 0.1 kts). Records describing stationary ships were omitted from the study to focus only on the operations of ships in transit. For detailed consideration of individual cases where ships were trapped in ice during transit, the impact on operations could still be inferred from manual analysis of the proceeding and subsequent AIS points and differences in reported speeds versus the actual time elapsed between points.

Following the initial filtering of the dataset, ice conditions were extracted from the CIS ice chart archive corresponding to each individual AIS record's Lat-Lon coordinates and timestamp. CIS ice chart shapefile polygons are classified as either *ice*, *open-water*, or *land*. Any AIS records contained within *land* polygons, such as ships transiting a canal or locks, were omitted from the study. A substantial portion of the remaining AIS records described ship operations in *open-water* polygons due to variation in year-to-year ice season duration and regional variation in the distributions of ice throughout the lakes. For the analysis of ship traffic, only AIS points within *ice* polygons were considered for statistical analysis of historical ship operations. This also encompasses trace ice conditions, where CIS provides an ice concentration of 0.1 tenths (occasionally without a corresponding ice type). In total, 139,287 AIS records corresponded to open water conditions. These were removed from the dataset, leaving 123,630 records for ice operations.

A list of all unique ships with AIS records in the remaining AIS dataset was then compiled. Any ships in this list with no records within regions containing 1/10 or greater ice coverage were highlighted. To produce the final AIS dataset used for analysis, all records for these ships were then removed, as they were assumed for be transiting the lakes at times or locations where ice was not a relevant navigational hazard. In total, 390 unique ships were identified that have operated in ice conditions with 1/10 or greater coverage.

3.3.2 Verification of Ship Ice Classes

To analyze ship operations using the POLARIS methodology, it was necessary to verify the ice-class (or lack thereof) of ships known to have operated in the region within the studied timeframe. Comparison of ship operations to POLARIS recommendations could only be performed for this subset of ships that were verified to possess (or lack) an ice class outlined within the POLARIS methodology.

Due to the multi-national nature of shipping operations in the Great Lakes and the lack of a universally adopted ship registration or ice classification system, this was not a straightforward task. The identified ships operate out of various jurisdictions worldwide, and under different classification or registration societies, each with differing degrees of publicly accessible information and their own ice class notations. The closest thing currently available to a comprehensive and publicly accessible database for this information was equasis.org, which provides links to registration society pages for the ships within its database.

Ice-class information was investigated on a ship-by-ship basis for all unique ships (as per ship-specific IMO identification numbers) with AIS records in the final filtered dataset (ie: the subset of ships that experienced ice conditions with 1/10 or greater coverage). The most success was found through classification society information available via equasis.org. For ships that were not indexed there, some larger operators had publicly available datasheets for their fleets that contained ice class information. Others were verified through news publications and hobbyist websites such as boatnerd.com, which was especially helpful for cases when ships changed names or owners, as there were some instances of this occurring within the studied timeframe.

Of the identified ships, 114 were verified to have a POLARIS ice class, while 14 others possessed alternative ice classes and the remaining 262 were either unclassed, could not be verified, or possessed an ice class lower than the lowest outlined within POLARIS ("IC"). While no Polar Class ships were identified in these data, five Canadian Coast Guard ships and four US Coast Guard ships were identified with comparable icebreaking capabilities to Polar Class ships. The final subset of the dataset corresponding to ice operations of transiting POLARIS ice class ships consisted of 15,072 records.

3.3.3 Calculation of POLARIS RIO Values

The POLARIS methodology defines the use of Risk Index Outcome (RIO) values as a means of providing operator guidance relating to a ship's expected operational capacity in specific ice conditions. When applying the POLARIS methodology, a ship is assigned a Risk Index based on its ice class. This Risk Index defines an appropriate set of Risk Index Values (RIVs) that correspond to the relative level of risk posed by the different stages of sea ice used by POLARIS. The table of Risk Indices contained within the POLARIS methodology is shown in Table 3.2.

Table 3-2: Original table of POLARIS RIVs for sea ice (IMO, 2016).

Ice Class	Ice-Free	New Ice	Grey Ice	Grey-White Ice	Thin First Year Ice, 1st Stage	Thin First Year Ice, 2nd Stage	Medium First Year Ice, less than 1 m thick	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Light Multi Year Ice, less than 2.5 m thick	Heavy Multi Year Ice
PC1	3	3	3	3	2	2	2	2	2	2	1	1
PC2	3	3	3	3	2	2	2	2	2	1	1	0
PC3	3	3	3	3	2	2	2	2	2	1	0	-1
PC4	3	3	3	3	2	2	2	2	1	0	-1	-2
PC5	3	3	3	3	2	2	1	1	0	-1	-2	-2
PC6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
PC7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
IA Super	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8
Not Ice Strengthened	3	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-8

A ship's RIO value for a given set of ice conditions (an ice regime) may then be calculated by the summation of the concentration (in tenths) of each ice type immediately surrounding a ship multiplied by the ship's corresponding RIVs for each ice type (IMO, 2016). This equation is shown below:

$$RIO = (C_1 \times RIV_1) + (C_2 \times RIV_2) + (C_2 \times RIV_2) + \dots (C_n \times RIV_n)$$

Where $C_1 \dots C_n$ are the concentrations (in tenths) of ice types within the ice regime; and $RIV_1 \dots RIV_n$ are the corresponding Risk Index Values for each ice type.

When interpreting ice conditions extracted from CIS ice charts for analysis using the POLARIS method, lake ice types were assigned RIVs from the closest first-year sea ice equivalent by thickness within POLARIS, which uses WMO terminology for sea ice types. Most lake ice types have clear sea ice equivalents, and for these lake ice types CIS even assigns the same ice chart egg codes as their sea ice counterparts. However, while the thickness range for *Thick Lake Ice* (30-70cm) best corresponds to *Thin First-Year Ice* (30-70cm), POLARIS only provides RIVs for the first and second stage subcategories with thicknesses of 30-50cm and 50-70cm, respectively. To account for this, RIVs were chosen for *Thick Lake Ice* assuming an even split between the two subcategories. Similarly, POLARIS differs from WMO nomenclature in providing an additional RIV subcategory for *Medium First-Year Ice* (normally 70-120cm) for ice known to be less than 100cm thick. The corresponding lake ice category, *Very Thick Lake Ice*, applies for all lake ice greater than 70cm thick (Canadian Ice Service, 2016). As ice thicknesses in the Great Lakes are known to exceed 100cm (U.S. Army Engineer District Detroit, 1979), RIVs for this category were conservatively taken from the broader *Medium First-Year Ice* category.

Mappings for the chosen ice type equivalencies are shown in Table 3.3, and the proposed modified table of Risk Indices that was used for lake ice in the calculations described by this analysis is shown in Table 3.4.

Table 3-3: Table of equivalencies used to map POLARIS RIVs to CIS lake ice types.

CIS Stage-of-Development for Lake Ice	Equivalent POLARIS Ice Type
New Lake Ice (<5cm)	New Ice (<10cm)
Thin Lake Ice (5-15cm)	Grey Ice (10-15cm)
Medium Lake Ice (15-30cm)	Grey-White Ice (15-30cm)
Thick Lake Ice (30-70cm)	50% Thin First Year Ice, 1st Stage (30-50cm), 50% Thin First Year Ice, 2nd Stage (50-70cm)
Very Thick Lake Ice (>70cm)	Medium First Year Ice (70-120cm)

Table 3-4: Table of proposed POLARIS-like RIVs for lake ice RIO calculations based on POLARIS RIVs for sea ice as per Table 3-3.

Ice Class	New Lake Ice	Thin Lake Ice	Medium Lake Ice	Thick Lake Ice	Very Thick Lake Ice
PC1	3	3	3	2	2
PC2	3	3	3	2	2
PC3	3	3	3	2	2
PC4	3	3	3	2	2
PC5	3	3	3	2	1
PC6	2	2	2	1.5	0
PC7	2	2	2	1	-1
IA Super	2	2	2	1.5	-1
IA	2	2	2	0.5	-2
IB	2	2	1	-0.5	-3
IC	2	1	0	-1.5	-4
Not Ice Strengthened	1	0	-1	-2.5	-5

Chapter 4:

Analysis of Ice Conditions

4.1 Overview

As discussed within the previous chapter, an understanding of the range and severity of ice conditions expected throughout the Great Lakes region during both typical and severe ice seasons is important to provide context when interpreting historic ship ice operations in the region. Given that the ship data used for this research covers the period of 2010 to 2019, a parallel analysis of ice conditions in the lakes over the same period is most directly relevant for assessing the range of ice conditions ship operators expected and chose to operate within.

This chapter provides an original analysis of the ice conditions seen in the lakes during the studied period of 2010 to 2019. The analysis is intended to complement the earlier studies cited which relate to historic ice conditions in the region for prior decades. The latest of these (Wang, 2017) covers the majority of this period, from 2010 to 2017. The methodologies used for the present analysis that discuss *Ice Extent/Percent Ice Cover* and *Ice Season Duration* are similar to that used in the cited studies. However, one notable difference is that these are based on data obtained from NOAA published ice charts, versus the Canadian Ice Service's digital charts that were used for the present analysis.

The analysis presented in this chapter also differs from those studies with its inclusion of *Equivalent Thickness*, which is used to describe ice thickness as a single value parameter for comparative analysis and illustration. It is calculated as the weighted mean thickness of the component ice types within a particular ice regime (multiplied by their respective partial concentrations) and excludes any partial concentration of open water. This was included given the significance of ice thickness in the context of the safety profile of ship operations in ice. Ice thickness is especially relevant when predicting potential hazards posed by ice, whereas previous studies have focused primarily on the relevance of ice cover extent to climatology models.

4.2 Percent Ice Cover

4.2.1 Maximum Ice Cover

Ice conditions in the Great Lakes are known to be highly variable from year-to-year, and so the potential presence of ice along the route of a Winter transit through the lakes is highly dependent on the severity of that specific ice season. One of the earlier cited studies of the region's ice climatology (Assel, 2005) used the analysis of maximum and seasonal progression of ice cover for ice seasons from 1973 to 2002 to characterize the severity of a given season's ice cycle as a mild, typical, or severe ice cycle. This methodology was applied for both the Great Lakes as a whole and for each individual lake. Similar climatology studies were later published for more recent years, although none of which that are currently available include the later years covered by the present analysis of ice seasons from winter 2010 to 2019.

A similar approach to Assel's was taken here for comparative analysis of the relative severity of the ice seasons presently studied. Table 4-1: Maximum ice extent and CIS chart publication date of occurrence within each Great Lakes region for ice seasons from winter 2010 to 2019. below outlines the seasonal maximum ice extent (in percent ice cover over the corresponding region) by region and the CIS chart publication date at which it occurred. When multiple ice charts highlighted the same maximum ice extent (ie: 100% ice coverage), the median publication date was chosen.

Table 4-1: Maximum ice extent and CIS chart publication date of occurrence within each Great Lakes region for ice seasons from winter 2010 to 2019.

Ice Season	Overall Great Lakes	Upper St. Lawrence River	Lake Ontario	Lake Erie	St. Clair River to Detroit River	Lake Huron	Lake Michigan	Lake Superior
2009 - 2010	31.5% Apr 17	100.0% May 10	14.3% Apr 10	97.5% May 25	100.0% Jun 5	39.4% May 27	25.2% May 4	28.6% Apr 24
2010 - 2011	41.8% Jan 31	100.0% Feb 19	32.3% Feb 24	100.0% Jan 31	100.0% Jan 28	66.2% Feb 24	29.2% Feb 3	30.9% Mar 31
2011 - 2012	12.5% Mar 5	99.6% Mar 5	2.4% Jan 16	10.2% Jan 26	74.3% Feb 16	24.5% Mar 5	13.2% Mar 5	9.9% Feb 20
2012 - 2013	41.3% Feb 18	100.0% Feb 19	21.2% Feb 11	87.3% Feb 11	100.0% Jan 28	50.6% Feb 18	26.0% Feb 18	37.2% Feb 18
2013 - 2014	95.6% Mar 6	100.0% Mar 1	63.4% Mar 6	100.0% Feb 11	100.0% Jan 28	100.0% Feb 23	96.4% Mar 5	100.0% Feb 25
2014 - 2015	92.3% Feb 28	100.0% Feb 14	85.9% Feb 18	100.0% Feb 20	100.0% Feb 17	100.0% Mar 1	75.7% Feb 28	100.0% Feb 27
2015 - 2016	30.2% Feb 15	100.0% Feb 20	23.4% Feb 15	79.6% Feb 15	100.0% Feb 17	40.9% Mar 3	23.5% Feb 18	19.5% Feb 15
2016 - 2017	21.4% Mar 14	96.6% Feb 17	6.8% Mar 14	36.7% Feb 8	95.0% Feb 7	37.8% Mar 14	19.3% Jan 18	19.9% Mar 14
2017 - 2018	72.1% Feb 11	100.0% Feb 1	26.4% Jan 17	100.0% Feb 9	100.0% Jan 25	84.7% Feb 11	53.4% Feb 11	80.5% Feb 11
2018 - 2019	84.0% Mar 9	100.0% Feb 14	40.0% Mar 1	98.5% Mar 2	100.0% Jan 30	99.4% Mar 9	57.6% Mar 8	99.0% Mar 8

From this data, it is clear that the degree of ice presence in the lakes is highly variable from year to year. The 2013 – 2014 ice season had a maximum overall ice extent of 95.6%, whereas the 2011 – 2012 ice season had a maximum of only 12.5%. Other seasons span the entire range between these values.

4.2.2 Seasonal Progression of Ice Extent

To determine potential differences in the timeline of ice development of severe versus milder ice seasons, three representative years were chosen to characterize mild, moderate, and severe ice seasons based on their overall maximum ice extent values across the entire Great Lakes region. These include the aforementioned 2013 – 2014 ice season (the greatest maximum ice extent) and the 2011 – 2012 ice season with the least. As one of the two median seasons, the 2012 – 2013 ice season was chosen as a representative “moderate” ice season with a maximum ice extent of 41.3%. The 2010 – 2011 ice season was a potential alternative, with a maximum ice extent of 41.8%. However, the 2012 – 2013 season was instead chosen for detailed analysis here due the increased AIS data available for that year, as discussed later in Chapter 5.

The seasonal development of ice in the lakes was visualized by plotting daily percent ice cover value for both the overall Great Lakes and each region on a single plot for each studied ice season. These plots are shown here for the chosen representative mild, moderate, and severe ice seasons. For all remaining ice seasons, comparable figures to the ones shown in this chapter for the representative ice seasons are included in Appendix C.

The methodology used to produce these plots started with the calculation of the maximum ice extent values and dates described earlier in Table 4-1. To determine those dates, it was first necessary to calculate the daily percent ice cover of each subregion and for the Great Lakes region as a whole. After rasterizing the available Canadian Ice Service ice charts, the daily percent ice cover of each Great Lakes region was calculated as the mean daily total ice concentration over all uniformly sampled gridded points contained within that region. A total concentration of 0 was included in this daily concentration calculation for ice-free points. While this data was sampled at differing spatial resolutions by subregion, this had no bearing on the overall percent ice cover value for the entire Great Lakes as it was calculated by weighted average of daily ice extent of each subregion normalized to their respective areas.

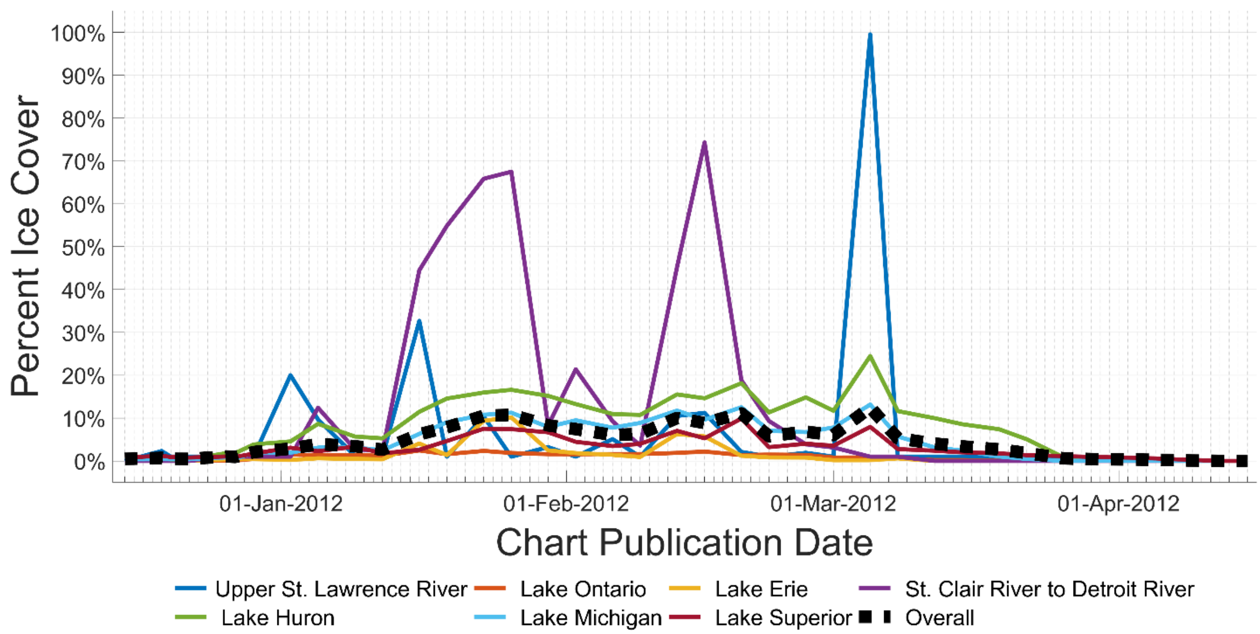

Figure 4-1: Seasonal progression of ice extent within each Great Lakes subregion during the "mild" 2011 – 2012 ice season.

The 2011 – 2012 ice season depicted in Figure 4-1 was the mildest ice season of the studied period with a maximum ice extent of only 12.5%. For the overall region and each of the five Great Lakes, ice cover rarely exceeded 10%, and Lake Ontario in particular had effectively no ice cover the entire season. Lake Huron consistently exhibited the greatest ice cover with periods of ice cover of approximately 20%, including one larger spike in March. The larger lakes (Lakes Superior, Michigan, and Huron) all seem to demonstrate a slow increase in cover at the beginning of the season and slow decline near its end.

The most notable features evident here are surges of ice cover in the river subregions, which include the St. Clair to Detroit River subregion and the upper St. Lawrence River. The St. Clair region (which also includes the relatively small Lake St. Clair) appears to experience a period of significant ice growth in January (up to a maximum of 70%), which rapidly declines in early February before another large spike in ice cover. The St. Lawrence River saw modest ice cover (up to a maximum slightly over 30%) a number of times in January, but little more the rest of the season until a very large spike in early March that approaches 100% ice cover. At this late in the season, this possibly correlates to a major ice jamming event due to influx from the source lakes during Spring breakup (U.S. Army Engineer District Detroit, 1979), but could also be the result of a rapid freezing event as most other regions concurrently experience a small spike in ice cover.

From this example of an atypically "light" ice season, one can infer than even the mildest ice seasons can pose significant ice-related hazards to shipping operations due to how rapidly ice can form and accumulate at chokepoints along the lakes' shipping lanes. This is especially noteworthy given that the most significant hazards during light ice seasons are likely to occur later in a season, close to the time when the Seaway typically reopens and shipping traffic in the lakes substantially increases. This is no coincidence, as the Seaway administrators are aware of this and inform their decision to reopen the Seaway based on their assessment of the shipping hazards posed by ice. However, extra caution should be taken by ship operators near the beginning of the shipping season due to these potential risks even after mild winters – there is always a possibility for localized high concentrations of ice late in the season even when the rest of the lakes are largely ice-free.

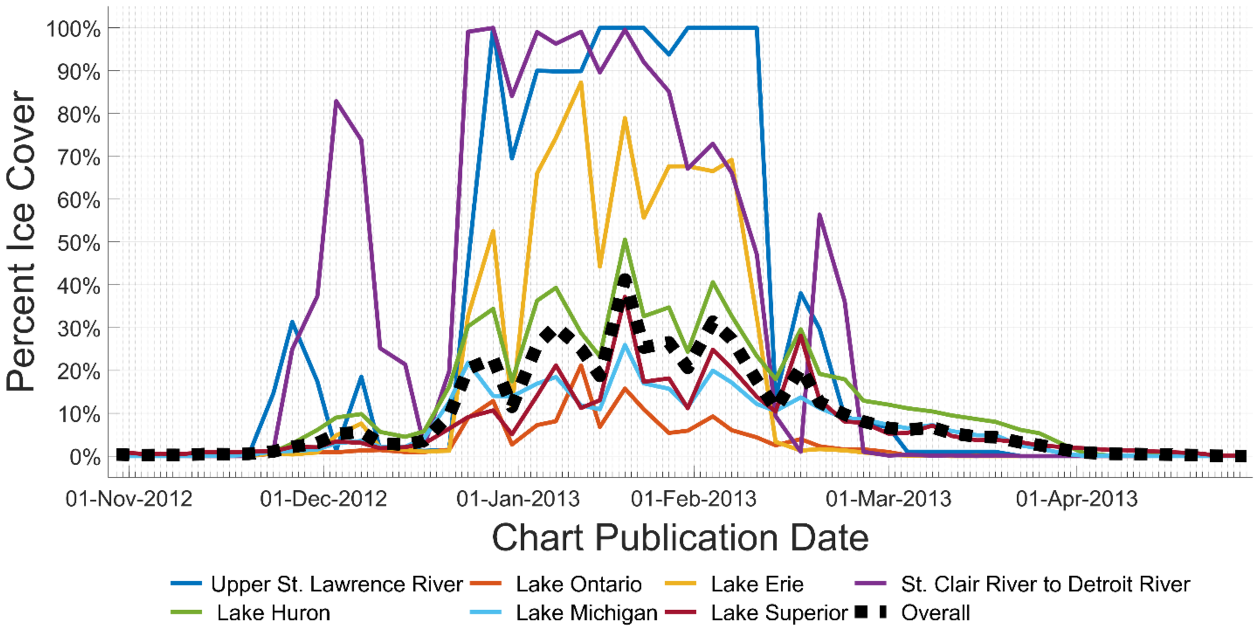

Figure 4-2: Seasonal progression of ice extent within each Great Lakes subregion during the "moderate" 2012 – 2013 ice season.

The 2012 – 2013 ice season shown in Figure 4-2 can be viewed as a more typical season within the Great Lakes. Overall, the five Great Lakes themselves show similar trends to the slow development and decline in ice cover as the largest three lakes did in the previous ice season, albeit to much greater peak ice cover percentages. Lake Erie, in particular, experienced a significantly higher ice cover than the other lakes, at a steady 60% to 80% cover through much of January and February. A significant difference from the prior season is the exhibited behavior of the two river regions. Both the St. Lawrence River and St. Clair to Detroit subregions show spikes in December before developing lasting ice cover (>80%) in January that lasts throughout the season until late February. At the beginning of March, the St. Clair region demonstrates a final spike to 60%. This follows a spike (and subsequent decline) in ice cover in the upper lakes, and thus could be attributed to a jamming event as a result of ice migration. Interestingly, this effect is not seen within Lake Erie for this ice season, which is relatively ice free at the time.

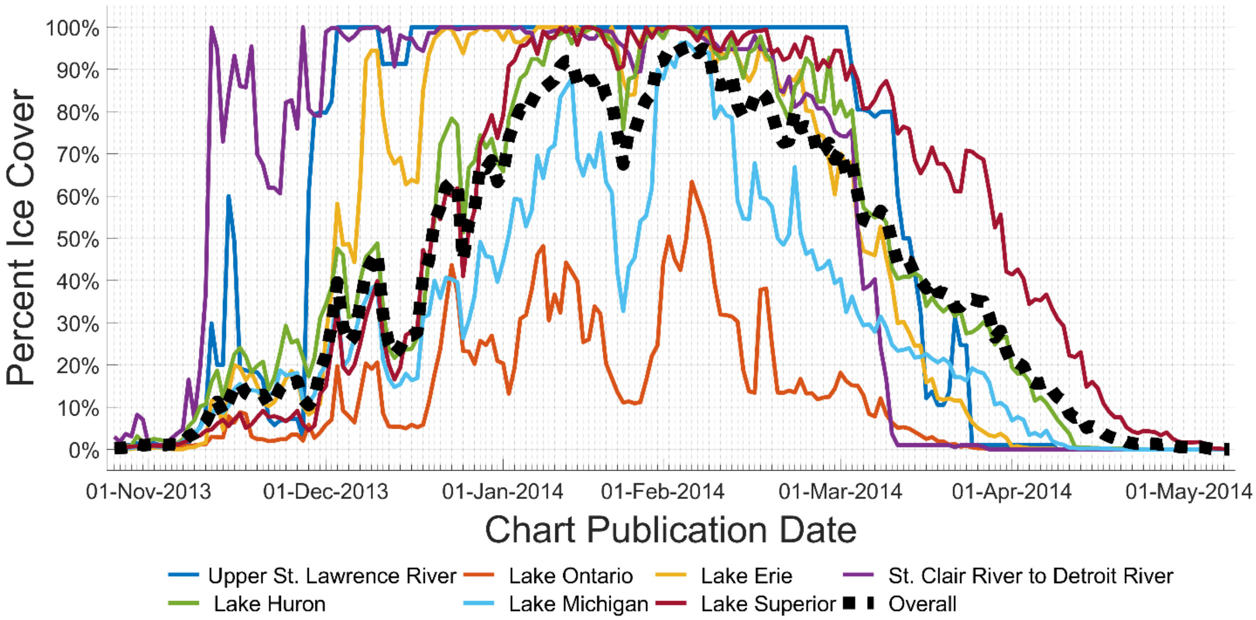

Figure 4-3: Seasonal progression of ice extent within each Great Lakes subregion during the "severe" 2013 – 2014 ice season.

The 2013 – 2014 ice season in Figure 4-3 was the most severe season of the studied period, and all regions demonstrate significantly different patterns than the previously highlighted seasons. Rather than experiencing periodic spikes in ice cover, both river subregions develop extensive ice cover between November and early December that persists until mid-March. By January, all subregions except lakes Michigan and Ontario approach 100% ice cover that lasts the entire typical season through to March. Even Lake Ontario, which in lighter years can see almost no ice cover at all, experienced ice cover greater than 20% for much of the season, with spikes up to 60%. In Lake Superior, notable ice cover persisted through all of April and into May.

With ice-cover this extensive and lasting, it would be expected that many lasting pockets of hazardous ice remain throughout the region well into the shipping season. While the majority of ice seasons are nowhere near as severe, the potential for winters such as this clearly demonstrates a need for effective guidelines for ship operations in lake ice. This is essential for vessels to operate through the wide variety of this region's potential ice conditions safely and effectively.

4.3 Ice Season Duration

An alternative means of quantifying the severity of a given ice season and its potential impact on shipping operations is an analysis of ice season duration. The date at which ice first forms along a desired route is critical for route planning purposes, given that the presence of ice can completely change the safety profile of a particular ship's planned transit through the lakes. It is also for this reason that ship operators must have accurate metrics for assessing their ship's operational capability through particular ice conditions. This would be required in the event that they unexpectedly require transit through early ice along a planned route near the end of a shipping season. There is also the potential impact of unexpectedly late ice that may disrupt route planning at the beginning of a shipping season. However, this implicates fewer vessel safety concerns given the higher certainty involved when forecasting the continued presence of presently observable ice.

For this analysis, the presence of ice is defined as a local ice concentration of 1/10 or higher of any thickness found anywhere within the defined region. The daily value was taken as published on the nearest CIS ice chart within 3 days, excluding days beyond the first and last published charts of a season (beyond the limits of which all regions are considered ice-free). Figure 4-4 is intended to provide a yearly overview of each studied ice season by illustrating the total number of days with ice present within each Great Lakes region across the analyzed ice seasons.

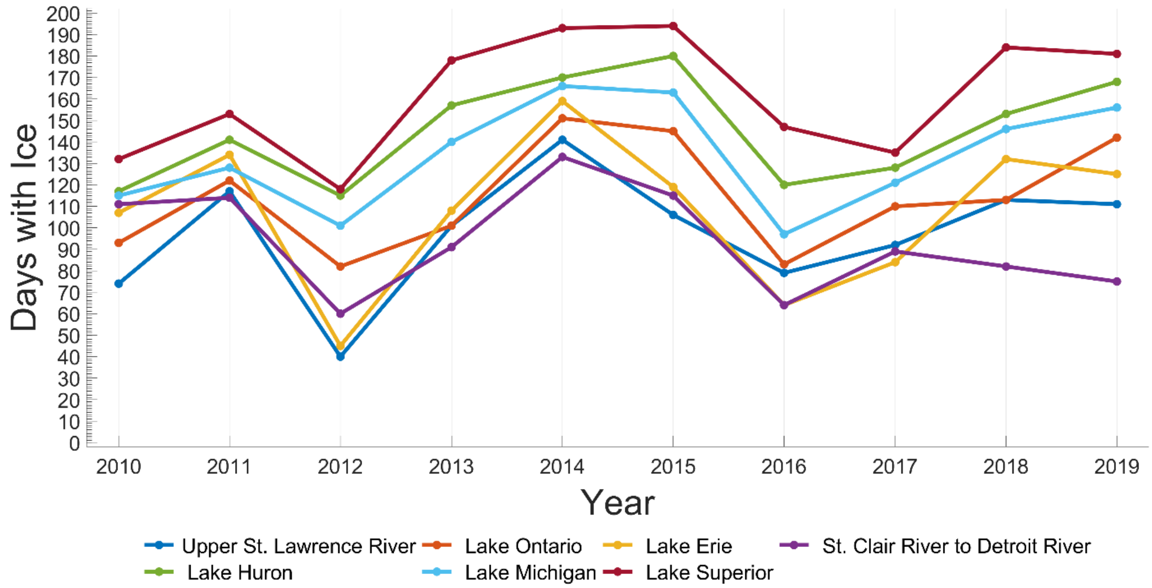

Figure 4-4: Number of days with local ice concentrations of at least 1/10 within each Great Lakes region for all ice seasons from winters 2010 to 2019.

Furthermore, the actual start and end dates for each ice season as well as the date of maximum ice extent (as discussed previously in Section 4.2) are plotted for the overall Laurentian Great Lakes region in Figure 4-5 below.

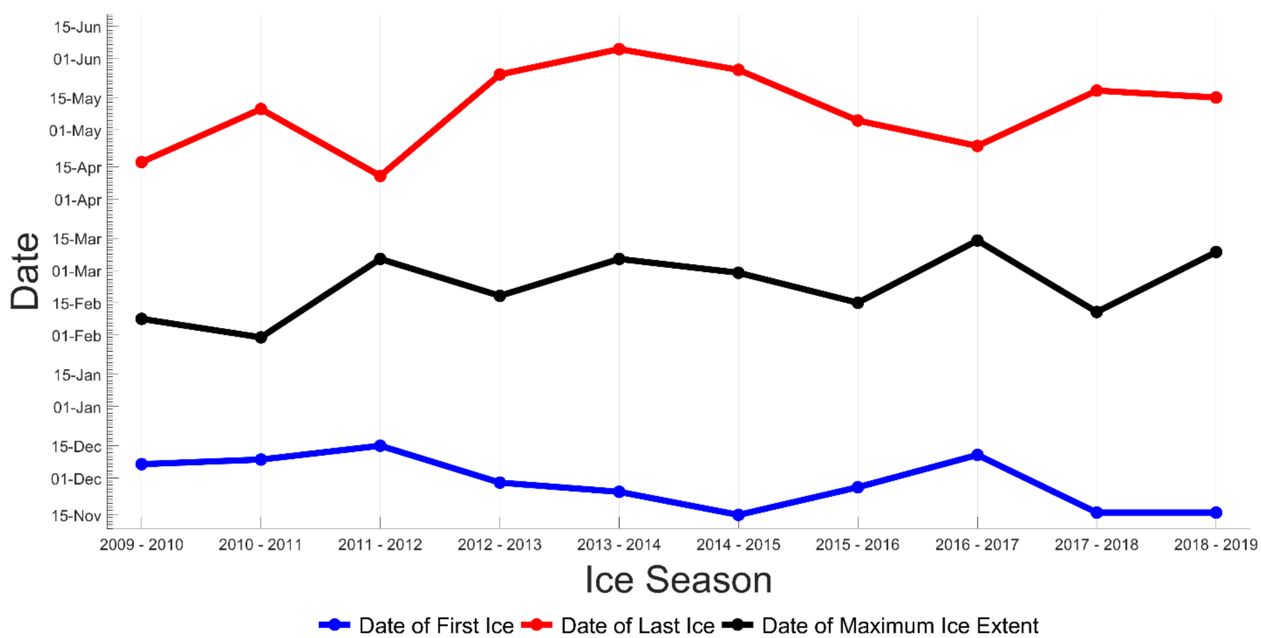

Figure 4-5: Seasonal dates of first and last ice as well as maximum ice extent for the entire Laurentian Great Lakes region for ice seasons from winter 2010 – 2019.

Interestingly, a general trend can be seen where a relatively later date of maximum ice extent tends to follow a later date of last ice in more severe ice seasons (such as 2014 and 2015). However, in the mildest ice seasons (2012 and 2017), a relatively late date of maximum ice extent also occurs, however it is very close to the last date with any ice in those seasons which also demonstrate the latest dates of first ice appearance).

Additional plots comparable to Figure 4-5 for the overall Laurentian Great Lakes region can be found in Appendix C that depict the dates of first, last, and maximum ice for each season for the identified Great Lakes subregions.

4.4 Typical Ice Presence and Severity

The distributions presented in this section are intended to provide an estimate for likely ice conditions that one may expect throughout the Great Lakes region in an ice season of typical severity, based on the recent ten-year period covered by the analysed data. The distributions are aggregated monthly for December to May for ice seasons from 2010 to 2019. While November and June do occasionally see the first and last ice of some ice seasons, it is not frequent nor extensive enough to produce visually meaningful distributions. Additionally, there were no identified occurrences of ship operations in ice for these months (and indeed, there were only few occurrences for December and May). This topic is discussed in detail in Chapter 5.

As was evident from the previous analysis within this chapter, it is clear that there is significant year-to-year variability in the potential severity and duration of a given ice season in the Laurentian Great Lakes. Knowing this, these distributions can be used as a benchmark to compare the presence and severity of ice during a specific time period to the typical conditions that would be expected for that month in the analysis of future ice seasons.

The *Probability of Ice Present* and *Mean Equivalent Thickness* parameters used to generate these distributions were calculated at gridded sample points taken across the Great Lakes region. The *Probability of Ice Present* is given by the percent number of days with a local ice concentration of at least 1/10 divided by the total number of days within that distribution's month throughout the 10-year sample period. The *Mean Equivalent Thickness* parameter is the mean of *Equivalent Thickness* (as described in section 4.1) at each gridded point on days with 1/10 or greater local total ice concentration. As such, the *Equivalent Thickness* of ice-free days or days with only trace ice present are not included in the calculation (similarly to how the partial concentration for open water is not included in the calculation of *Equivalent Thickness)*. On the maps for *Mean Equivalent*

Thickness, subregions where there was no ice present at any point during the studied period are shown in black and have undefined value (as there was no data available to perform the calculation). These correspond to subregions with a "*Probability of Ice Present*" of exactly 0.

4.4.1 Expected December Ice Conditions

December is the earliest month that has seen any significant ice development throughout the lakes, and it is the month when a season's first ice charts are typically published. Extensive ice coverage during December has been rare, and when present, it was restricted to shorelines and semi-enclosed areas. In some of these areas, ice thicknesses can occasionally reach notable levels even this early in the ice season.

Lake Ontario rarely develops ice in December except along the shorelines, mainly to the north. Eastern Lake Erie seems to follow a similar pattern. The area from Western Lake Erie through to Lake St. Clair and Southern Lake Huron more likely develops ice in December, but rarely to notable thicknesses. A number of enclosed bays within Lake Huron and Lake Michigan see consistent ice in December, as well as Lake Huron's northern shoreline and the passage to Lake Superior, but little elsewhere and none at either lake's interior. Lake Superior is largely ice-free in December, with the exception being the bays to the far north that very consistently develop ice this early in the season.

The main takeaway from this is that some localized areas seem to consistently develop December ice; specifically, the bays along northern Lake Superior and waterways surrounding the Soo Locks between Lake Superior and Lake Huron. Within these subregions, ice appears to have been present on upwards of 75% of December days during the 10-year period, with a low (but not insignificant) mean equivalent thickness of up to 20cm. Elsewhere, the mean equivalent thickness when ice was present appears to be 10cm or less.

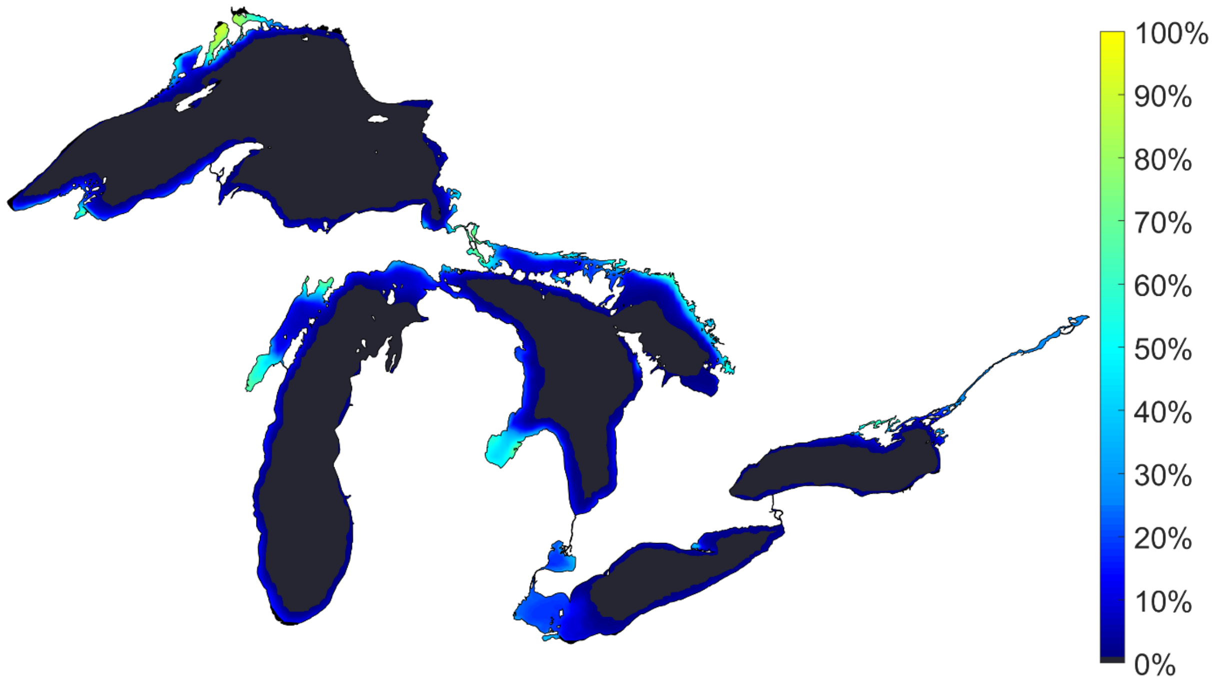

Figure 4-6: Spatial distribution of daily-averaged probability of ice presence throughout the Great Lakes for December days from 2009 to 2018.

Figure 4-7: Spatial distribution of daily-averaged equivalent ice thickness throughout the Great Lakes for days with ice present during the month of December from 2009 to 2018.

4.4.2 Expected January Ice Conditions

January tends to be the month when the majority of early ice growth occurs in the Great Lakes. Overall, the distribution is similar to December's with larger regions for potential ice and higher mean equivalent thicknesses.

Most of Lake Ontario is typically ice-free still in December, with the exception of the northern shore. Lake Erie is the only lake that frequently sees ice cover (at 50% incidence) across the entire lake, including its interior. This increases to 80% for its western half and into Lake St. Clair (for which the incidence approaches 100% along the eastern shore). The same semi-enclosed regions and shorelines of lakes Huron, Michigan, and Superior where ice has been present in December again demonstrate consistent presence of ice in January. The ice incidence approaches 100% of January days in most of these locations. Generally, the mean equivalent thickness in these areas is around 20cm, and up to 40cm in northern Lake Superior. The probability of ice present approaches 80% northern Lake Huron and Michigan, and elsewhere along the shorelines of lakes Huron, Michigan, and Superior it is close to 50%.

In general, ice has been present throughout the majority of the Great Lakes region at some point during January of the studied period. The only exceptions where no ice has occurred include the interiors of Lakes Michigan and Ontario, and small patches at the innermost areas of Lakes Superior and Huron. For the remaining areas where ice has been present, the mean equivalent thickness is relatively low at approximately 10cm, indicating early-stage ice growth.

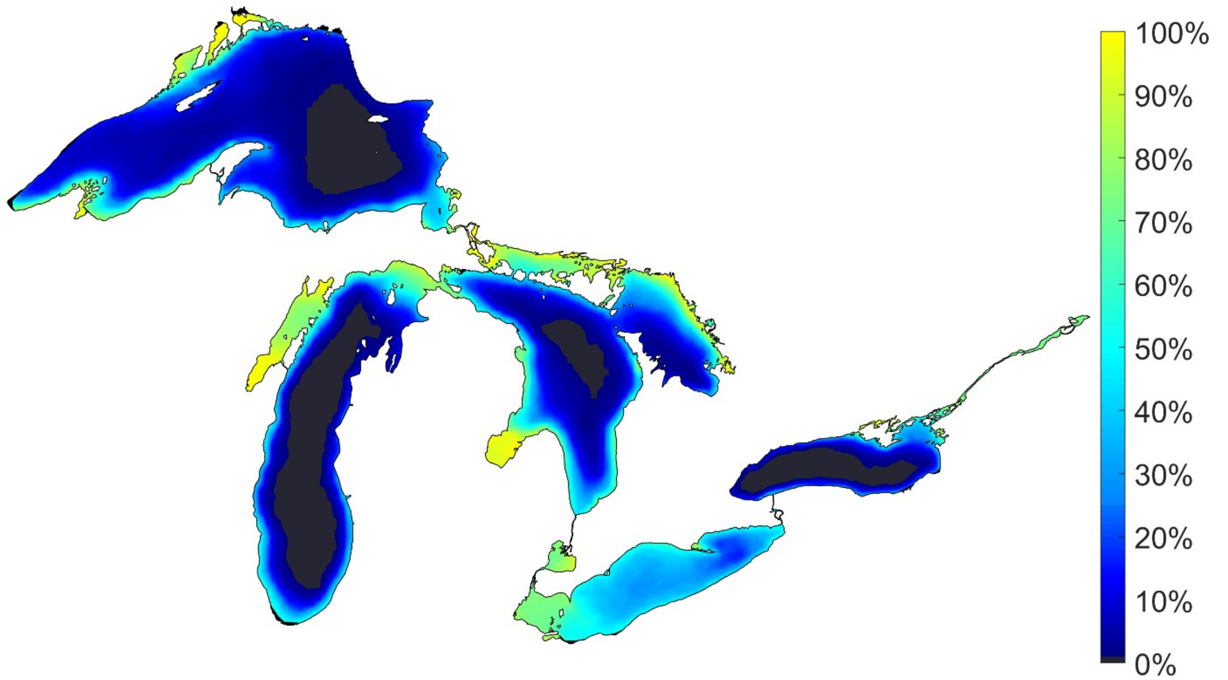

Figure 4-8: Spatial distribution of daily-averaged probability of ice presence throughout the Great Lakes for January days from 2010 to 2019.

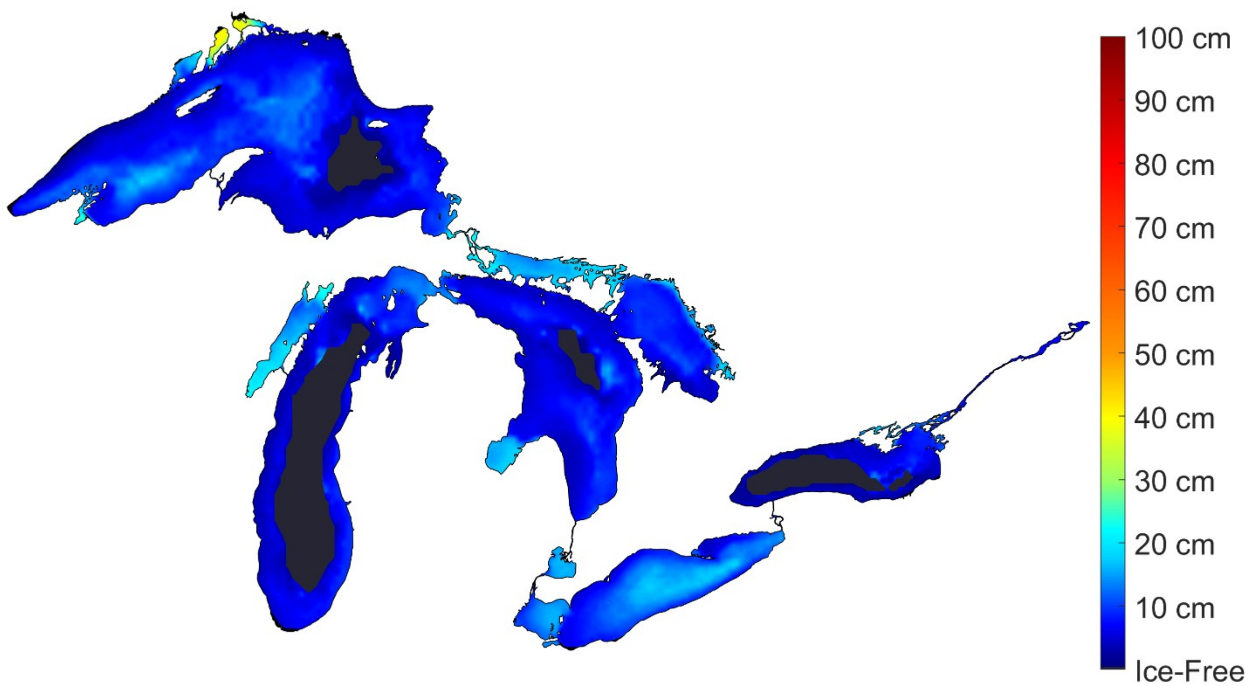

Figure 4-9: Spatial distribution of daily-averaged equivalent ice thickness throughout the Great Lakes for days with ice present during the month of January from 2010 to 2019.

4.4.3 Expected February Ice Conditions

February continues the trends seen in January, with a similar distribution of ice presence that also extends into the interior of all lakes. Given the differences in mean equivalent thickness between the two months despite similar distributions of ice presence, it is clear that consistently high ice growth occurs throughout the lakes during February.

The shorelines of all lakes aside from Lake Ontario, and the semi-enclosed regions described earlier continue to show consistent ice presence in February, at close to 100%. The interior of Lake Ontario and southern Lake Michigan are more typically ice-free. The entirety of Lake Erie and nearby Lake St. Clair are also notable, as they show the presence of ice for approximately 80% of February days. Elsewhere, the shorelines of Lake Huron, Lake Michigan, and Lake Ontario all demonstrate ice presence on 60-80% of February days.

The mean thickness for most of these regions is between 20 to 40cm, with the exception being northern Lake Superior, at upwards of 75cm. Elsewhere, the mean equivalent thickness ranges between 10cm and 20cm for most of the Lakes' interiors aside from Lake Ontario and Lake Michigan.

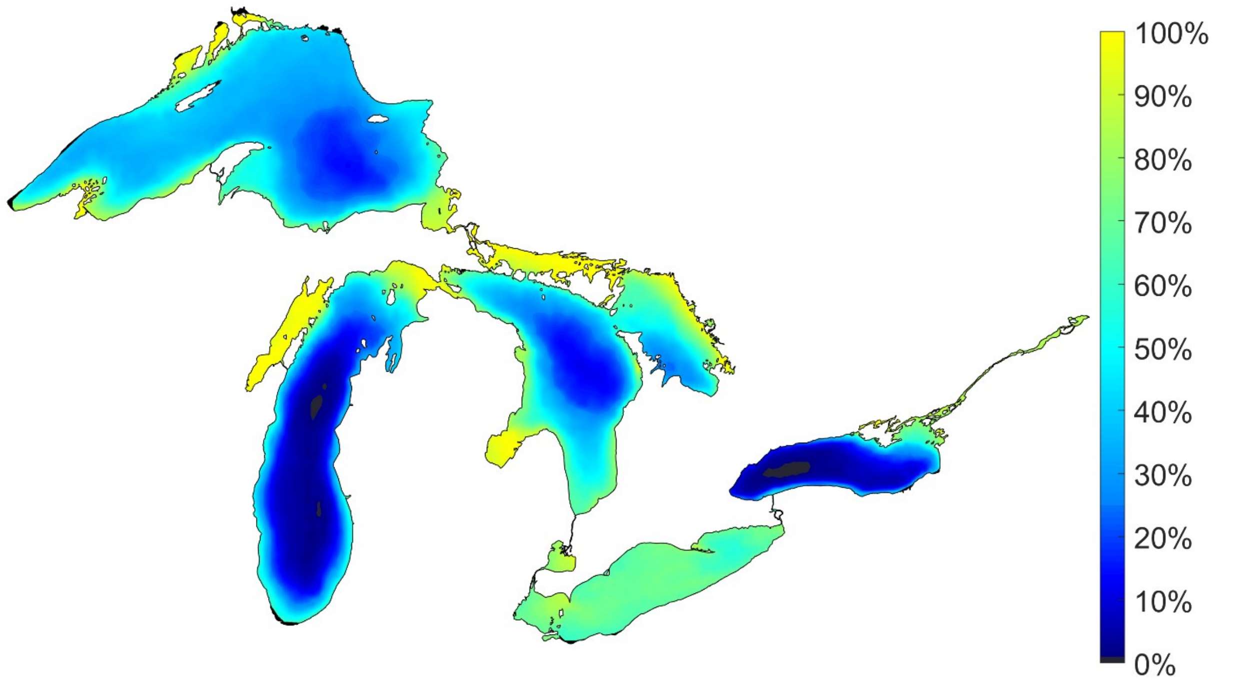

Figure 4-10: Spatial distribution of daily-averaged probability of ice presence throughout the Great Lakes for February days from 2010 to 2019.

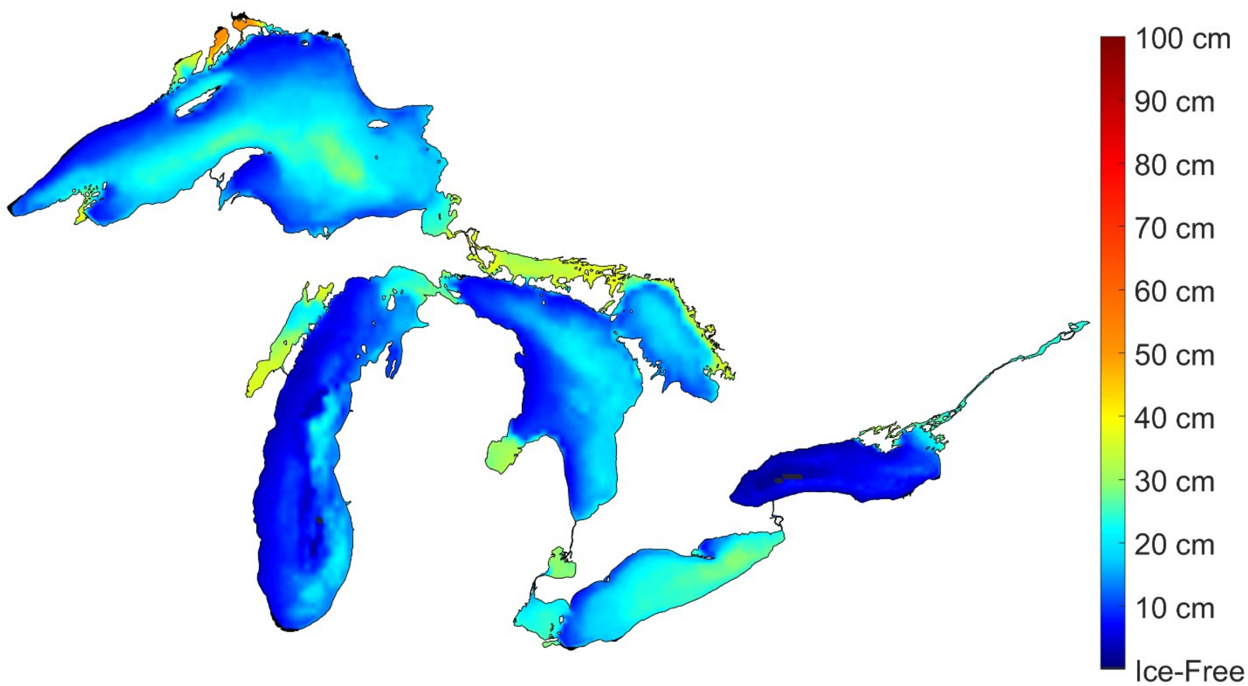

Figure 4-11: Spatial distribution of daily-averaged equivalent ice thickness throughout the Great Lakes for days with ice present during the month of February 2010 to 2019.

4.4.4 Expected March Ice Conditions

March seems to demonstrate the most consistently heavy ice conditions throughout the Great Lakes. While the overall probability of ice present is not as high as February, the ice thicknesses are consistently much greater. The shoreline and interior of western Lakes Erie and Huron show high equivalent thicknesses of approximately 60cm, and of up to 40cm throughout the majority of the lakes' interior regions excluding the eastern halves of Lakes Michigan, Huron, and Ontario. This may be the result of ice movement through the lakes following its spring breakup, as broken ice flows downstream and reconsolidates along bottlenecks in the waterway.

Some isolated regions in the lakes (such as northern Lake Superior) appear to demonstrate close to 100cm mean equivalent thicknesses, given by persistent 10/10 coverage of Very Thick Lake Ice, the maximum thickness category used by Canadian Ice Service for the region.

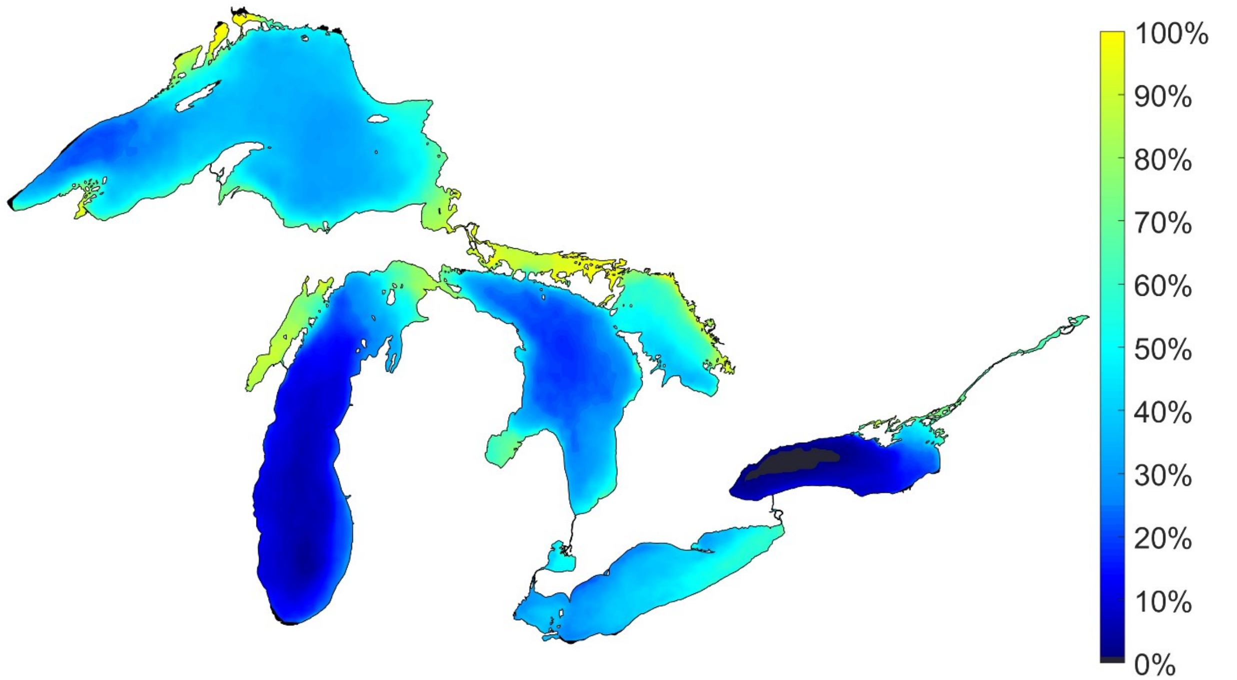

Figure 4-12: Spatial distribution of daily-averaged probability of ice presence throughout the Great Lakes for March days from 2010 to 2019.

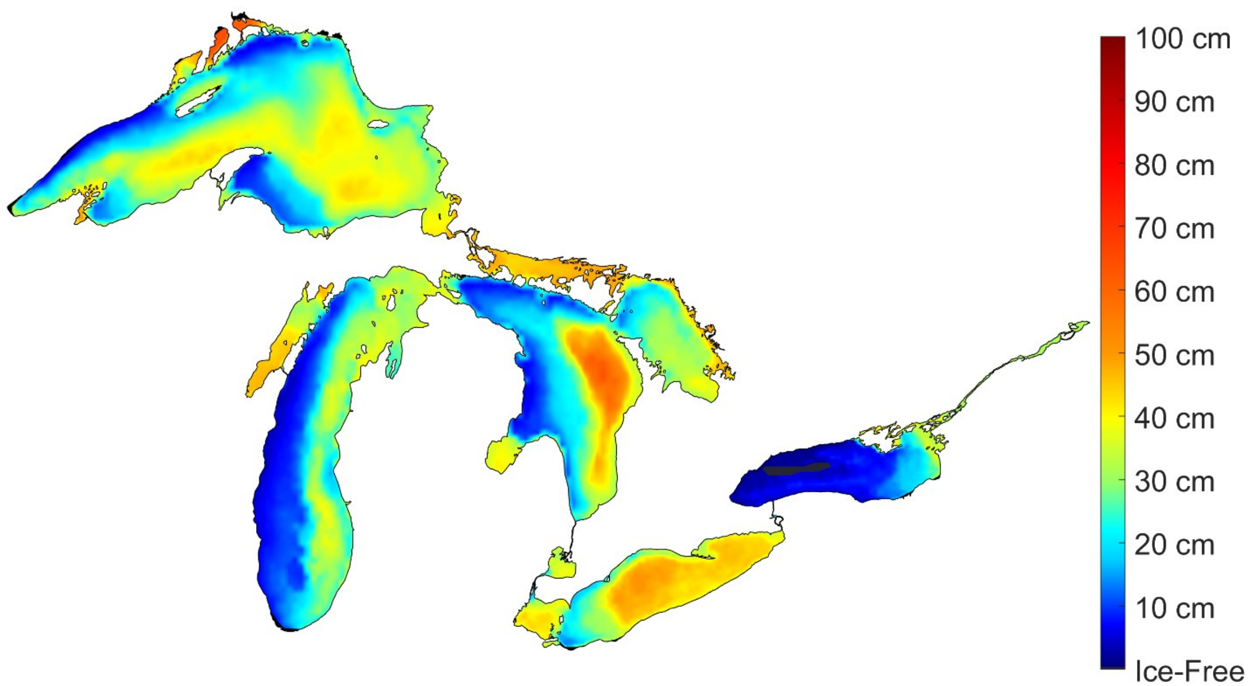

Figure 4-13: Spatial distribution of daily-averaged equivalent ice thickness throughout the Great Lakes for days with ice present during the month of March from 2010 to 2019.

4.4.5 Expected April Ice Conditions

The distributions for April indicate that the thawing and breakup of ice is typically well underway by this month, with a low overall distribution of ice presence that no longer follows the shoreline. Lake Ontario, Lake Erie, Lake Michigan, and Lake Superior show skewed distributions of ice presence in the west-east direction, ranging from 0% to approximately 40%. This aligns with expectations for ice migration that follow the current, which may result in potential pile-ups at bottlenecks in more severe winters. Lake Erie, in particular, shows a strong gradient that is opposite to the trends demonstrated in the early season months. Northern Lake Huron demonstrates a high probability of ice, leading up to Lake Superior which has a slight west-east skew in ice presence with a mean of approximately 30%. Higher rates of occurrence can be seen within at its northern bays and the passage between it and Lake Huron.

Of particular interest is that the mean equivalent thickness is particularly high throughout the entire region, ranging from 40cm to 80cm for most lakes where ice has been present. This suggest that April ice, while not consistent, is typically especially severe where and when it does occur, likely as a result of pileups and reconsolidation of broken ice.

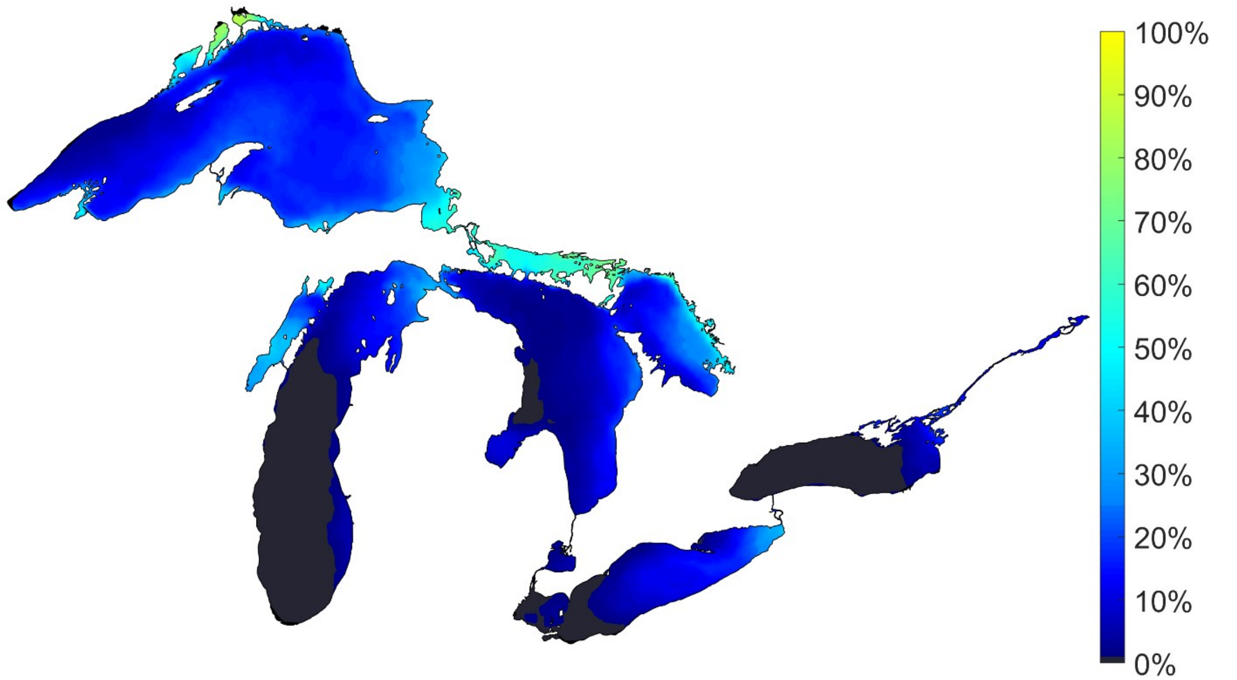

Figure 4-14: Spatial distribution of daily-averaged probability of ice presence throughout the Great Lakes for April days from 2010 to 2019.

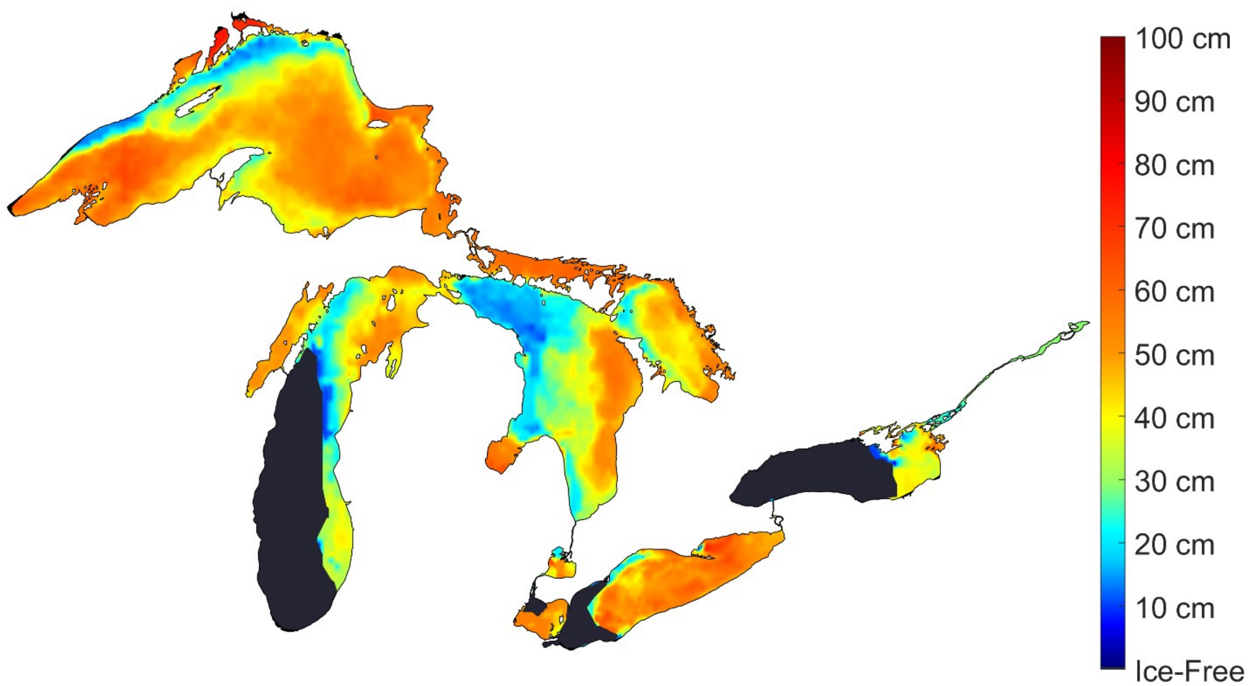

Figure 4-15: Spatial distribution of daily-averaged equivalent ice thickness throughout the Great Lakes for days with ice present during the month of April from 2010 to 2019.

4.4.6 Expected May Ice Conditions

Ice has been rare in the lakes in May and has only occurred in a few locations with an incidence peaking at approximately 20% of May days in eastern Lake Superior and northern Lake Huron. In the bays of northern Lake Superior, this incidence increases to approximately 30 to 40%. However, similarly to April, despite the infrequent ice occurrences, the distribution of mean equivalent thickness indicates that ice conditions are typically very severe when it is present. This could be especially problematic for ships transiting to and from Lake Superior in particular, which must be wary for potential isolated patches of severe ice along bottlenecks within an otherwise ice-free environment.

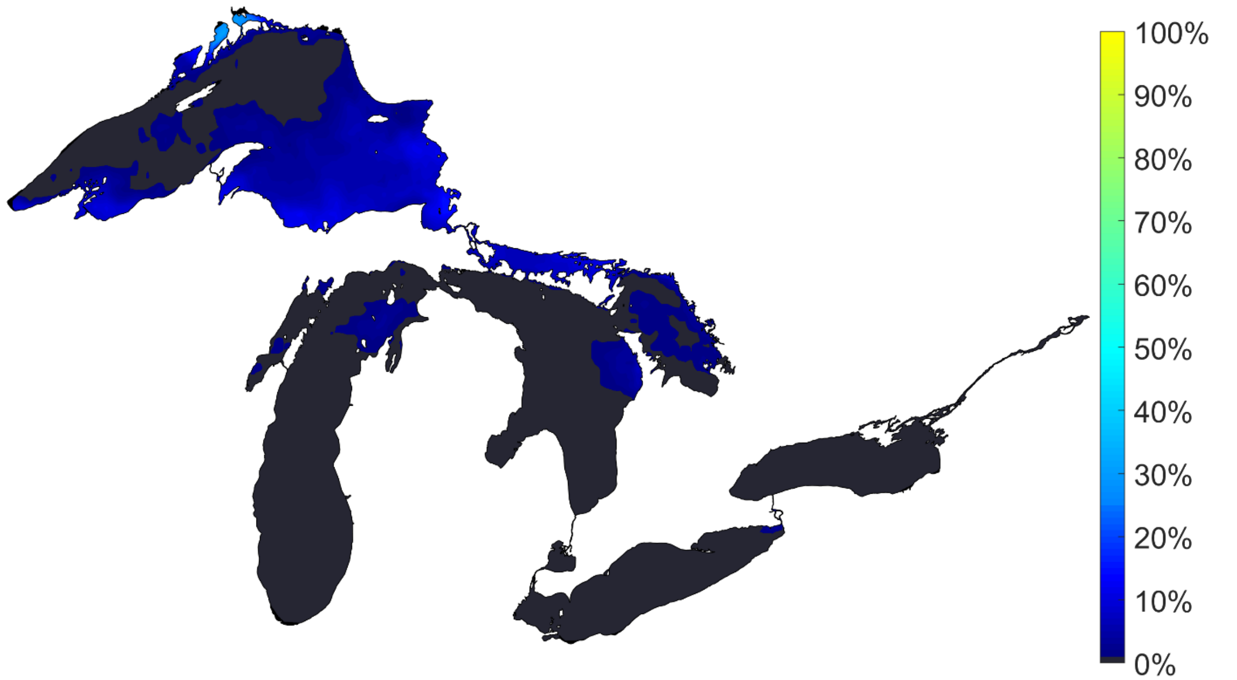

Figure 4-16: Spatial distribution of daily-averaged probability of ice presence throughout the Great Lakes for May days from 2010 to 2019.

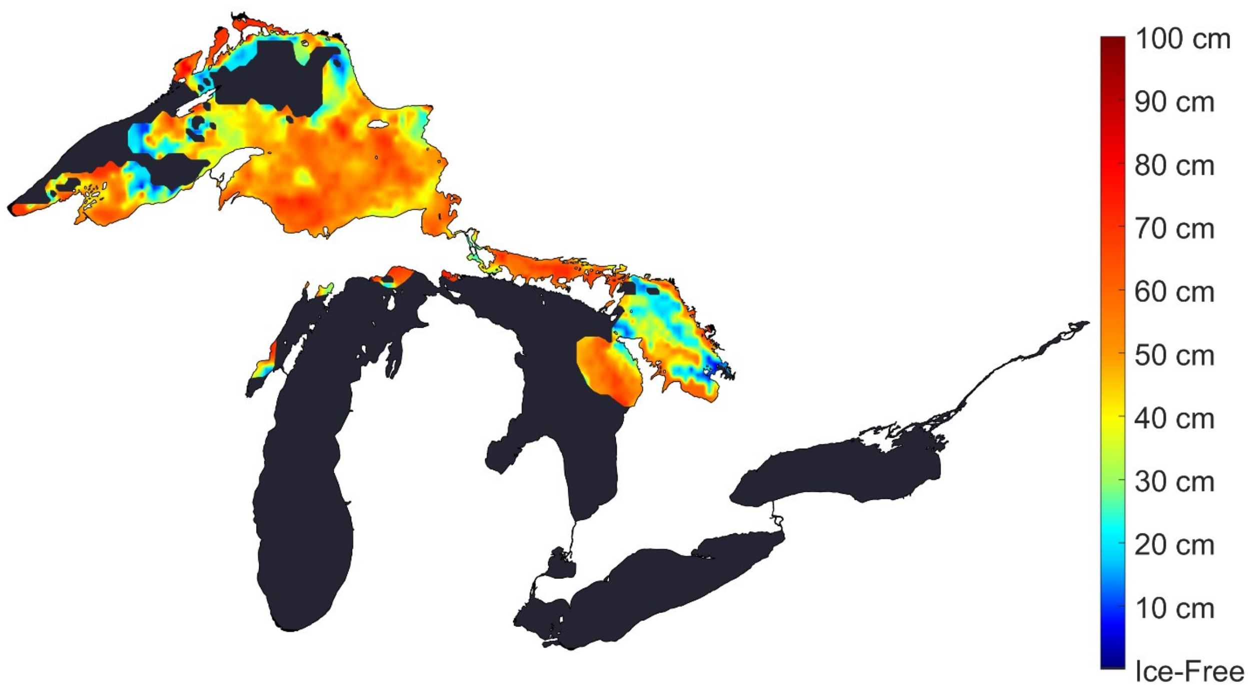

Figure 4-17: Spatial distribution of daily-averaged equivalent ice thickness throughout the Great Lakes for days with ice present during the month of May from 2010 to 2019.

Chapter 5:

Analysis of Ship Traffic

5.1 Overview of AIS Dataset

Historical AIS records for ships operating in the North American Great Lakes region for ice seasons between 2010 and 2019 were used to analyze freshwater ice operations in the region and to assess current operational practices. The initial dataset comprised a total of 262,945 individual AIS records. However, given the focus of the present work on ships transiting through ice, AIS records for stationary ships (with AIS-recorded speeds equal or less than 0.1 knots) were excluded from this dataset. Historical ice condition information was then compiled for the times and locations of each AIS data point. Analysis of these data revealed that 139,287 AIS records corresponded to open water conditions. These were removed from the dataset, leaving 123,630 records for ice operations.

In total, 390 unique ships were identified that have operated in ice conditions with 1/10 or greater coverage. Ice-class information was obtained for these ships on a ship-by-ship basis, primarily through classification society information available via http://www.equasis.org or from ship specifications provided by operators. Since knowledge of a ship's ice class is required to apply the POLARIS methodology, it was necessary to restrict the analyzed data to only the subset corresponding to ships with verifiable ice class. Of the identified ships, 114 were verified to have a POLARIS ice class, while 14 others possessed alternative ice classes and the remaining 262 were either unclassed, could not be verified, or possessed an ice class lower than the lowest outlined within POLARIS ("IC"). While no Polar Class ships were identified in these data, five Canadian Coast Guard ships and four US Coast Guard ships were identified with comparable icebreaking capabilities to Polar Class ships. The final subset of data corresponding to ice operations of transiting POLARIS ice class ships consisted of 15,072 records, summarized by ice season in Table 5-1.

Table 5-1: Summary of AIS records used for this analysis.

Ice Season	All Ships		POLARIS Ice Class Ships	
	Total	Ice Present	Total	Ice Present
January 1, 2010 - March 31, 2010	454	219	141	113
December 15, 2010 - April 15, 2011	34	0	2	0
January 1, 2012 - March 31, 2012	2328	512	237	50
January 1, 2013 - April 30, 2013	13,082	4,699	2,249	670
December 1, 2013 - May 15, 2014	41,756	22,977	7,367	3,787
January 1, 2015 - May 15, 2015	50,378	25,457	4,663	2,193
January 1, 2016 - March 31, 2016	5,654	3,284	753	430
December 15, 2016 - April 15, 2017	55,296	28,852	5,780	2,880
December 5, 2017 - May 15, 2018	38,654	18,227	5,739	2,424
January 1, 2019 - April 30, 2019	55,309	19,403	7,722	2,525

It is clear here that the number of available AIS records increased substantially between 2012 and 2014. This is expected to be largely the result of increases in AIS coverage over the Great Lakes region during this period rather than significantly increased winter shipping traffic in the region.

5.2 Overview of AIS-Derived RIO Values

Using the historical ice condition information and known ice classes of the studied vessels, the POLARIS methodology was applied to calculate RIO values corresponding to each AIS record in the dataset. The distribution of calculated RIO values covers a wide range, with the majority of records (89%) having positive RIO values that would correspond to *normal operations* under POLARIS guidelines. Of these data, a total of 5,784 (39%) points correspond to ice conditions resulting in an RIO between 0 and 29 and 7,491 (50%) points were in trace ice conditions that would result in an RIO between 29 and 30. The remaining 1,684 points (11%) had an RIO less than 0, for which the POLARIS methodology would recommend *operation subject to special consideration*. The histogram in Figure 5-1 shows the probability distribution of calculated RIO values for the full dataset. Note that the bin width for the 29 to 30 range was modified to highlight the comparatively high percentage of AIS records corresponding to ship operations in trace ice conditions with concentrations <1/10.

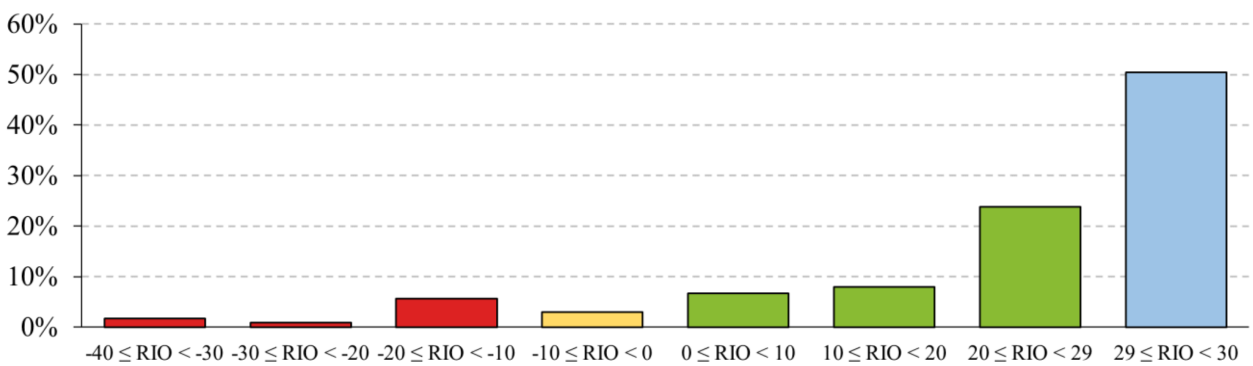

Figure 5-1: Histogram of RIO values for ships with verified ice class in the dataset.

Overall, only a small percentage of cases correspond to the lower RIO ranges below 0, with a few instances of highly negative RIOs below -20. While these results provide insight into general trends, caution should be exercised in reading too much into the highly negative RIO values in this preliminary study. The current approach cannot directly account for icebreaker support, navigation through broken ice channels, differences between actual local ice conditions versus general ice chart conditions (e.g. possible navigable leads through heavy ice), or other mitigating actions that may have been employed. A more-detailed breakdown of these calculated RIO values is shown in Table 5-2 by month of the studied period. Corresponding numbers of icebreaker AIS records in ice concentrations of 1/10 or greater are included to highlight when their presence may have been used to mitigate otherwise heavy ice conditions.

Table 5-2: Monthly AIS-record breakdown for ice-class ships and icebreakers

Time Period		AIS Record Count			
Year	Month	Positive RIO	Negative RIO	Trace Ice	Icebreaker
2010	January	0	0	51	0
2010	February	46	0	0	0
2010	March	0	0	44	0
2011	April	0	0	2	0
2012	January	1	0	87	22
2012	February	0	0	55	14
2012	March	0	0	94	1
2013	January	8	0	53	24
2013	February	44	0	19	16
2013	March	94	38	333	186
2013	April	99	24	1537	0
2013	December	508	0	1947	88
2014	January	173	6	33	159
2014	February	122	40	0	165
2014	March	26	243	52	492
2014	April	492	512	1436	632
2014	May	2	56	1719	58
2015	January	319	3	102	173
2015	February	251	81	16	163
2015	March	141	222	39	479
2015	April	239	198	2099	318
2015	May	3	1	949	0
2016	January	24	0	172	32
2016	February	64	0	102	8
2016	March	10	0	381	32
2016	December	790	0	2017	52
2017	January	112	0	353	128
2017	February	82	0	315	46
2017	March	119	5	641	204
2017	April	35	2	1309	5
2017	December	290	0	880	43
2018	January	204	12	107	118
2018	February	52	3	27	121
2018	March	6	4	211	221
2018	April	57	38	1761	51
2018	May	139	10	1938	12
2019	January	189	0	524	194
2019	February	446	2	197	168
2019	March	394	50	657	519
2019	April	234	134	4895	607

For visual analysis of a potential relationship between icebreaker activity and ship operations in ice, the above data from Table 5-2 was plotted as is shown in Figure 5-2 below. Only months with a non-zero number of ice-class ship AIS records in ice concentrations of 1/10 or greater were included in this plot. As such, it should be noted that the x-axis is discontinuous.

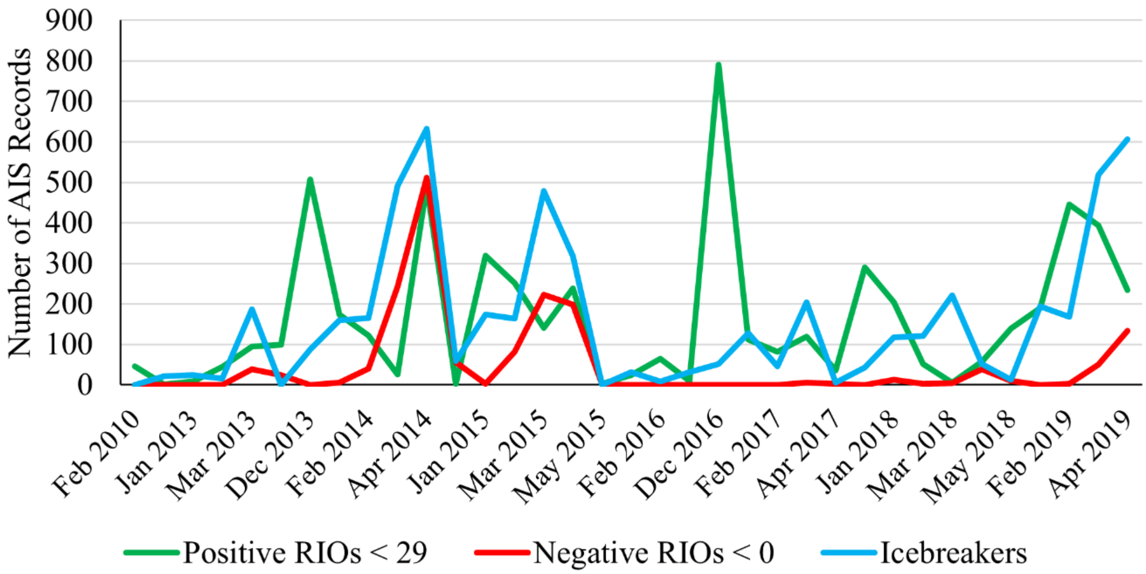

Figure 5-2: Plot of monthly AIS Records for ice-class ships and icebreakers in ice concentrations of 1/10 or greater.

At first glance, the data shown in Figure 5-2 indicates a substantial correlation between icebreaker activity and ship operations in ice. Peak icebreaker activity during the studied 10-year period coincides with those months with the greatest incidence of negative RIOs, which include March and April 2014, March and April 2015, and April 2019. These months also align with higher-than-typical occurrences of positive RIOs (for ice operations). Notably, there is not a higher rate of icebreaker activity for months with the greatest numbers of positive RIOs that do not also have high occurrences of negative RIOs. For example, December and January 2013, December and January 2017, and January 2018 all have very high occurrences of positive RIOs, few to no occurrences of negative RIOs, and relatively little icebreaker activity. In these years, there tends to be some icebreaker activity later in the season (ie: March and April), but with approximately half as many icebreaker AIS record occurrences as the corresponding months during peak years where there were also significant numbers of negative RIO values calculated for ice-class ships.

The above analysis of this data implies that ice management operations are significantly increased in the Great Lakes as a mitigating measure during seasons when hazardous ice conditions that pose a threat to shipping operations are present (as calculated using the POLARIS method and described methodology). This analysis is further expanded in Appendix D, which includes monthly plots of icebreaker and ice-class ship AIS record positions during months when negative RIO values were calculated. Monthly plots demonstrate a correlating spatial relationship between negative RIO occurrence and icebreaker operations along shared routes during nearly all months with negative RIO values. For months that don't, such as some negative RIO values calculated in Lake Michigan in April 2014, icebreaker presence was still apparent along the same route during the previous month.

While the analysed data was grouped monthly, the correlating spatial relationship between negative RIO occurrence and icebreaker operations along shared routes in Appendix D strongly suggests that a significant portion of negative RIOs are likely representative of ship operations in managed ice. Since this is not captured in the calculation of RIO values using the present methodology (based on historical ice chart data), it is highly plausible that there are "false negative" RIOs that were calculated from this dataset that do not accurately reflect the true risk profile of those ship operations with icebreaker assistance or escort. This is particularly important when estimating lower bounds for potential RIO values based on the most highly negative RIO values that were calculated, as these were based on nominal regional ice conditions and not the true local ice regime that likely included managed ice.

5.2.1 Monthly Summaries of AIS-Derived RIO Values

In order to identify subregions that may be particularly challenging for ship operations and to provide further context for the analysis of calculated RIO values, the positions of analyzed AIS data have been plotted over maps of the Great Lakes. These maps are shown below in this section and are grouped by month from January through April, when negative RIO values primarily occurred in the region. While the months of November, December, May, and June have also had occasional ice presence in the lakes during the studied period, there have been few to no negative RIO occurrences during these months. As such, no distributions of RIO occurrences were generated for them.

The AIS data representing ice class ship operations in trace ice or greater is plotted in blue, green, yellow, or red, based on RIO range. In addition, icebreaker AIS records in 1/10 or higher ice concentrations are depicted as blue "X" markers, which identify locations where ice management operations potentially occurred during the 10-year period. For each month, regional breakdowns of RIO occurrence for each lake and subregion are depicted by pie charts (using the same color scheme as the AIS datapoints) with callouts from their described regions.

It is important to note that these maps depict aggregate data taken across multiple ice seasons. As such, the presence of icebreaking ships only highlights subregions in which they have operated and does not necessarily mean they were operating as an escort at the specific times when negative RIO values were calculated. However, if more detailed consideration of negative RIO instances is desired (such as to determine whether or not an icebreaker escort was likely present), additional maps of more specific time periods can be found in Appendix D.

Overall, it was observed that negative RIO values tended to occur in specific regions throughout the lakes. In particular, Lake Erie (as well as the neighbouring waterway between it and Lake

Huron that includes Lake St. Clair, the St. Clair River and Detroit River) can be seen to experience consistently heavy ice conditions that resulted in negative RIO values throughout the entire ice season. The passages between Lake Huron and both Lake Michigan and Lake Superior demonstrate similar trends of heavy ice conditions later in the ice season.

The distributions of calculated RIO values and icebreaker operations appear to align with the known practices of Canadian and US coast guards (English, Hackston, Greenway, & Helland, 2014). Icebreaking ships have frequently operated in the areas with the highest density of negative RIO values, and few negative RIO values occur in areas where no icebreaker has operated. This further implies that at least some portion of negative RIO values that were calculated at these locations may not accurately reflect the actual local ice conditions ships were operating in if one assumes they were operating with an icebreaker escort or travelling along maintained shipping routes.

5.2.2 Monthly RIO Summary for January (2010-2019)

Few negative RIO values were calculated for ship operations in January, presumably because the heavier ice conditions that would produce them do not tend to develop until later in the ice season. The negative RIO values that were calculated are primarilly restricted to Lake Erie and the St. Clair River/Lake St. Clair between it and Lake Huron. The majority of other points represent RIO values between 0 and 29, present in all lakes except Lake Ontario, which would indicate that extensive mild ice conditions throughout the majority of the region are typically present in Jauary.

There have been icebreaker operations in January within Lake Erie and the St. Clair river near the locations of negative RIO values, although it is also apparent that icebreakers maintain passages between Lake Huron and Lakes Superior and Michigan. Icebreaker operations can also be seen around Manitoulin Island in Lake Huron, and near major ports in Lake Superior and Lake

Michigan (which include Thunder Bay and Duloth in Lake Superior, Green Bay in Lake Michigan, and to a lesser extent, Milwaukee and Chicago further south).

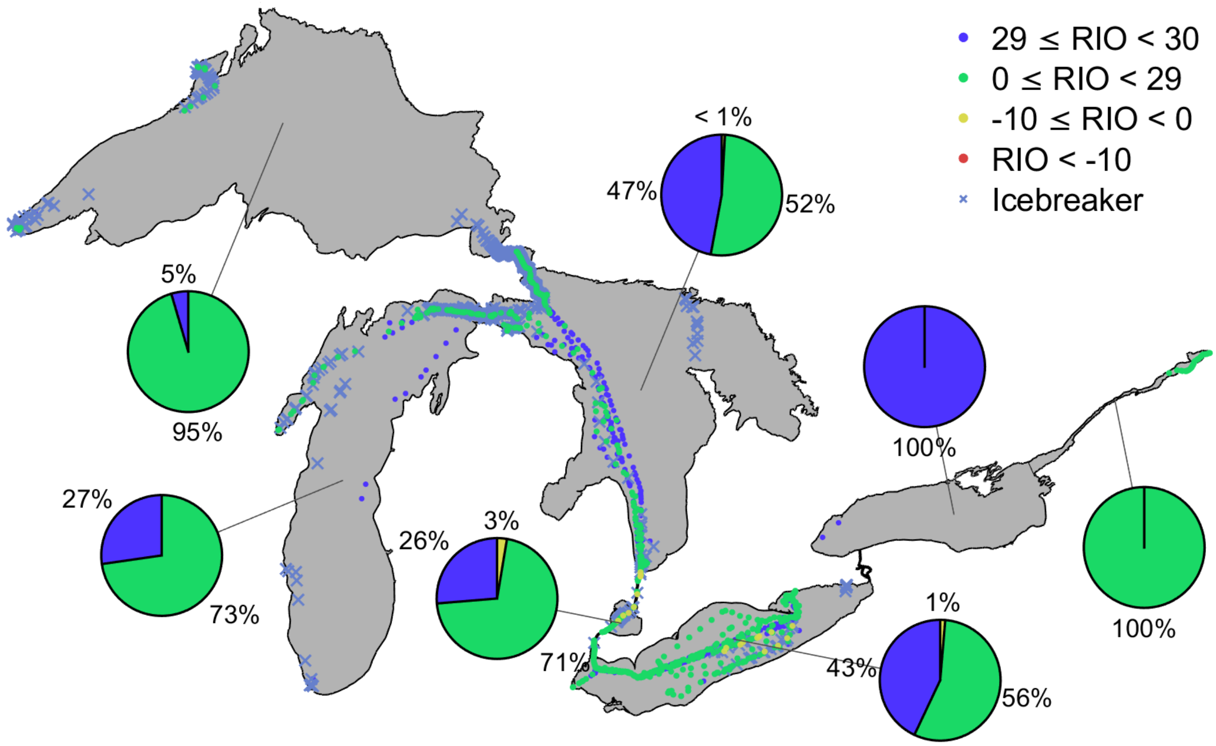

Figure 5-3: Distribution of calculated RIO values for ice class ships and icebreaker positions during the month of January from 2010 to 2019.

5.2.3 Monthly RIO Summary for February (2010-2019)

A greater number of negative RIO values were calculated for operations during February than for January, which remain isolated to the same general region that includes Lake Erie, the Detroit River, Lake St. Clair, and the St. Clair River. There are significantly fewer points representing trace ice conditions in February, and the shipping lane through Lake Huron to Sault Ste. Marie is largely populated with RIO values between 0 and 29.

Icebreaker operations can be seen within Lake Erie alongside the locations of negative RIO values, and it appears that icebreakers also maintain a passage between Lake Huron and Lake Michigan, on at least one occasion through to Chicago. No AIS points are contained within Lake Superior during February, which is likely a result of heavy ice conditions that preclude ship operations as well as the closure of the Soo Locks in mid-January.

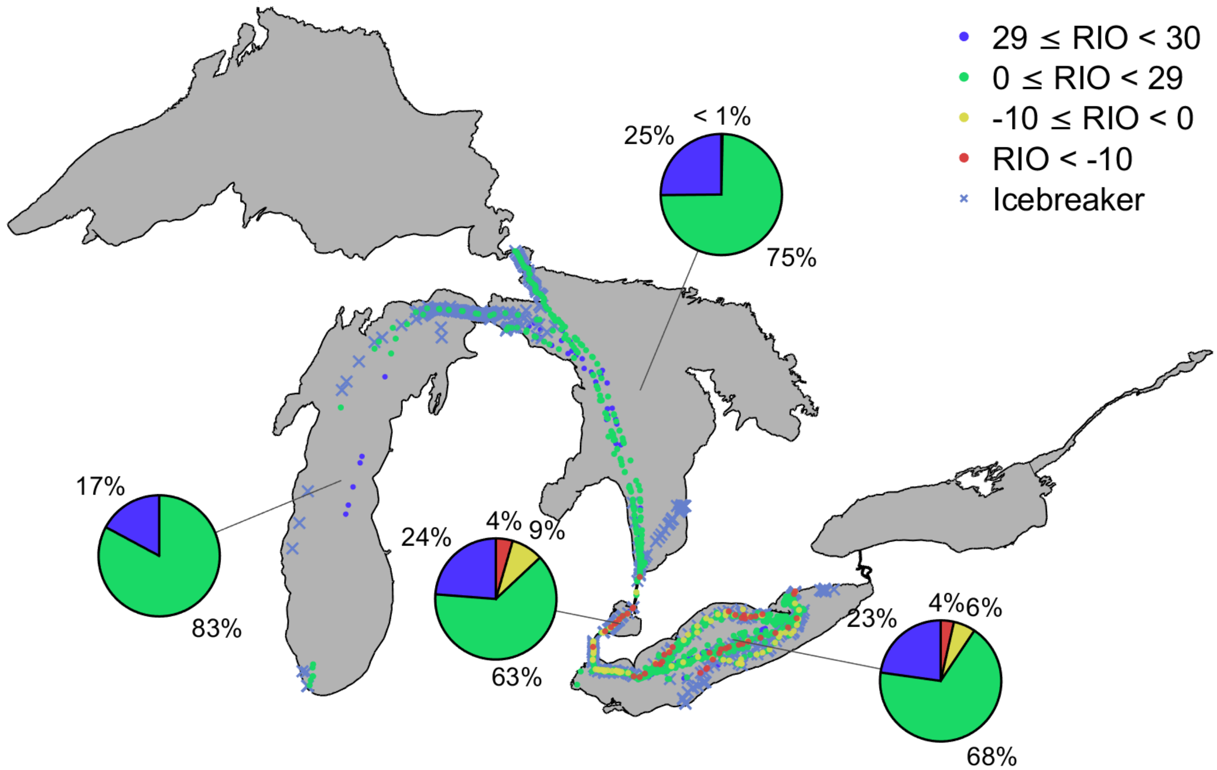

Figure 5-4: Distribution of calculated RIO values for ice class ships and icebreaker positions during the month of February from 2010 to 2019.

5.2.4 Monthly RIO Summary for March (2010-2019)

Substantially more data was available for March than previous months, which can be attributed to higher traffic once the Seaway (typically) reopens from winter shutdown by the middle of the month, as well as more frequent presence of ice in March along trafficked routes. A dense cluster of negative RIO values is again present in Lake Erie, the Detroit River, Lake St. Clair, and the St. Clair River. Unlike previous months, additional clusters of negative RIO values can be seen between Lake Huron and Lakes Superior and Michigan.

However, there also appears to be heavy icebreaker support during March in all three regions with negative RIO clusters. Additional negative RIO values can be seen in the ports of Thunder Bay and Duloth in Lake Superior, with corresponding icebreaker records in said areas. Elsewhere, a mix of operations in mild and trace ice conditions (with icebreaker support/presence) can be seen within Lake Huron and along the St. Lawrence River. Operations within Lake Ontario, southern Lake Michigan, and the interior of Lake Superior were primarily in trace ice conditions. In these regions, there were correspondingly few icebreaker records beyond those along a route to Thunder Bay in Lake Superior.

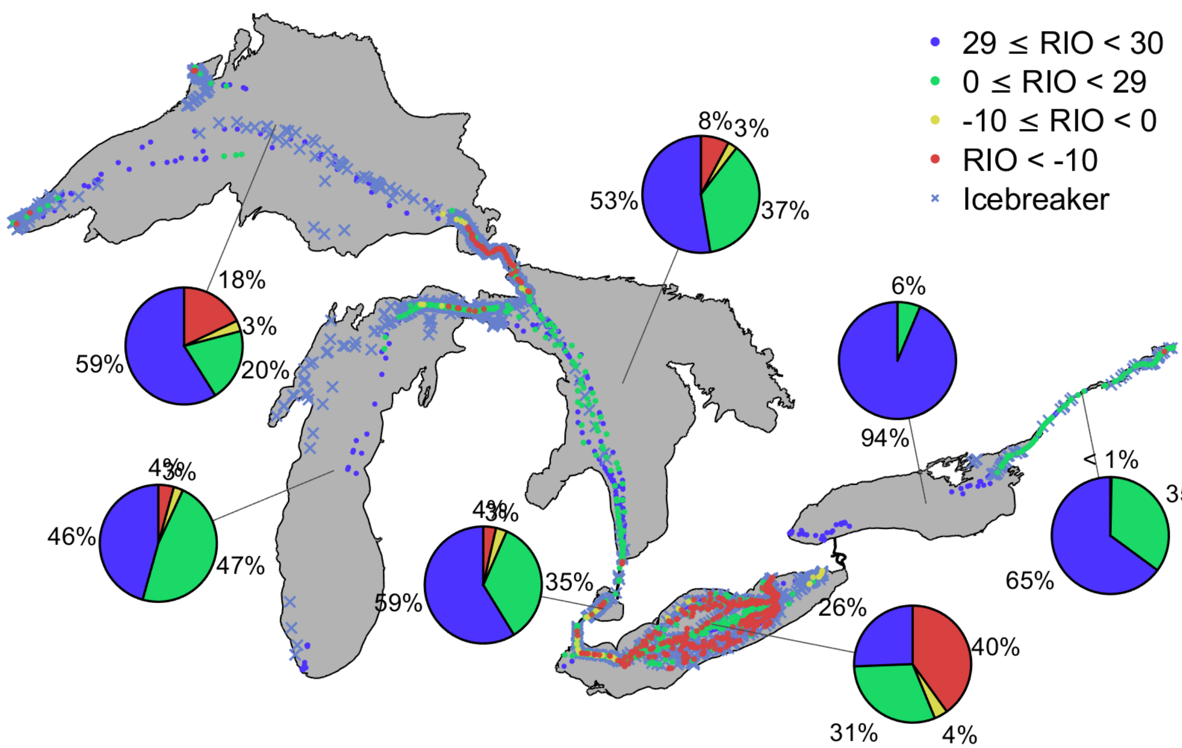

Figure 5-5: Distribution of calculated RIO values for ice class ships and icebreaker positions during the month of March from 2010 to 2019.

5.2.5 Monthly RIO Summary for April (2010-2019)

In general, the distribution of RIO values throughout the lakes was fairly similar between March and April, although the ratio of negative to positive RIO values was noticeably higher in April. A very large cluster of negative RIO values can be seen in the eastern half of Lake Erie, which is a known problem area for consistent ice build-up following the Spring breakup of ice further upstream (U.S. Army Engineer District Detroit, 1979). Additional clusters of negative RIO values exist between Lake Huron and Lakes Superior and Michigan, along the St. Lawrence River, and again near Thunder Bay and Duloth in Lake Superior.

Following the pattern demonstrated in March, icebreaker support is apparent at each of these locations, and additional points with negative RIO values can be seen within Lake Superior, northern Lake Michigan, and Lake St. Clair. There are relatively few points in mild ice conditions in April (with RIO values between 0 and 29), which would suggest that the majority of ship operations in ice during this month are within persisting patches of heavy ice and rubble buildup along chokepoints without alternative routes.

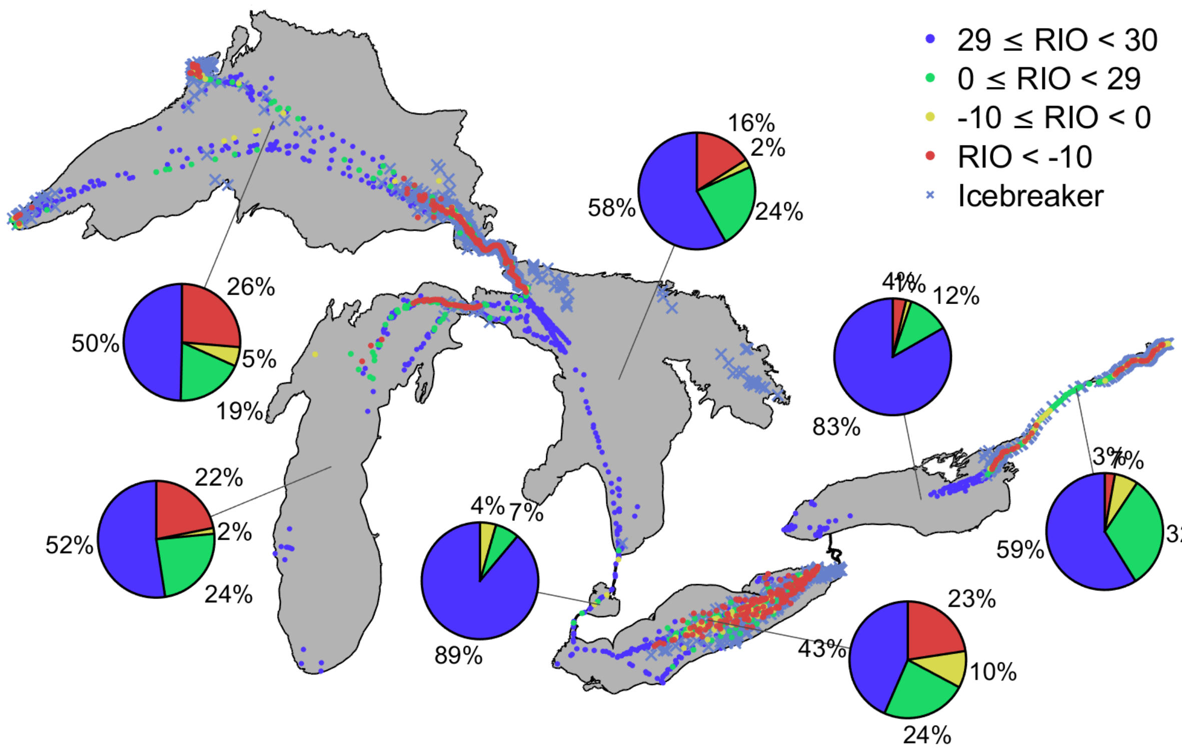

Figure 5-6: Distribution of calculated RIO values for ice class ships and icebreaker positions in during the month of April from 2010 to 2019.

5.3 Further Analysis of RIO Relationship to Ship Operations

Additional analysis of historic ship operations in the region was conducted within the context of the calculated RIO values. The objective of this analysis was to highlight potential relationships between other known operational factors (such as ship speed or vessel type) and the range of observed RIO values. This was expected to provide valuable insight into the current nature of ship operations in the region which could be compared to POLARIS guidelines and used to assess the relevance of these existing guidelines and feasibility of adapting them for operations in lake ice.

5.3.1 Ship Operating Speed

Probability Density Functions of ship speed were generated for RIO ranges as a means of comparing ship operations to POLARIS guidelines. While POLARIS recommendations make no distinction between RIO values between 0 and -10 versus those below -10 for non-Polar Class ships, separate distributions were generated for each range in order to highlight possible differences in operations during highly negative RIO values. Similarly, an additional distribution was generated for RIO values between 29 and 30 in order to provide a reference probability distribution for "ideal" operations when there is only trace ice present. Histograms with a bin width of 1 knot were used to generate these distributions, and a scaling factor was applied to each bin count to address differences in exposure at different speeds, assuming uniform or unbiased (speed independent) AIS reporting rates. This was achieved by multiplying the raw count in each bin by a factor equal to the bin's median speed prior to generating the distributions. These distributions are shown in Figure 5-7.

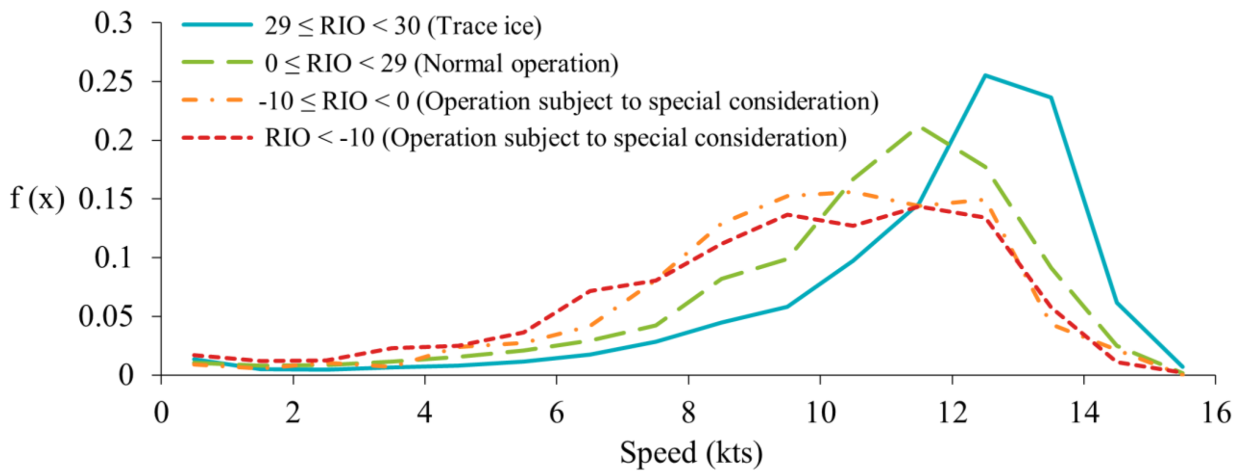

Figure 5-7: Probability Density Functions of ship speed, scaled to account for exposure.

The probability distributions of ship speed demonstrate a clear trend of speed reduction with increasingly negative RIO values, both for mild ice conditions versus trace ice and further reduced speed in increasingly severe ice (as indicated by increasingly negative RIO values). A potential factor that may have affected the extent of apparent speed reduction would be local variations in ice conditions that may allow ships to transit along relatively ice-free passages through the more heavily ice-covered regions described by the available ice charts. In addition, current practices during ice operations involve close coordination between commercial ships and both the Canadian and US coast guards, who perform ice management with dedicated icebreaking ships to maintain safe passages. Both coast guards are also known to provide ice-routing recommendations or operational restrictions such as daylight-only navigation in particularly hazardous ice conditions (English, Hackston, Greenway, & Helland, 2014).

The data presented here suggest Great Lakes operators take a flexible approach and reduce their speeds to reflect unfavorable ice conditions, although the degree of speed reduction differs from current POLARIS recommendations for ships in similar ice conditions (IMO, 2016). POLARIS conservatively recommends a speed limit of 3 knots for ships below Polar Class 5 (which applies to all ships in the dataset) during “elevated risk operations” corresponding to RIO values below 0. The speed limit recommendations for Polar Class ships (of 5 to 11 knots) more closely match the exposure-corrected median speeds for the AIS records in this dataset. However, ships with lower rated ice classes likely have their own ship-specific operational limits and procedures that could allow for higher transit speeds in particular ice conditions, which would be outlined within each ship’s specially tailored Polar Water Operational Manual (PWOM) as per the Polar Code. It appears that many ships of lower rated ice classes safely operate effectively in relatively mild ice conditions that could present potential issues to other ships of that same ice class. This implies that some portion of the studied ice-class ships may be ice-strengthened beyond the requirements of their rated ice-classes.

It should also be noted that speed values used to generate these distributions were obtained from ship AIS records, which correspond to speed-over-ground. Due to water currents along the river regions and enclosed waterways, the relative ice-ship velocity is potentially lower in many cases and may more closely reflect the speed recommendations suggested by the POLARIS methodology.

While further work is needed to assess the magnitude of speed reduction that is appropriate for the Great Lakes, the main observation in the context of the present research is that operators do currently employ speed reductions as an ice risk mitigation approach. A more complete assessment of local ice conditions and operational risk mitigations would be necessary in future work to assign appropriate speed reduction guidelines similar to those in POLARIS for operations in lake ice.

5.3.2 Vessel Type

Each AIS record includes a vessel type field which roughly classifies the type of ship that transmitted the signal. In order to further identify potential trends in differences of operational behavior in ice with respect to vessel type, the binned AIS data by RIO range (corresponding to the same operational risk category ranges used by POLARIS) was grouped by vessel type. This data is shown in Table 5-3.

Table 5-3: Number of AIS records per RIO bin for ice-class ships by vessel type.

Vessel Type	AIS Record Count by RIO Bin			
	RIO < -10	-10 ≤ RIO < 0	0 ≤ RIO < 29	29 ≤ RIO < 30
Bitumen Tanker	1	0	40	76
Bulk Carrier	573	227	2068	3193
Buoy/Lighthouse Vessel	20	3	64	103
Cement Carrier	0	0	19	73
Chemical/Oil Products Tanker	438	156	2053	2062
Fishing Support Vessel	3	0	2	32
General Cargo Ship	101	41	1173	1724
Oil Products Tanker	89	10	195	206
Self Discharging Bulk Carrier	0	4	87	63
Tug	14	4	83	72

The majority of verified ice class ships fell into one of three general categories: "Bulk Carrier," "Chemical/Oil Products Tanker," and "General Cargo Ship." A total of 55, 22, and 26 unique ships respectively were represented for these categories out of a total of 114 ice class ships. Visual breakdowns of the operational risk category RIO ranges for these three vessel types (and a combined category for vessels of other types) are shown on the pie charts below in Figure 5-8.

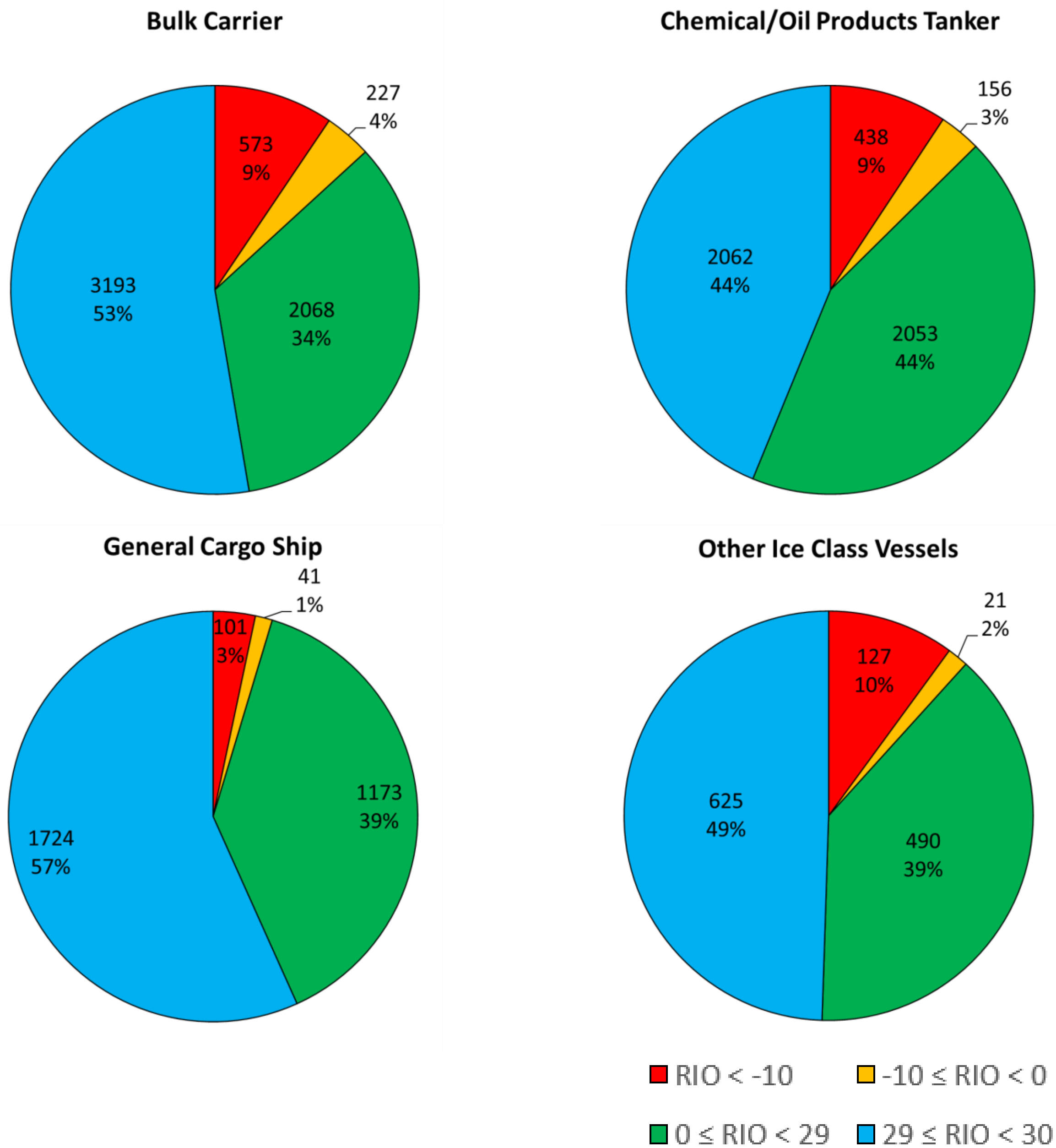

Figure 5-8: Relative occurrences of ice-class ship RIO values by ship classification for three most-represented vessel types and remaining ice-class vessels.

As this is a very high-level overview of broadly defined ship categories, it is difficult to draw specific conclusions from this data alone. However, it is evident that within the confines of this dataset, cargo ships spent a larger proportion of their operations in trace-ice conditions than bulk carriers and tankers. Similarly, those ships experienced a significantly decreased incidence of both slightly (<0) and significantly (<-10) negative RIO occurrences over the other two well-represented categories. Aside from natural variance within a limited dataset, there are a number of possible factors that may have contributed to this. For instance, it is possible that the "General Cargo Ship" category includes a number of ships that operate primarily around the population centres of the lower Great Lakes and thus spend a larger proportion of their operations within consistently ice-free regions such as Lake Ontario. Conversely, tankers and bulk carriers may service mines and refineries in more remote areas deeper in the Great Lakes which necessitates travel through consistently ice-covered passages. Due to the nature of their operations, these ships may also be less flexible in their schedules and may be more likely to operate through the winter months when other ships would elect to schedule transits during more favourable conditions. In either case, this may merit additional consideration in future work to provide context when developing guidelines and regulations for ship operations in lake ice.

Chapter 6:

Conclusion

6.1 Overview

A study of ice class ship operations in lake ice within the North American Great Lakes for ice seasons between 2010 and 2019 has been completed. In this investigation, the POLARIS methodology has been applied to calculate RIO values for ships of known ice-class operating in ice conditions based on ice charts corresponding to historical ship tracks obtained from AIS data. Additionally, a parallel analysis of ice conditions in the lakes over the same 10-year period was conducted to better understand and characterize the range and severity of ice conditions expected throughout the Great Lakes region during both typical and severe ice seasons. This provided additional context for the analysis of historic AIS data, as it highlighted the range of ice conditions that the region's ship operators expected and chose to operate within. Both aspects of this work estimated historic ice conditions using ice charts obtained from Canadian Ice Service's daily digital chart archive.

6.2 Results

6.2.1 Ice Condition Analysis

As the reviewed literature previously indicated, the 10-year analysis of seasonal ice conditions clearly affirmed that there is significant year-to-year variability in the potential severity and duration of a given ice season in the North American Great Lakes.

Of the ice seasons studied, the 2013 – 2014 ice season was the most severe and demonstrated a maximum overall ice extent of 95.6% across the entire Great Lakes region. The second-most severe ice season, 2014-2015, demonstrated a similarly high maximum ice extent of 92.3%. In comparison, the mildest ice season, the 2011 – 2012 ice season, had a maximum of only 12.5%, and the second-mildest ice season (2016-2017) demonstrated a maximum of 21.4%. Other seasons span the entire range between these values, with no clearly observable trends or bias towards particularly severe or mild seasons.

6.2.2 Ship Traffic Analysis

The results obtained from this study provide valuable insights into the nature of current ship operations in ice within the Great Lakes as viewed through the lens of the POLARIS method. Overall, the trends observed from historical ship operations suggest that current practices are well aligned with POLARIS guidelines (89% of ice operations correspond to positive RIO values) and that risk mitigating measures currently used in the Great Lakes, such as icebreaker support and speed reductions when transiting through ice, are compatible with the approaches recommended in POLARIS.

Additionally, the vast majority of negative RIO values that were calculated (1362 of 1684) occurred during 2014 and 2015, the two heaviest ice seasons during the studied period. This suggests that operators avoid potentially hazardous ice conditions when possible (as these do tend to occur somewhere within the lakes during most ice seasons), and rarely transit through heavily ice-covered waters except when no alternative route is available during the heaviest ice seasons. During these seasons, icebreaker activity was also at its highest in the region, suggesting their discretionary use during severe ice seasons to mitigate hazards posed to shipping operations.

For the present research that was described in this work, it should again be noted that approximate ice thickness equivalences between lake ice and sea ice types used in POLARIS have been assumed. Any future work of a similar nature with the aim of establishing new regulatory guidelines for ship operations in lake ice should absolutely explore this topic in further detail. Full-scale differences between sea and lake ice should be studied to determine whether they fall within the level of certainty allowable for an approximate index-based methodology such as POLARIS.

6.2.3 Icebreaker Operations

The analysis of the relationship between icebreaker operations and negative RIO occurrences implies that ice management operations are significantly increased in the Great Lakes as a mitigating measure during seasons when hazardous ice conditions that pose a threat to shipping operations are present (as calculated using the POLARIS method and described methodology). While the analysed data was grouped monthly, the correlating spatial relationship between negative RIO occurrence and icebreaker operations along shared routes in Appendix D strongly suggests that at significant portion of negative RIOs are likely representative of ship operations in managed ice.

6.2.4 Ship Operating Speed

The probability distributions of ship speed demonstrated binned by RIO range demonstrated a clear trend of speed reduction with increasingly negative RIO values, both for mild ice conditions versus trace ice and further reduced speed in increasingly severe ice. The data presented here suggest Great Lakes operators take a flexible approach and reduce their speeds to reflect unfavorable ice conditions, with distributions of ship speed for AIS records binned by RIO range skewing towards slower speeds with lower calculated RIO. However, the apparent degree of speed reduction differs from current POLARIS recommendations for ships in similar ice conditions, given that POLARIS conservatively recommends a speed limit of 3 knots for ships below Polar Class 5 (which applies to all ships in the dataset) during “elevated risk operations” corresponding to RIO values below 0. The speed limit recommendations for Polar Class ships (at 5 to 11 knots) more closely match the apparent typical speeds in ice for the AIS records in this dataset, which suggests that some portion of the studied ice-class ships may be ice-strengthened beyond the requirements of their rated ice-class. This discrepancy may be partially explained by AIS records including speed-over-ground versus relative speed between ships and the water current/ice motion. Due to water currents along the river regions and enclosed waterways, the relative ice-ship velocity is potentially lower in many cases and may more closely reflect the speed recommendations suggested by the POLARIS methodology.

6.2.5 Ship Type

The majority of verified ice class ships in the AIS dataset fell into one of three general categories: "Bulk Carrier," "Chemical/Oil Products Tanker," and "General Cargo Ship." While this aspect of the analysis was a high-level overview of broadly defined ship categories, it was evident that cargo ships spent a larger proportion of their operations in trace-ice conditions than bulk carriers and tankers. Correspondingly, cargo ships experienced a significantly decreased incidence of both slightly (<0) and significantly (<-10) negative RIO occurrences over the other two well-represented categories. There are a number of possible factors that may have contributed to this effect, such as the type of schedules these ships operate under, the areas they service, or potential differences of operator policy when route-planning with the potential for ice presence. Regardless of the specific root causes, this may merit additional consideration in future work to provide context when developing guidelines for ship operations in lake ice.

6.3 Recommendations for Future Work

While it is well known that lake ice and sea ice/glacial ice (as considered by the Polar Code) have different properties, it is not evident how such differences in ice types would translate into differences between the current POLARIS method and a modified "Freshwater POLARIS". To this end, additional research is needed to assess the impact of differences in ice properties in terms of potential for ship damage and appropriate speed limits, as well as assessing the need for possible modification of Risk Index Values for lake ice.

A more detailed analysis of the correlation between historical ship operations and icebreaking activity is suggested to provide a better understanding of the degree to which ships operate in managed ice conditions, especially of known specific instances of negative RIO occurrences.

Further exploration of the POLARIS guidelines in the context of adapting mitigating measures into operational guidance for the Great Lakes is also recommended. The use of a unified ice-class system for ships operating in the Great Lakes would be required to allow for the calculation of RIO values for all vessels in the region. Clarifying vessel ice classes would furthermore allow for the inclusion of verifiable un-strengthened (non-ice class) ships which in turn would expand the available dataset for future analysis.

Since ice conditions used in this study reflect general ice chart conditions rather than the specific ice conditions encountered by ships in transit, opportunities to obtain or record detailed local ice condition information should be explored where possible for analysis of historic ship operations (e.g. from ship logs or other ice record sources). A further recommendation for regulators looking to implement POLARIS-like guidelines for lake ice operations would be a data-collection initiative that encourages detailed record keeping of operational local ice conditions for ice class ships that transit the region.

However, in summary, the results of this preliminary study do suggest that a specifically tailored POLARIS-like methodology presents a promising approach to aid ship operations in lake ice conditions similar to that found within the Laurentian Great Lakes during the studied 10-year period. The potential to codify current best-practices for shipping operations in the Great Lakes into such a modified method would help ensure consistency in the assessment of operational capabilities and limitations for different classes of vessels operating in lake ice. This in turn would provide greater clarity regarding expected mitigating measures and would help support effective decision-making relating to ship operations in ice. Further work to advance this approach represents an exciting direction for continued research and development.

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Appendices

Appendix A

Ice Chart Interpretation

Appendix A1 Canadian Ice Service Egg Code Interpretation

Egg-Codes for Sea Ice Stages-of-Development (Canadian Ice Service, 2016).

Description	*Thickness*	*Code*
New ice	< 10 centimetres	1
Nilas, Ice rind	< 10 centimetres	2
Young Ice	10 - 30 centimetres	3
Grey Ice	10 - 15 centimetres	4
Grey-white ice	15 - 30 centimetres	5
First-year ice	>= 30 centimetres	6
Thin first-year ice	30 - 70 centimetres	7
First stage thin first-year	30 - 50 centimetres	8
Second stage thin first-year	50 - 70 centimetres	9
Medium first-year ice	70 - 120 centimetres	1·
Thick first-year ice	> 120 centimetres	4·
Old ice	-	7·
Second-year ice	-	8·
Multi-year ice	-	9·
Ice of land origin	-	▲·
Undetermined or unknown	-	X·

Egg-Codes for Lake Ice Stages-of-Development (Canadian Ice Service, 2016).

Description	*Thickness*	*Code*
New lake ice	< 5 centimetres	1
Thin lake ice	5 -15 centimetres	4
Medium lake ice	15 - 30 centimetres	5
Thick lake ice	30 -70 centimetres	7
Very thick lake ice	> 70 centimetres	1·

Appendix A2 SIGRID 3 Digital Chart Interpretation

Mandatory columns (fields) in the SIGRID-3 database file (WMO, 2004).

Column or Field number	*Column or Field name*	*Data Type*	*Description*
1	AREA	Double	Area of polygon in same units as those used for the projection
2	PERIMETER	Double	Perimeter of polygon in same units as those used for the projection
3	CT	Text	Total concentration
4	CA	Text	Partial concentration of thickest ice
5	SA	Text	Stage of development of thickest ice
6	FA	Text	Form of thickest ice
7	CB	Text	Partial concentration of second thickest ice
8	SB	Text	Stage of development of second thickest Ice
9	FB	Text	Form of second thickest ice
10	CC	Text	Partial concentration of the third thickest ice
11	SC	Text	Stage of development of third thickest ice
12	FC	Text	Form of third thickest ice
13	CN	Text	Stage of development of ice thicker than SA but with concentration less then 1/10
14	CD	Text	Stage of development of any remaining class of ice
15	FP	Text	Predominant form of ice
16	FS	Text	Secondary form of ice
17	Poly_type	Text	Either Land (L), Ice-free Water (W), or Ice of any concentration (I)
18…56	Optional fields	Text	-

SIGRID-3 codes for concentration, as used for variable identifiers CT, CA, CB, CC, AV, AK, AM, and AT (WMO, 2004).

Description	*Code*
Ice Free	55
Less than 1/10 (open water)	01
Bergy Water	02
1/10	10
2/10	20
3/10	30
4/10	40
5/10	50
6/10	60
7/10	70
8/10	80
9/10	90
10/10	92
9/10 –10/10 or 9+/10	91
8/10 – 9/10	89
8/10 – 10/10	81
7/10 – 9/10	79
7/10 – 8 /10	78
6/10 – 8/10	68
6/10 – 7/10	67
5/10 – 7/10	57
5/10 – 6/10	56
4/10 – 6/10	46
4/10 – 5/10	45
3/10 – 5/10	35
3/10 – 4/10	34
2/10 – 4/10	24
2/10 – 3/10	23
1/10 – 3/10	13
1/10 – 2/10	12
Undetermined / Unknown	99

Enumerated SIGRID-3 Codes for thickness of ice or stage of development, as used for variable identifiers SA, SB, SC, CN, and CD (WMO, 2004).

Description	*Thickness*	*Code*
Ice Free	-	55
Brash Ice	Given by fields AV, AT, AM, AT	70
No Stage of Development	-	80
New Ice	< 10 cm	81
Nilas, Ice Rind	< 10 cm	82
Young Ice	10 - <30 cm	83
Grey Ice	10 - <15 cm	84
Grey - White Ice	15 - <30 cm	85
First Year Ice	≥30 - 200 cm	86
Thin First Year Ice	30 - <70 cm	87
Thin First Year Stage 1	30 - <50 cm	88
Thin First Year Stage 2	50 - <70 cm	89
For Later Use	-	90
Medium First Year Ice	70 - <120 cm	91
For Later Use	-	92
Thick First Year Ice	≥120 cm	93
For Later Use	-	94
Old Ice	-	95
Second Year Ice	-	96
Multi-Year Ice	-	97
Glacier Ice	-	98
Undetermined/Unknown	-	99

Appendix B

Selected MATLAB Code

Appendix B1 Load Ice Chart(s) for Date Range

```
function ind_list = getChartInds(startDate, endDate)
        load chartref.mat %Index of available charts

        date_list = startDate:endDate; %Assumed to be datetime
        ind_list = zeros(size(date_list,1),1);

        for i = 1:size(date_list,1)
            if ~isempty(refchart([refchart.datenum] == april_days(i,1)).chartind)
                ind_list(i) = refchart([refchart.datenum] ==
        date_list(i,1).chartind);
            else
                ind_list(i) = 0;
            end
        end
end


function [ice_chart] = loadChart(chart_ind,chart_dir,chart_list)

        delete([chart_dir 'Current Chart\*'])
        untar([chart_dir 'Archive\' chart_list(chart_ind).name],[chart_dir
        'Current Chart']); %Extract Ice Chart to working folder

        chart_name = dir([chart_dir 'Current Chart\*.shp']);
        proj_name = dir([chart_dir 'Current Chart\*.prj']);
        ice_chart = shaperead([chart_dir 'Current Chart\' chart_name(1).name]);

        icePolys = strcmp({ice_chart.POLY_TYPE},'I');
        waterPolys = strcmp({ice_chart.POLY_TYPE},'W');
        landPolys = strcmp({ice_chart.POLY_TYPE},'L');

        remainingPolys = ~(icePolys | waterPolys | landPolys);
        if remainingPolys
            newPolyType = ice_chart(remainingPolys).POLY_TYPE;
        end

        ice_chart = ice_chart(icePolys | waterPolys);

        if size(proj_name,1)>0
            proj_file = fileread([chart_dir 'Current Chart\' proj_name(1).name]);
            proj = projcrs(proj_file);
            for i = 1:size(ice_chart,1)
                [ice_chart(i).Y,ice_chart(i).X] =
        projinv(proj,ice_chart(i).X,ice_chart(i).Y);
            end
        end

end
```

Appendix B2 Interpret Ice Regime from Ice Chart Data

```
function [iceCond] = parseChart(regionCond)
if strcmp(regionCond.POLY_TYPE,'W')
    iceCond = struct('TotalIce', 0,...
        'NewLakeIce', 0,...
        'ThinLakeIce', 0,...
        'MediumLakeIce', 0,...
        'ThickLakeIce', 0,...
        'VeryThickLakeIce', 0,...
        'OtherIce',0);
elseif strcmp(regionCond.POLY_TYPE,'I')
    iceCond = struct('TotalIce', 0,...
        'NewLakeIce', 0,...
        'ThinLakeIce', 0,...
        'MediumLakeIce', 0,...
        'ThickLakeIce', 0,...
        'VeryThickLakeIce', 0,...
        'OtherIce',0);

    CT = regionCond.CT;
    CT = str2double(CT);

    if CT > 0
        CA = regionCond.CA;
        CA = str2double(CA);
        CB = regionCond.CB;
        CB = str2double(CB);
        CC = regionCond.CC;
        CC = str2double(CC);
        SA = regionCond.SA;
        SA = str2double(SA);
        SB = regionCond.SB;
        SB = str2double(SB);
        SC = regionCond.SC;
        SC = str2double(SC);
        if CT == 91 || CT == 92
            iceCond.TotalIce = 10;
        else
            iceCond.TotalIce = CT/10;
        end

        % Egg Codes:
        % 81 - 'New Lake Ice', '<5 cm', '1'
        % 84 - 'Thin Lake Ice', '5-15cm', '4'
        % 85 - 'Medium Lake Ice','15-30cm','5'
        % 87 - 'Thick Lake Ice','30-70cm','7'
        % 91 - 'Very Thick Lake Ice','>70cm','1.'
        % 99 - Possibly ice chunks?
        % 86 - Possibly a river ice type?
        % 83 - Appears in northern lake huron
        % -9 - Blank/missing
```

```
if iceCond.TotalIce > 0
    if CA < 0 && CB < 0 %CA not filled in if only one ice type is present
        if SA == 81
            iceCond.NewLakeIce = iceCond.TotalIce;
        elseif SA == 84
            iceCond.ThinLakeIce = iceCond.TotalIce;
        elseif SA == 85
            iceCond.MediumLakeIce = iceCond.TotalIce;
        elseif SA == 87
            iceCond.ThickLakeIce = iceCond.TotalIce;
        elseif SA == 91
            iceCond.VeryThickLakeIce = iceCond.TotalIce;
        else
            iceCond.OtherIce = iceCond.TotalIce;
            if ~(SA == 99 || SA == 86 ||  SA == 83 ||SA == -9)
                warning('Unknown stage of development egg code')
            end
        end

    elseif CA > 0
        if SA == 81
            iceCond.NewLakeIce = CA/10;
        elseif SA == 84
            iceCond.ThinLakeIce = CA/10;
        elseif SA == 85
            iceCond.MediumLakeIce = CA/10;
        elseif SA == 87
            iceCond.ThickLakeIce = CA/10;
        elseif SA == 91
            iceCond.VeryThickLakeIce = CA/10;
        else
            iceCond.OtherIce = CA/10;
            if ~(SA == 99 || SA == 86 || SA == 83 || SA == -9)
                warning('Unknown stage of development egg code')
            end
        end

        if CB > 0
            if SB == 81
                iceCond.NewLakeIce = iceCond.NewLakeIce + CB/10;
            elseif SB == 84
                iceCond.ThinLakeIce = iceCond.ThinLakeIce + CB/10;
            elseif SB == 85
                iceCond.MediumLakeIce = iceCond.MediumLakeIce + CB/10;
            elseif SB == 87
                iceCond.ThickLakeIce = iceCond.ThickLakeIce + CB/10;
            elseif SB == 91
                iceCond.VeryThickLakeIce = iceCond.VeryThickLakeIce + CB/10;
            else
                iceCond.OtherIce = CB/10;
                if ~(SB == 99 || SB == 86 || SB == 83 || SB == -9)
                    warning('Unknown stage of development egg code')
                end
            end
```

```
                    if CC > 0
                        if SC == 81
                            iceCond.NewLakeIce = iceCond.NewLakeIce + CC/10;
                        elseif SC == 84
                            iceCond.ThinLakeIce = iceCond.ThinLakeIce + CC/10;
                        elseif SC == 85
                            iceCond.MediumLakeIce = iceCond.MediumLakeIce + CC/10;
                        elseif SC == 87
                            iceCond.ThickLakeIce = iceCond.ThickLakeIce + CC/10;
                        elseif SC == 91
                            iceCond.VeryThickLakeIce = iceCond.VeryThickLakeIce +
CC/10;
                        else
                            iceCond.OtherIce = CC/10;
                            if ~(SC == 99 || SC == 86 || SA == 83 || SC == -9)
                                warning('Unknown stage of development egg code')
                            end
                        end
                    end
                end
            end
        end
    end

    if iceCond.NewLakeIce +...
                  iceCond.ThinLakeIce+...
                  iceCond.MediumLakeIce+...
                  iceCond.ThickLakeIce+...
                  iceCond.VeryThickLakeIce+...
                  iceCond.OtherIce~= iceCond.TotalIce
        iceCond.OtherIce = iceCond.TotalIce - (iceCond.NewLakeIce +...
                                    iceCond.ThinLakeIce+...
                                    iceCond.MediumLakeIce+...
                                    iceCond.ThickLakeIce+...
                                    iceCond.VeryThickLakeIce);
        warning('Total ice concentration does not match sum of ice types')
    end
else
    iceCond = struct('TotalIce', [],...
        'NewLakeIce', [],...
        'ThinLakeIce', [],...
        'MediumLakeIce', [],...
        'ThickLakeIce', [],...
        'VeryThickLakeIce', [],...
        'OtherIce', []);
end

clearvars -except iceCond
end
```

Appendix B3 Calculate RIO and Equivalent Thickness from Lake Ice Regime

```
function [RIO] = getRIO(iceCond,iceClass)
ice_cond = struct('IceFree', 10-iceCond.Total,... % Sea Ice Equivalent Types
    'NewIce', iceCond.NewLakeIce,...
    'GreyIce', iceCond.ThinLakeIce,...
    'GreyWhiteIce', iceCond.MediumLakeIce,...
    'ThinFirstYear1', iceCond.ThickLakeIce/2,...
    'ThinFirstYear2', iceCond.ThickLakeIce/2,...
    'MediumFirstYearSub1m', 0,...
    'MediumFirstYear', iceCond.VeryThickLakeIce,...
    'ThickFirstYear', 0,...
    'SecondYear', 0,...
    'LightMultiYear', 0,...
    'HeavyMultiYear', 0);
if strcmp(iceClass,'PC1')
    riskIndex = [3 3 3 3 2 2 2 2 2 2 1 1];
elseif strcmp(iceClass,'PC2')
    riskIndex = [3 3 3 3 2 2 2 2 2 1 1 0];
elseif strcmp(iceClass,'PC3')
    riskIndex = [3 3 3 3 2 2 2 2 2 1 0 -1];
elseif strcmp(iceClass,'PC4')
    riskIndex = [3 3 3 3 2 2 2 2 1 0 -1 -2];
elseif strcmp(iceClass,'PC5')
    riskIndex = [3 3 3 3 2 2 1 1 0 -1 -2 -2];
elseif strcmp(iceClass,'PC6')
    riskIndex = [3 2 2 2 2 1 1 0 -1 -2 -3 -3];
elseif strcmp(iceClass,'PC7')
    riskIndex = [3 2 2 2 1 1 0 -1 -2 -3 -3 -3];
elseif strcmp(iceClass,'IASuper')
    riskIndex = [3 2 2 2 2 1 0 -1 -2 -3 -4 -4];
elseif strcmp(iceClass,'IA')
    riskIndex = [3 2 2 2 1 0 -1 -2 -3 -4 -5 -5];
elseif strcmp(iceClass,'IB')
    riskIndex = [3 2 2 1 0 -1 -2 -3 -4 -5 -6 -6];
elseif strcmp(iceClass,'IC')
    riskIndex = [3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8];
elseif strcmp(iceClass,'Unstrengthened')
    riskIndex = [3 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -8];
end
RIO = riskIndex(1)*ice_cond.IceFree + ...
    riskIndex(2)*ice_cond.NewIce + ...
    riskIndex(3)*ice_cond.GreyIce + ...
    riskIndex(4)*ice_cond.GreyWhiteIce + ...
    riskIndex(5)*ice_cond.ThinFirstYear1 + ...
    riskIndex(6)*ice_cond.ThinFirstYear2 + ...
    riskIndex(7)*ice_cond.MediumFirstYearSub1m + ...
    riskIndex(8)*ice_cond.MediumFirstYear + ...
    riskIndex(9)*ice_cond.ThickFirstYear + ...
    riskIndex(10)*ice_cond.SecondYear + ...
    riskIndex(11)*ice_cond.LightMultiYear + ...
    riskIndex(12)*ice_cond.HeavyMultiYear;
end
end
```

```
function [eqThickness] = getEqThickness(iceCond)

NewLakeIce = 2.5; % <5cm
ThinLakeIce = 10; % 5-15cm
MediumLakeIce = 22.5; % 15-30cm
ThickLakeIce = 50; % 30-70cm
VeryThickLakeIce = 100; % >70cm


eqThickness = (iceCond.NewLakeIce * NewLakeIce +...
              iceCond.ThinLakeIce * ThinLakeIce +...
              iceCond.MediumLakeIce * MediumLakeIce +...
              iceCond.ThickLakeIce * ThickLakeIce +...
              iceCond.VeryThickLakeIce * VeryThickLakeIce)/10;
end
```

Appendix C
Great Lakes Ice Conditions For 2010-2019 Ice Seasons

Appendix C1 Tables of Regional First and Last Ice Occurrences

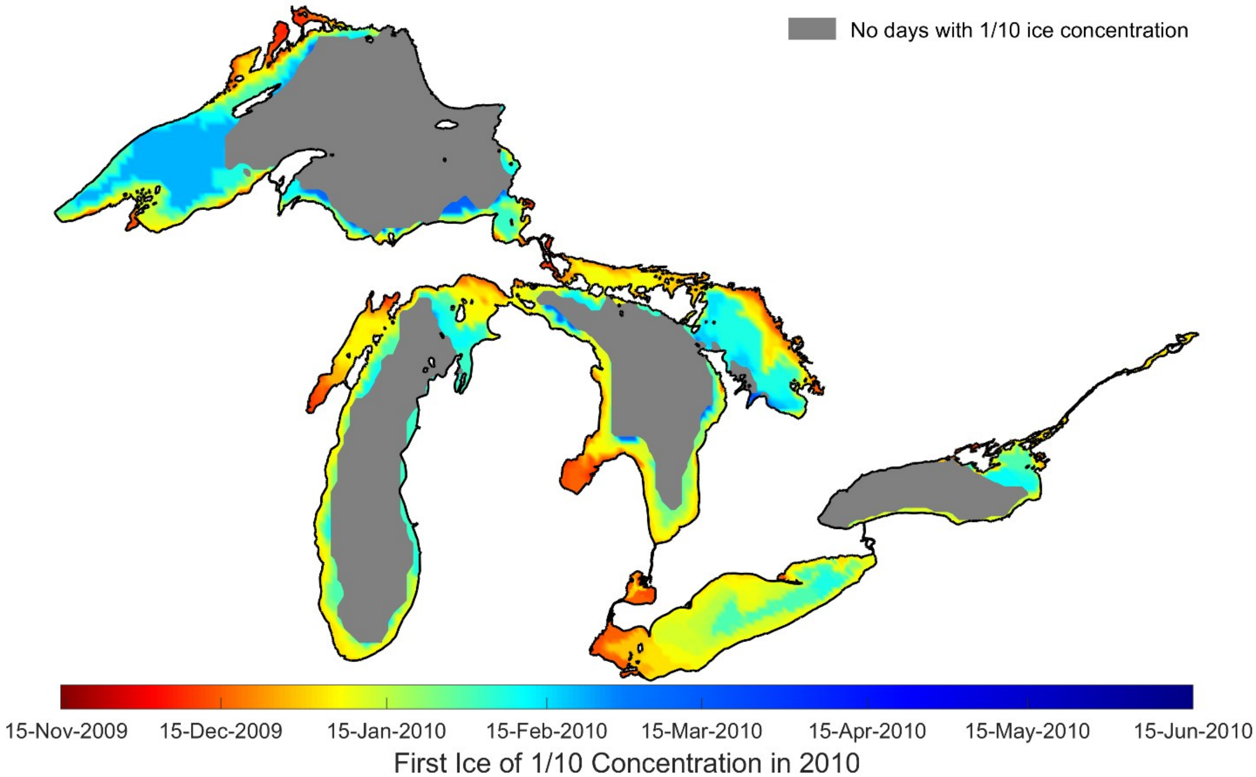
Appendix C1.1 Seasonal dates for first occurrences of ice >1/10 concentration

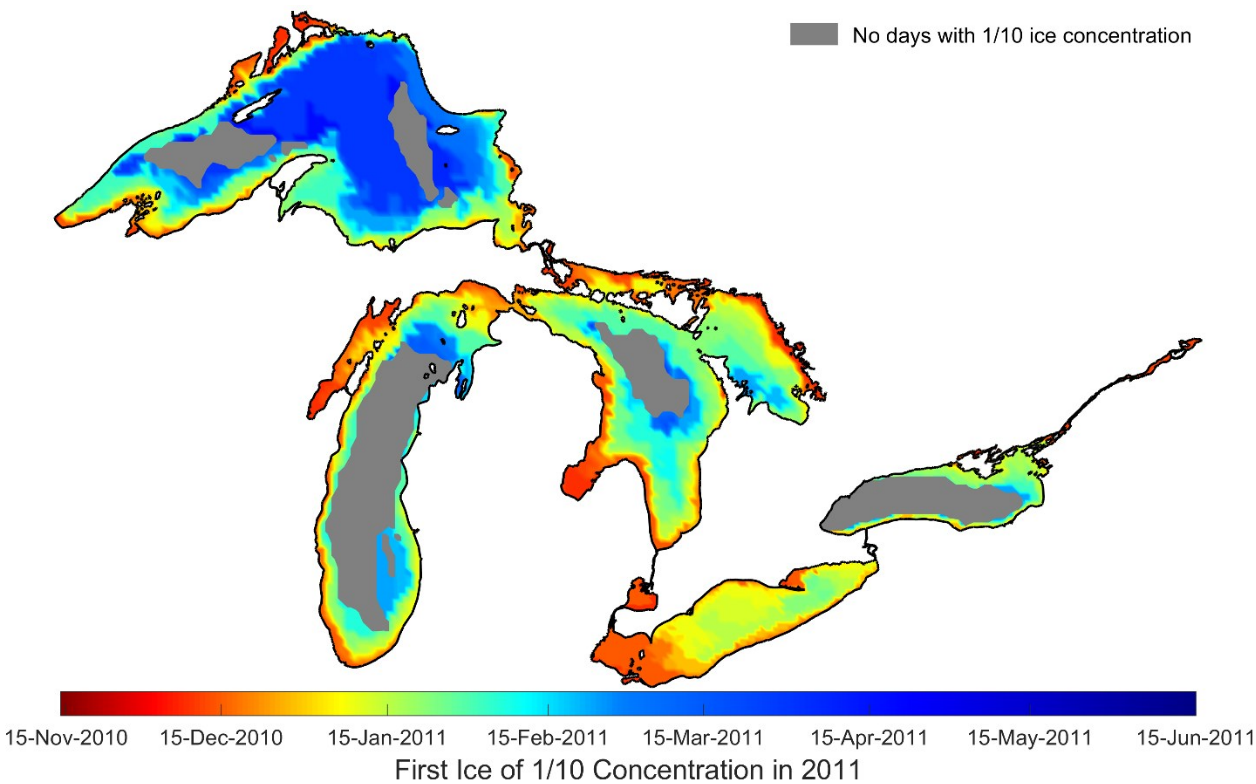
Ice Season	Overall Great Lakes	Upper St. Lawrence River	Lake Ontario	Lake Erie	St. Clair River to Detroit River	Lake Huron	Lake Michigan	Lake Superior
2009 – 2010	Dec 07	Dec 23	Dec 13	Dec 13	Dec 07	Dec 09	Dec 07	Dec 07
2010 – 2011	Dec 09	Dec 09	Dec 09	Dec 09	Dec 09	Dec 09	Dec 09	Dec 09
2011 – 2012	Dec 15	Dec 18	Dec 18	Jan 04	Dec 15	Dec 15	Dec 15	Dec 15
2012 – 2013	Nov 29	Dec 23	Dec 23	Dec 23	Dec 02	Dec 12	Nov 29	Nov 29
2013 – 2014	Nov 25	Nov 29	Nov 25	Nov 25	Nov 25	Nov 27	Nov 25	Nov 25
2014 – 2015	Nov 15	Jan 01	Nov 24	Nov 23	Nov 16	Nov 18	Nov 15	Nov 15
2015 – 2016	Nov 27	Dec 30	Dec 30	Jan 05	Dec 29	Dec 29	Nov 27	Nov 27
2016 – 2017	Dec 11	Dec 16	Dec 15	Dec 13	Dec 11	Dec 12	Dec 11	Dec 11
2017 – 2018	Nov 16	Dec 13	Dec 13	Dec 11	Dec 11	Dec 11	Nov 16	Nov 16
2018 – 2019	Nov 16	Dec 21	Nov 21	Dec 10	Nov 18	Nov 21	Nov 16	Nov 16

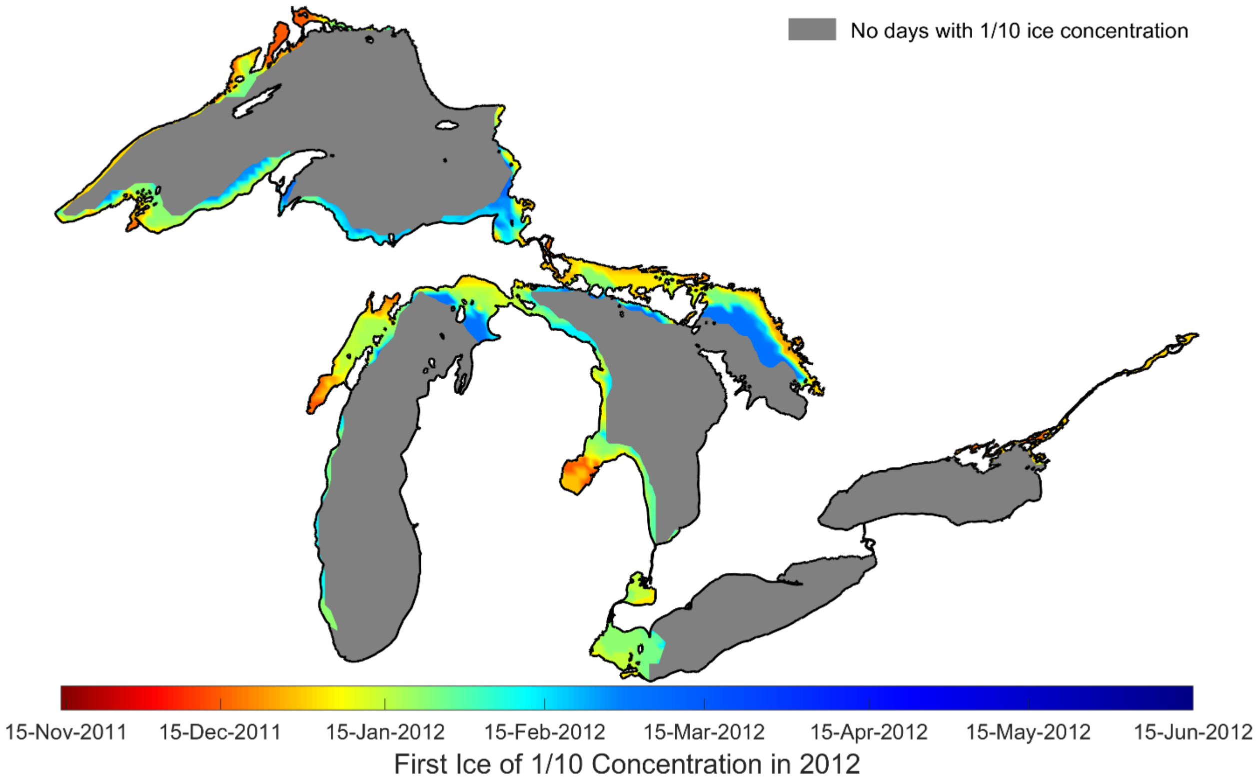
Appendix C1.2 Dates for last occurrences of ice >1/10 concentration

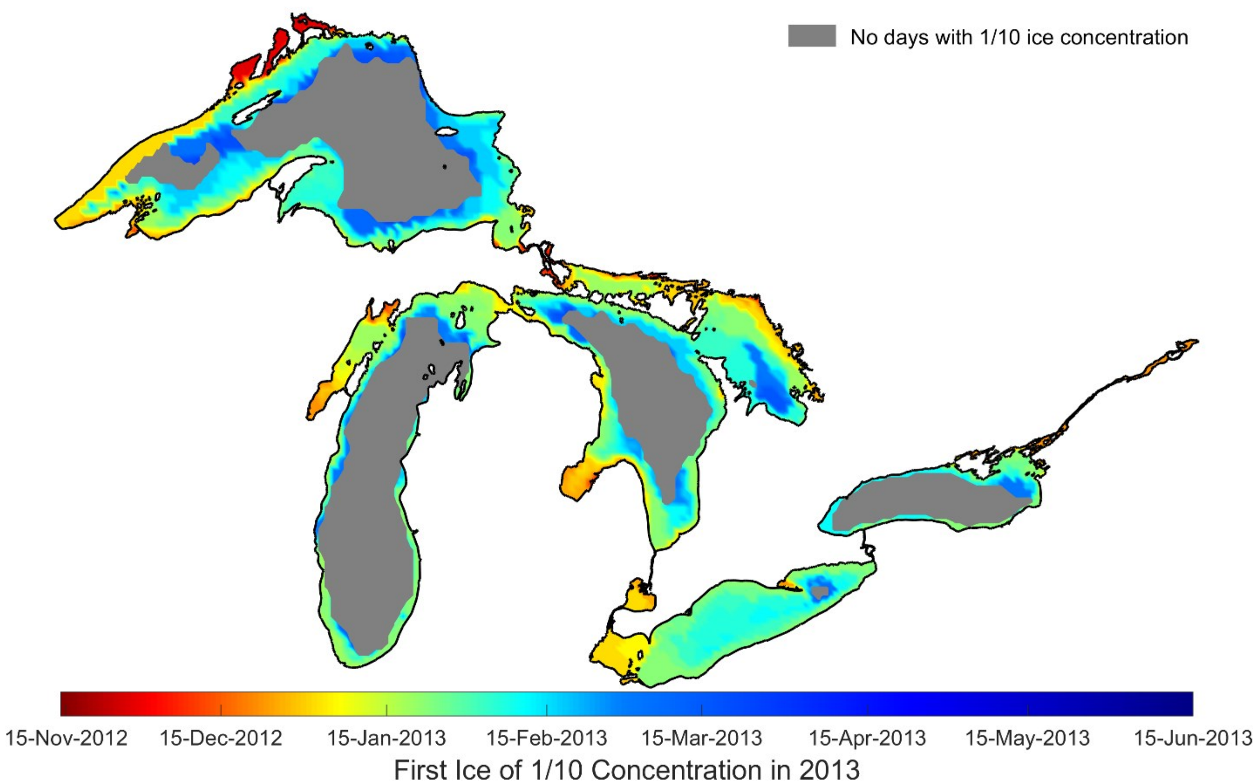
Ice Season	Overall Great Lakes	Upper St. Lawrence River	Lake Ontario	Lake Erie	St. Clair River to Detroit River	Lake Huron	Lake Michigan	Lake Superior
2009 – 2010	Apr 17	Mar 14	Mar 27	Mar 29	Apr 02	Apr 02	Apr 02	Apr 17
2010 – 2011	May 10	Apr 08	Apr 20	Apr 21	Apr 01	Apr 28	Apr 15	May 10
2011 – 2012	Apr 10	Mar 06	Mar 17	Feb 21	Mar 03	Apr 07	Mar 24	Apr 10
2012 – 2013	May 25	Apr 02	Apr 02	Apr 09	Mar 26	May 07	Apr 30	May 25
2013 – 2014	Jun 05	Apr 23	Apr 24	May 09	Apr 10	May 13	May 11	Jun 05
2014 – 2015	May 27	Apr 18	Apr 21	Apr 26	Apr 05	May 14	Apr 29	May 27
2015 – 2016	May 04	Mar 21	Apr 05	Mar 08	Mar 10	Apr 26	Apr 05	May 04
2016 – 2017	Apr 24	Apr 05	Apr 04	Mar 22	Mar 25	Apr 17	Apr 11	Apr 24
2017 – 2018	May 18	Apr 04	Apr 04	Apr 24	Mar 02	May 13	May 05	May 18
2018 – 2019	May 15	Apr 10	Apr 11	May 06	Mar 22	May 04	Apr 26	May 15

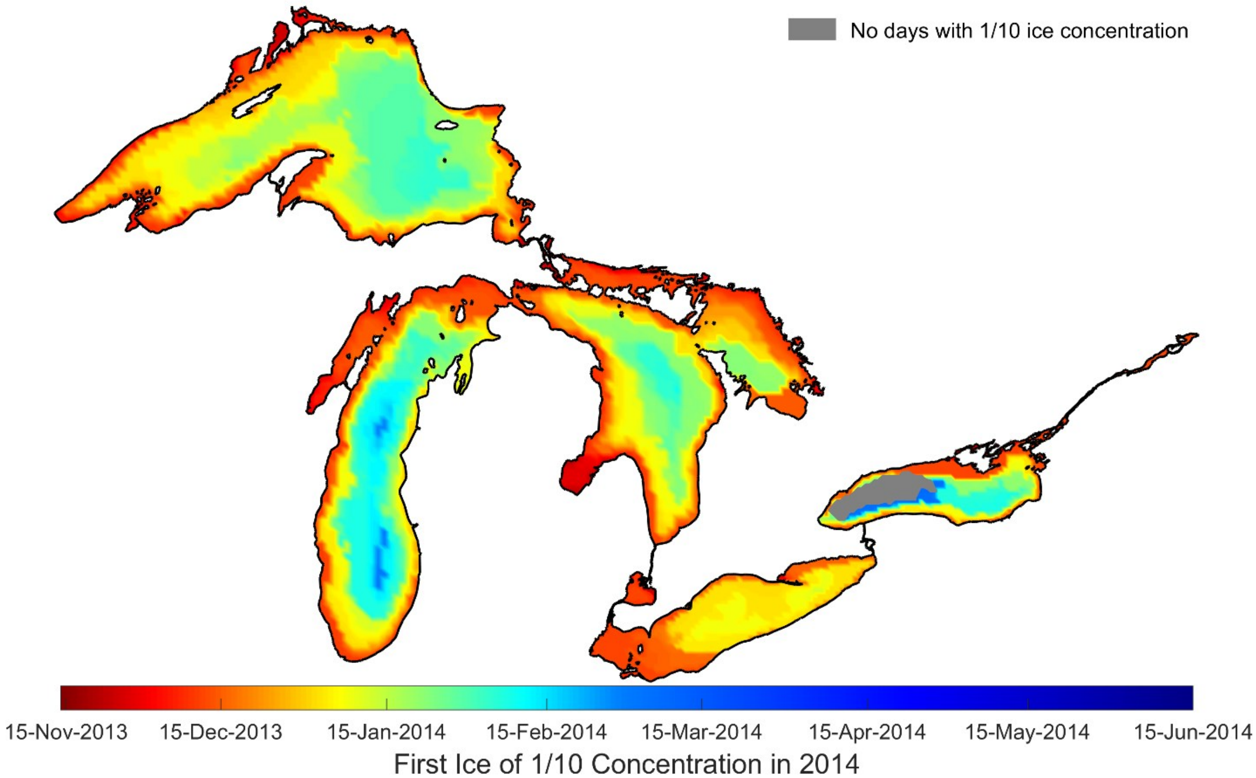
Appendix C2 Spatial Distributions of First Ice >1/10 Concentration

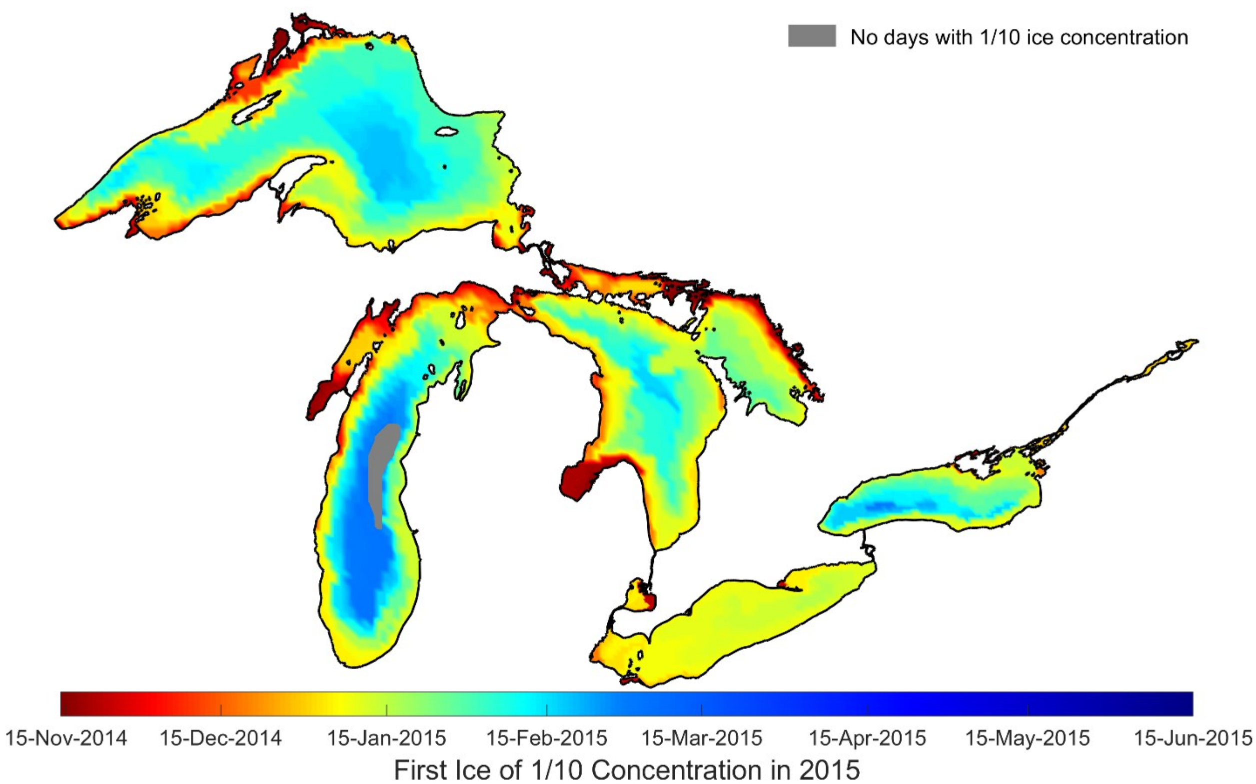


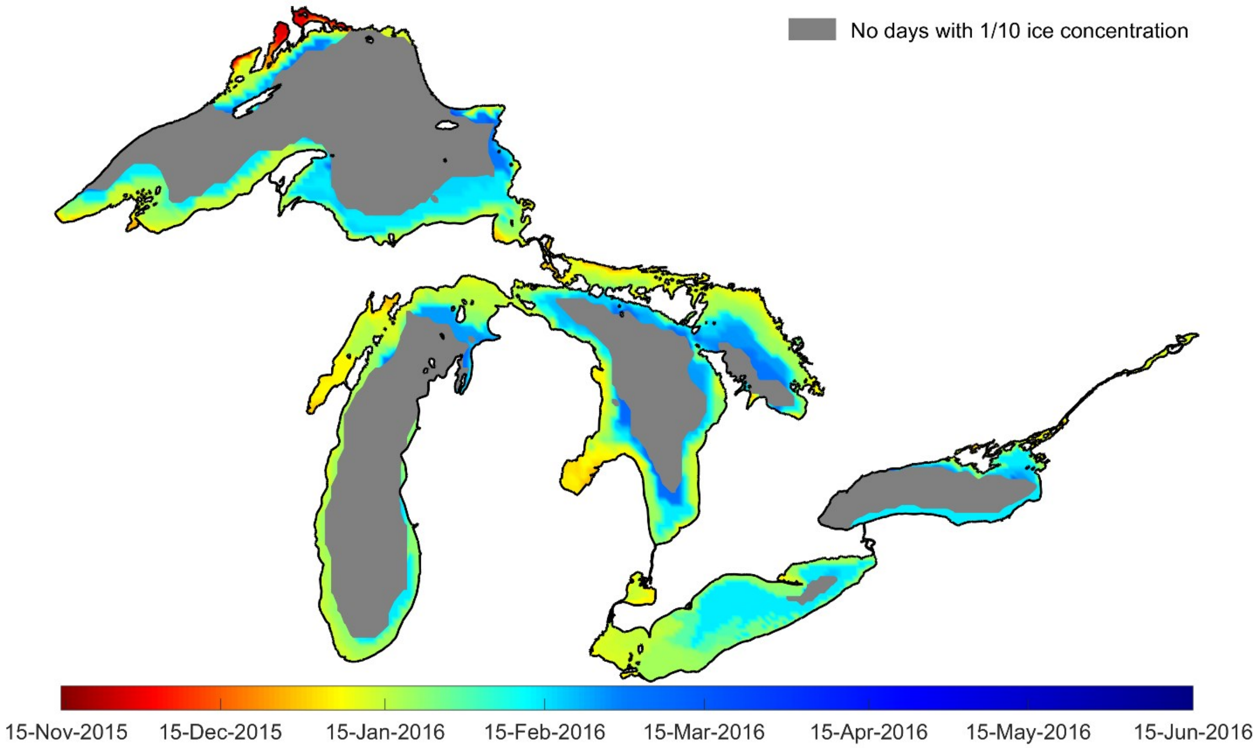



No days with 1/10 ice concentration
15-Nov-2011
15-Dec-2011
15-Jan-2012
15-Feb-2012
15-Mar-2012
15-Apr-2012
15-May-2012
15-Jun-2012
First Ice of 1/10 Concentration in 2012

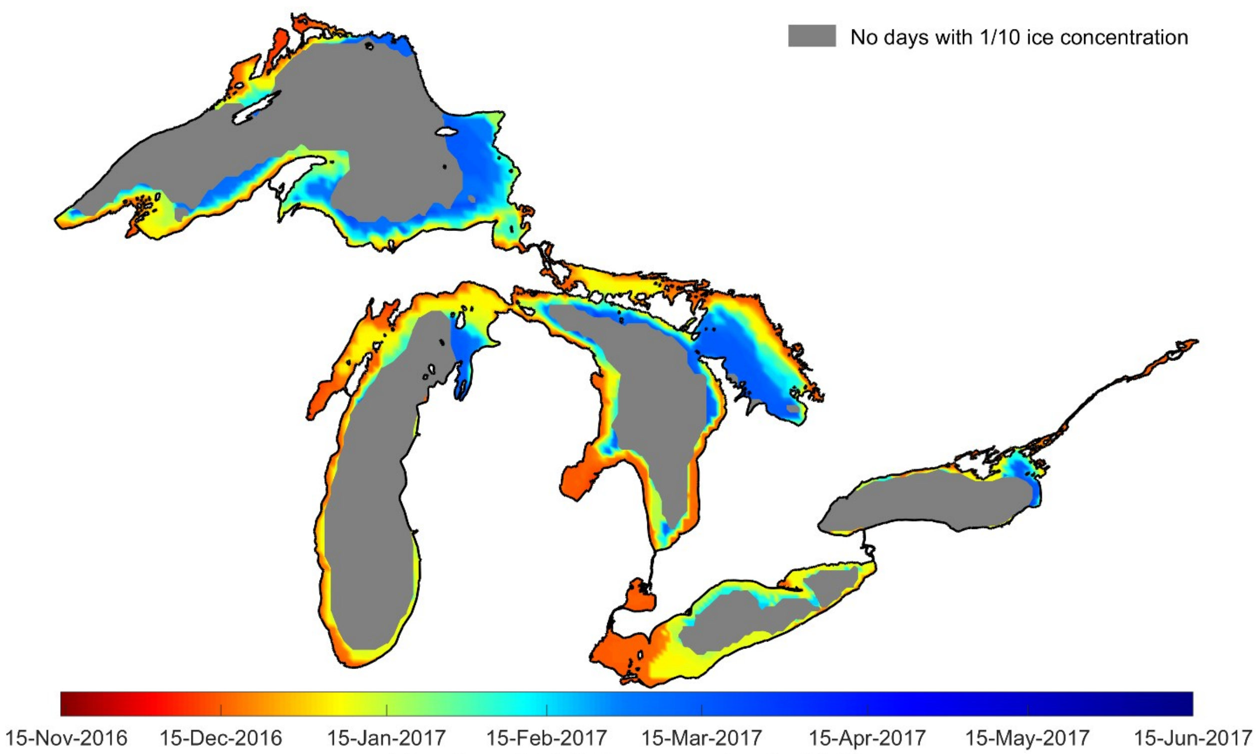

No days with 1/10 ice concentration
15-Nov-2012
15-Dec-2012
15-Jan-2013
15-Feb-2013
15-Mar-2013
15-Apr-2013
15-May-2013
15-Jun-2013
First Ice of 1/10 Concentration in 2013


No days with 1/10 ice concentration
15-Nov-2013
15-Dec-2013
15-Jan-2014
15-Feb-2014
15-Mar-2014
15-Apr-2014
15-May-2014
15-Jun-2014
First Ice of 1/10 Concentration in 2014

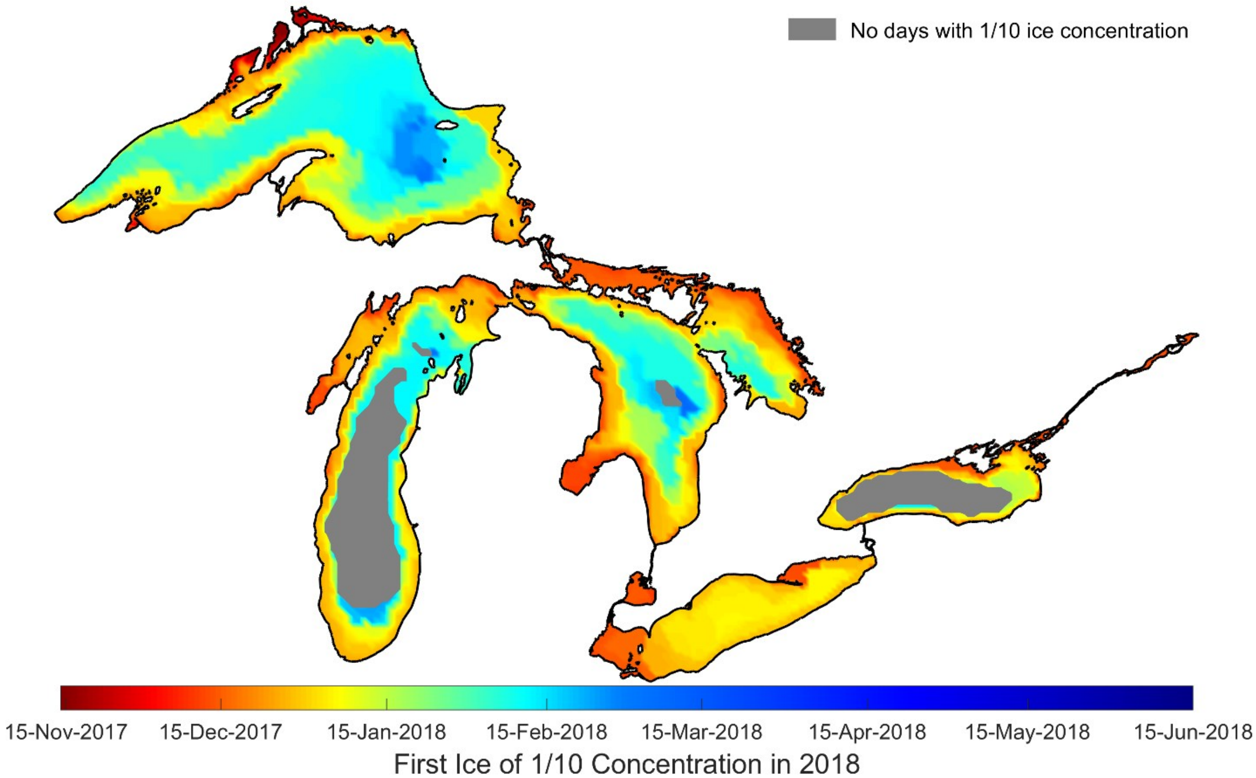

No days with 1/10 ice concentration
15-Nov-2014
15-Dec-2014
15-Jan-2015
15-Feb-2015
15-Mar-2015
15-Apr-2015
15-May-2015
15-Jun-2015
First Ice of 1/10 Concentration in 2015

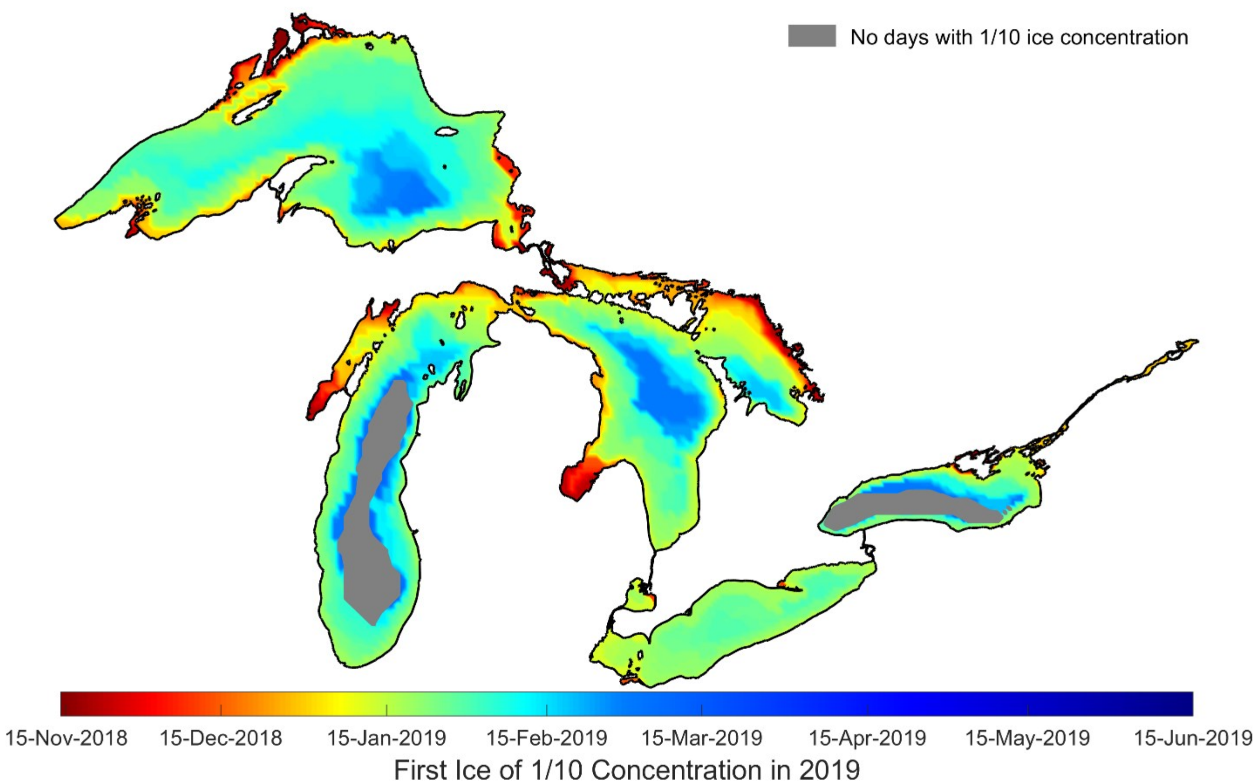


First Ice of 1/10 Concentration in 2016

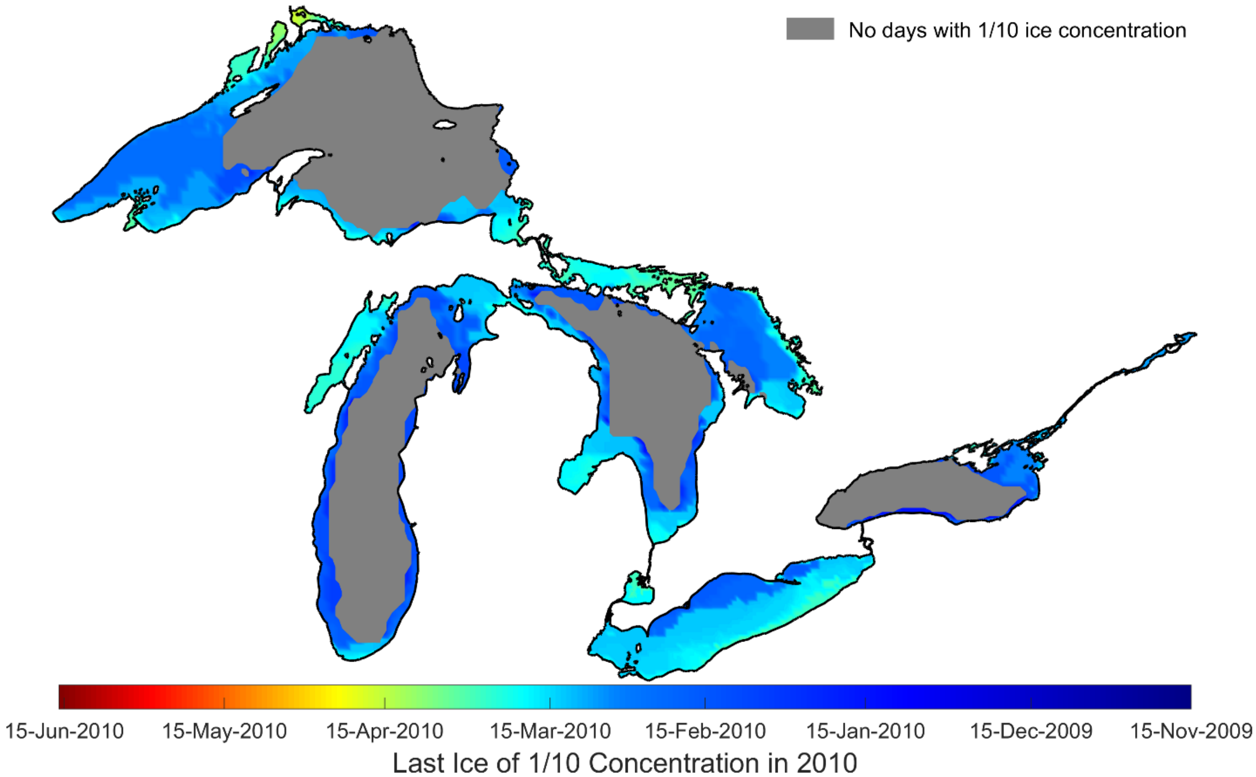


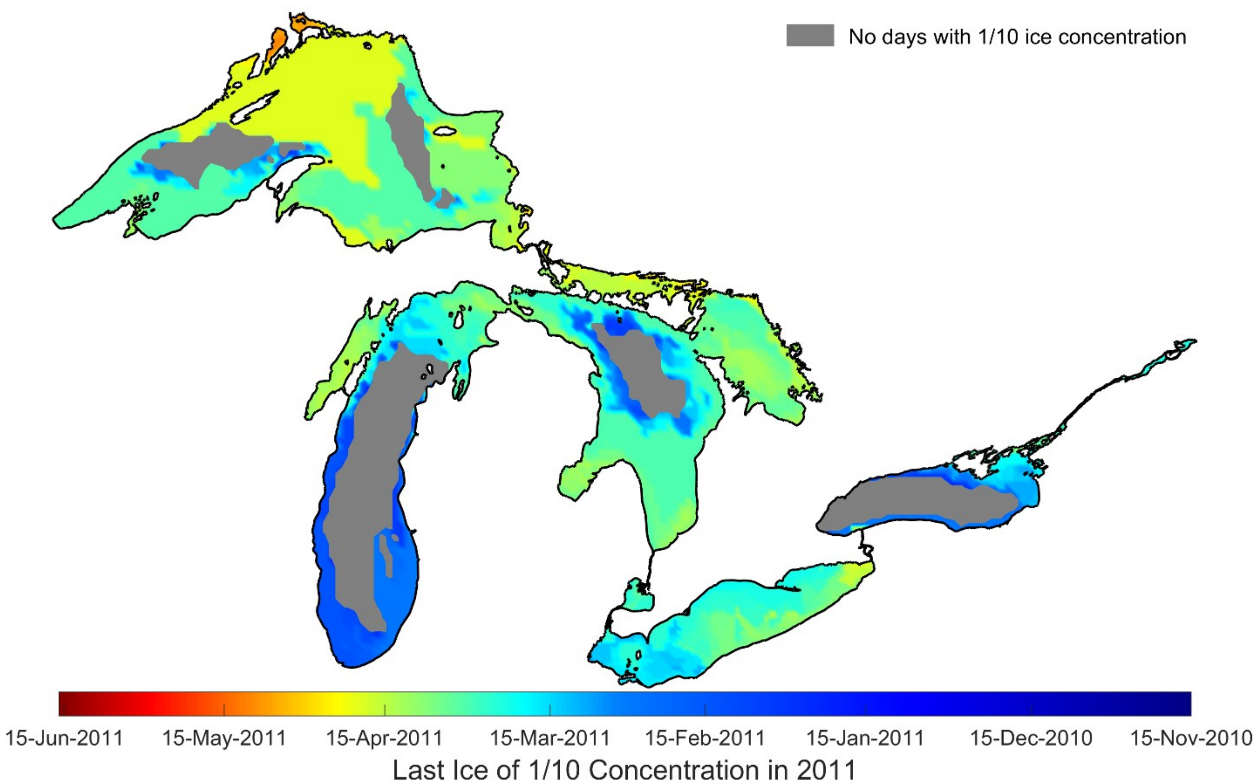
First Ice of 1/10 Concentration in 2017

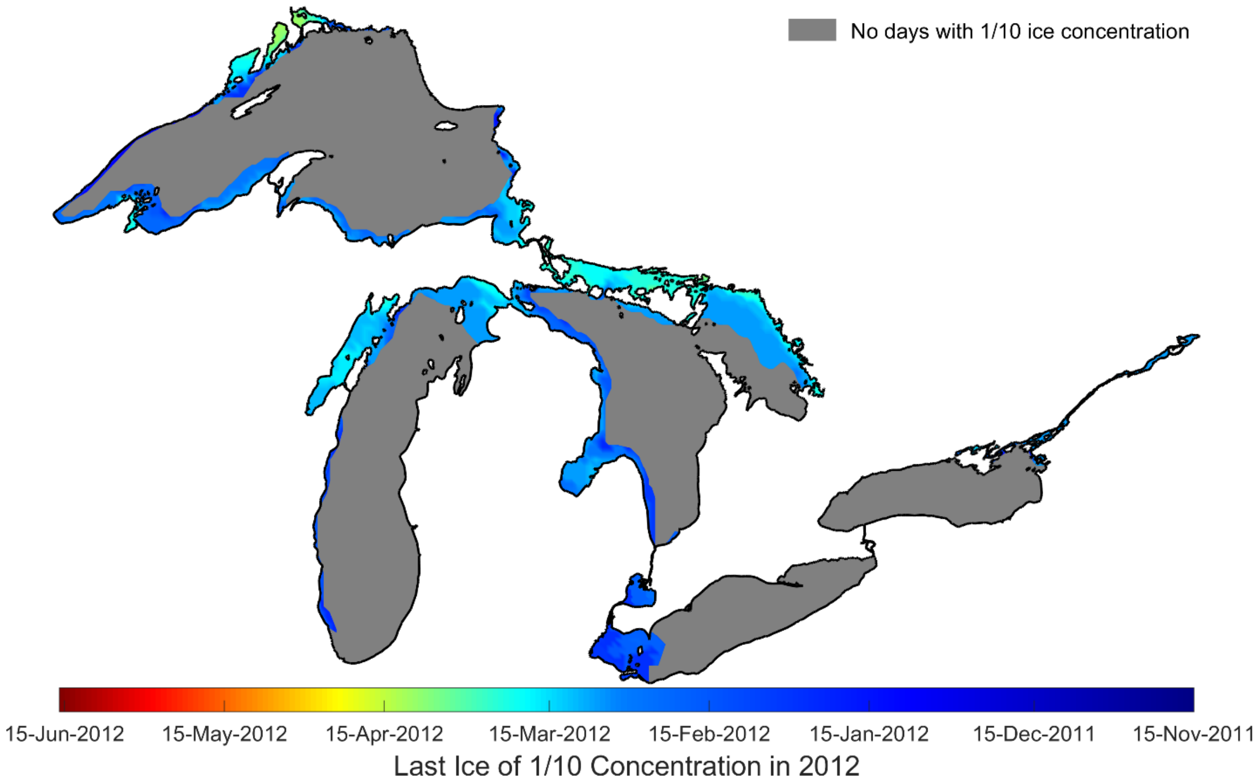

No days with 1/10 ice concentration
15-Nov-2017
15-Dec-2017
15-Jan-2018
15-Feb-2018
15-Mar-2018
15-Apr-2018
15-May-2018
15-Jun-2018
First Ice of 1/10 Concentration in 2018

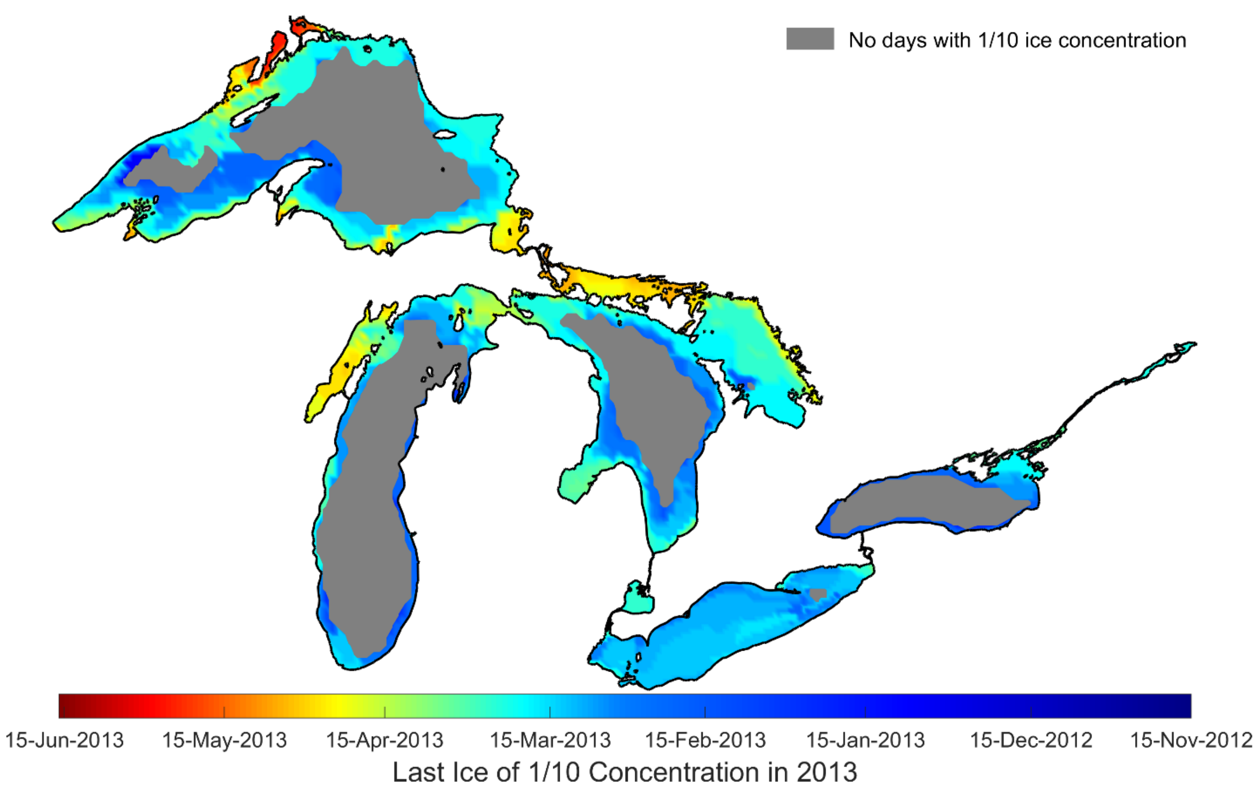

No days with 1/10 ice concentration
15-Nov-2018
15-Dec-2018
15-Jan-2019
15-Feb-2019
15-Mar-2019
15-Apr-2019
15-May-2019
15-Jun-2019
First Ice of 1/10 Concentration in 2019

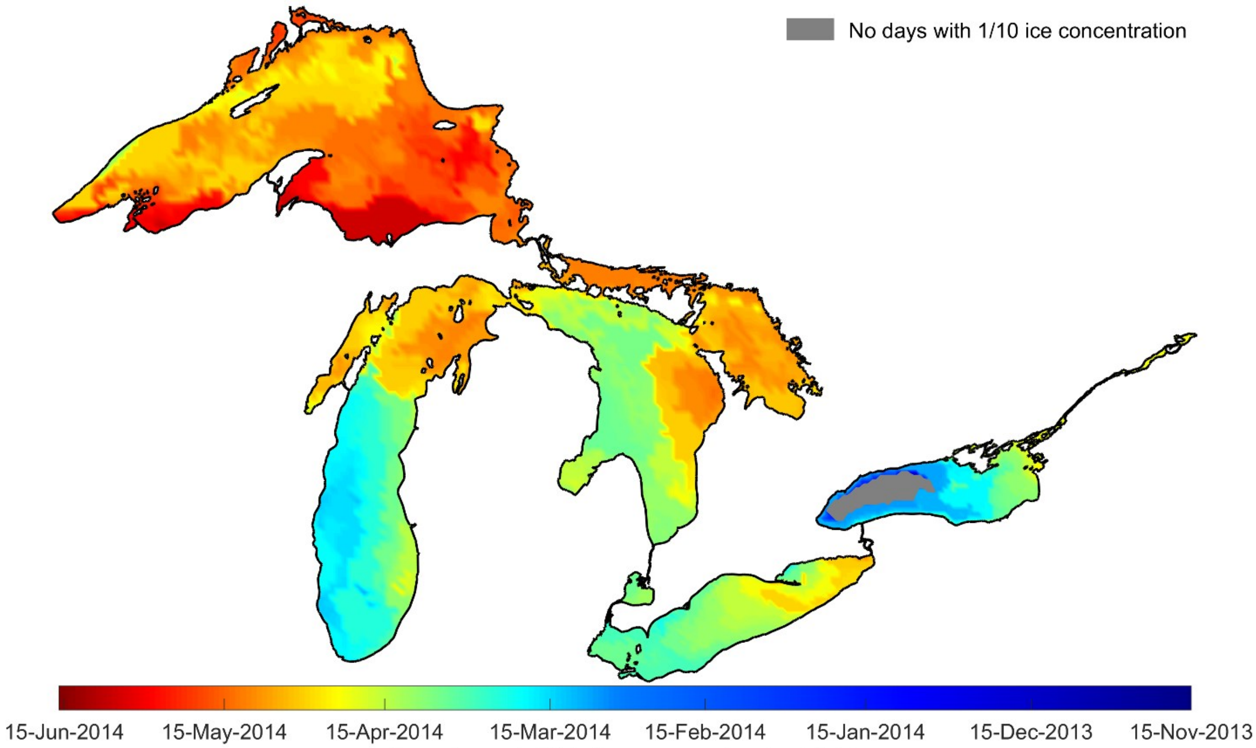
Appendix C3 Spatial Distributions of Last Ice >1/10 Concentration



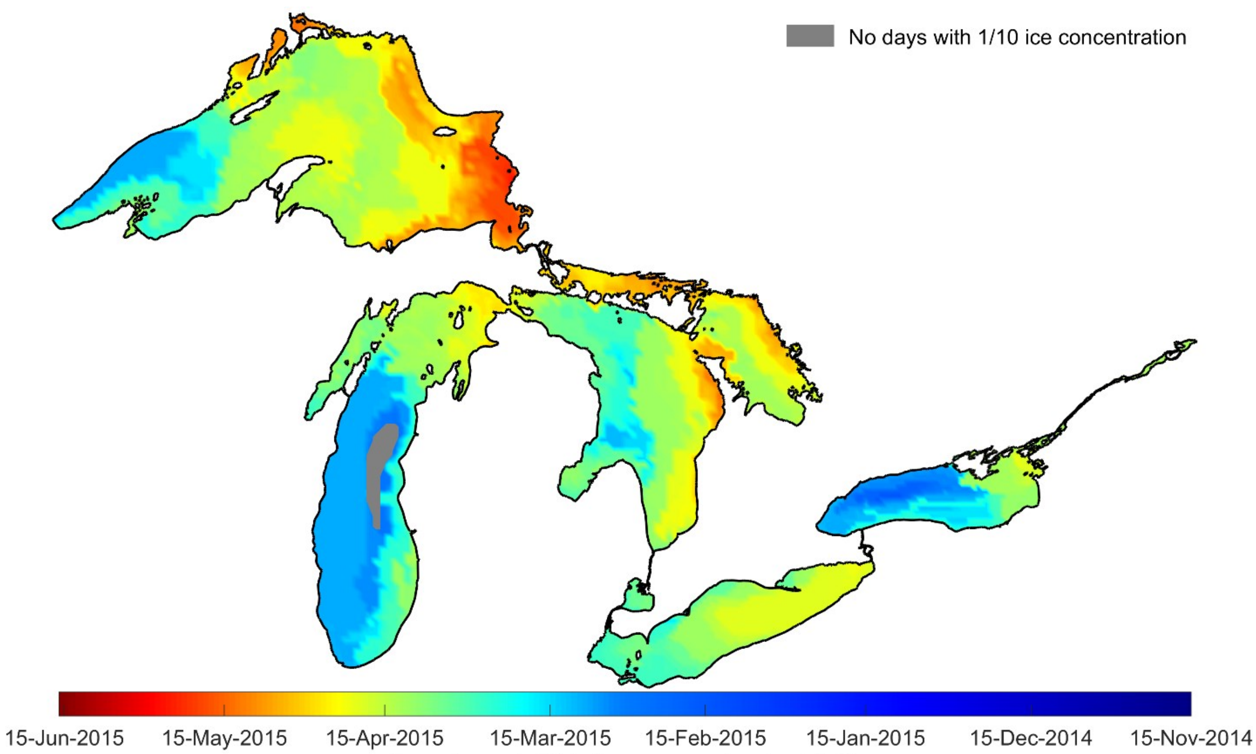



No days with 1/10 ice concentration
15-Jun-2012
15-May-2012
15-Apr-2012
15-Mar-2012
15-Feb-2012
15-Jan-2012
15-Dec-2011
15-Nov-2011
Last Ice of 1/10 Concentration in 2012

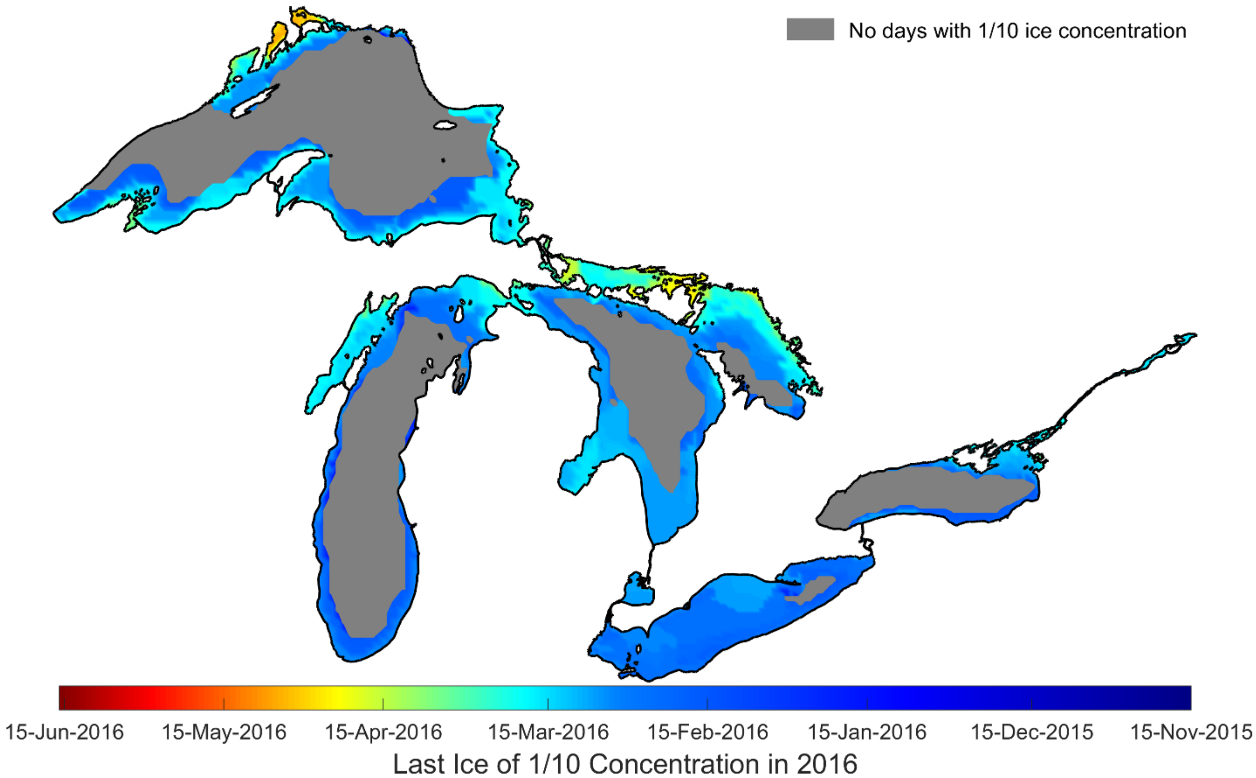

No days with 1/10 ice concentration
15-Jun-2013
15-May-2013
15-Apr-2013
15-Mar-2013
15-Feb-2013
15-Jan-2013
15-Dec-2012
15-Nov-2012
Last Ice of 1/10 Concentration in 2013

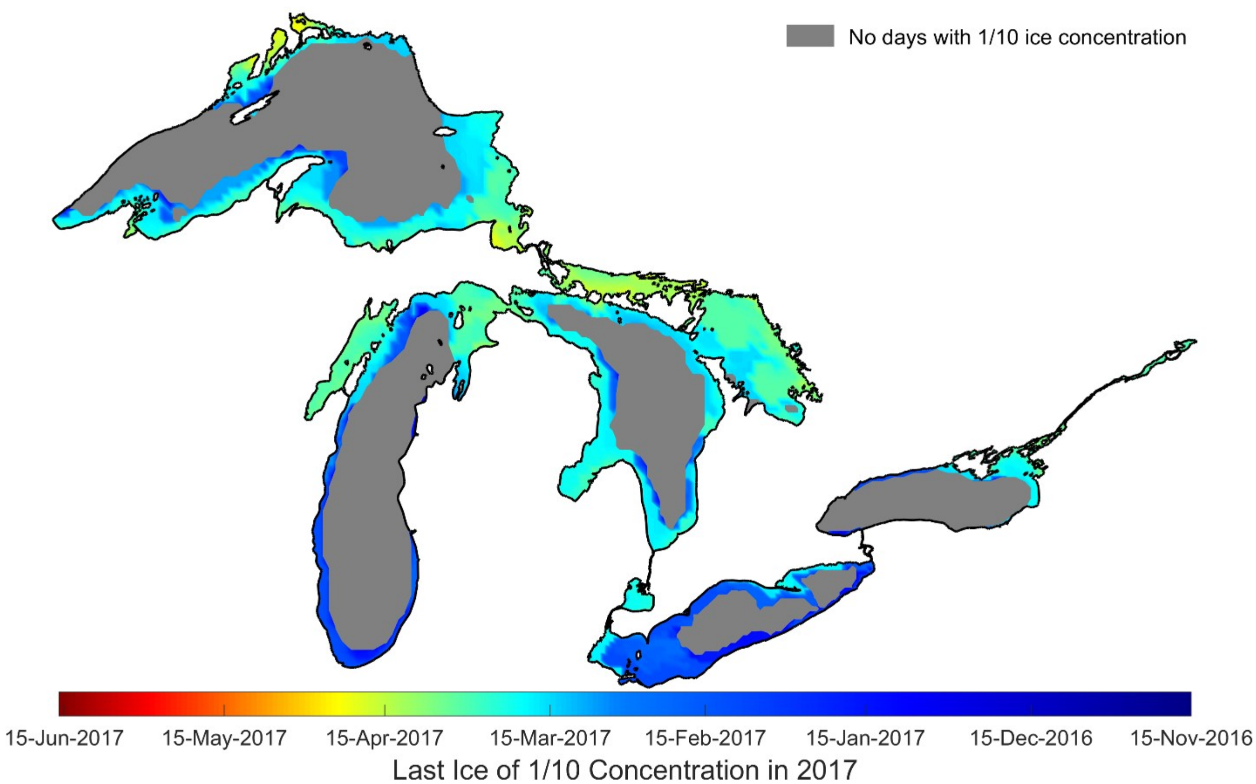


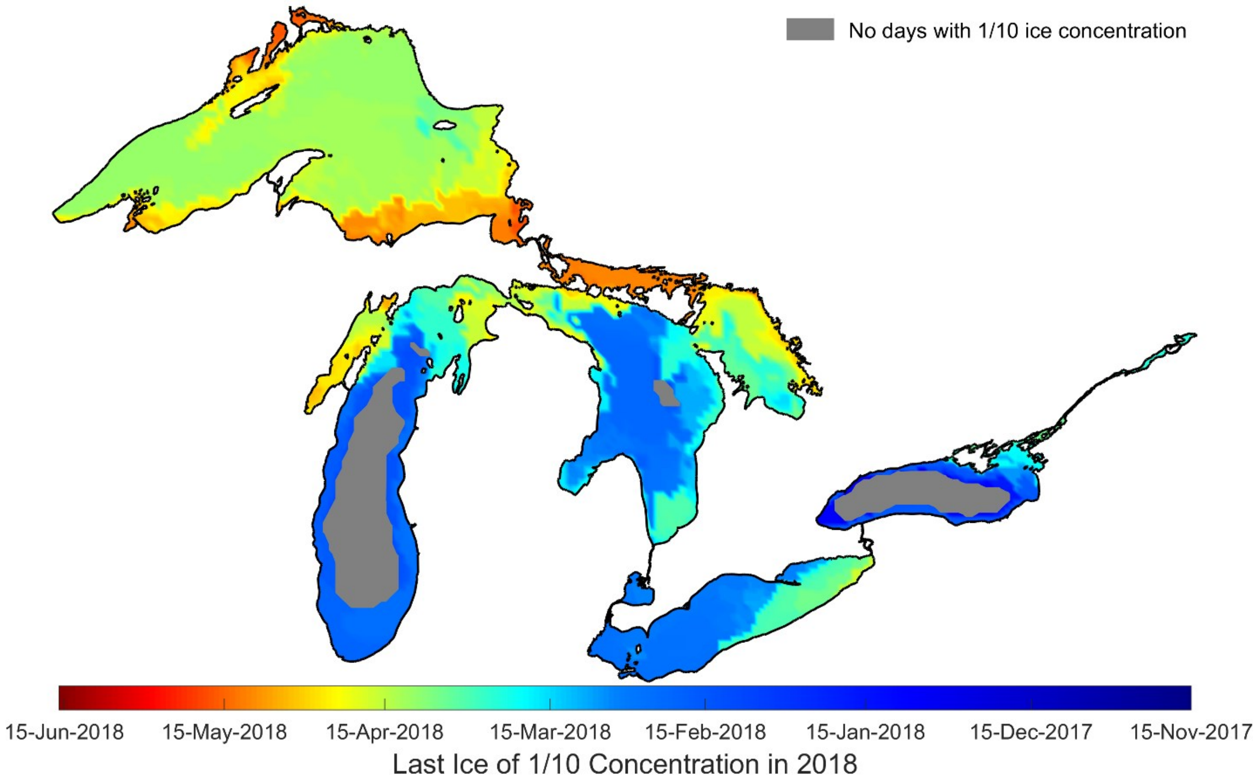
Last Ice of 1/10 Concentration in 2014

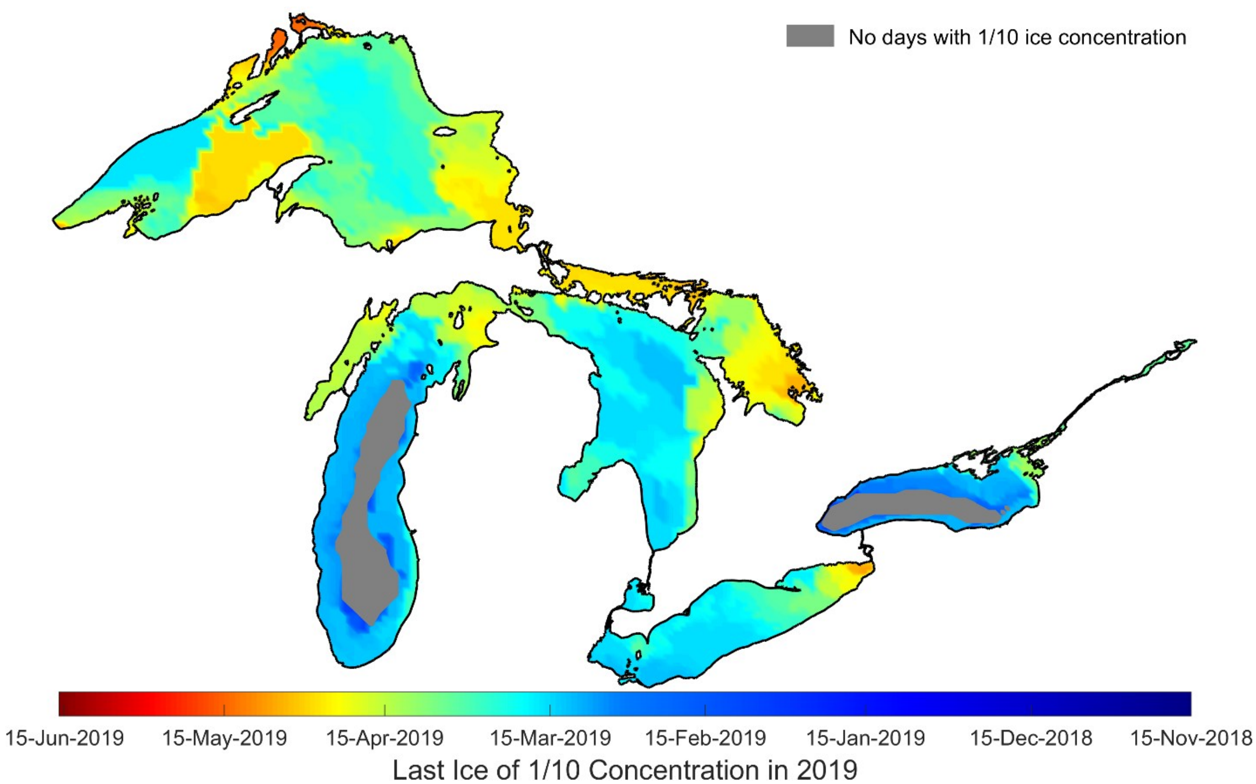


Last Ice of 1/10 Concentration in 2015


No days with 1/10 ice concentration
15-Jun-2016
15-May-2016
15-Apr-2016
15-Mar-2016
15-Feb-2016
15-Jan-2016
15-Dec-2015
15-Nov-2015
Last Ice of 1/10 Concentration in 2016

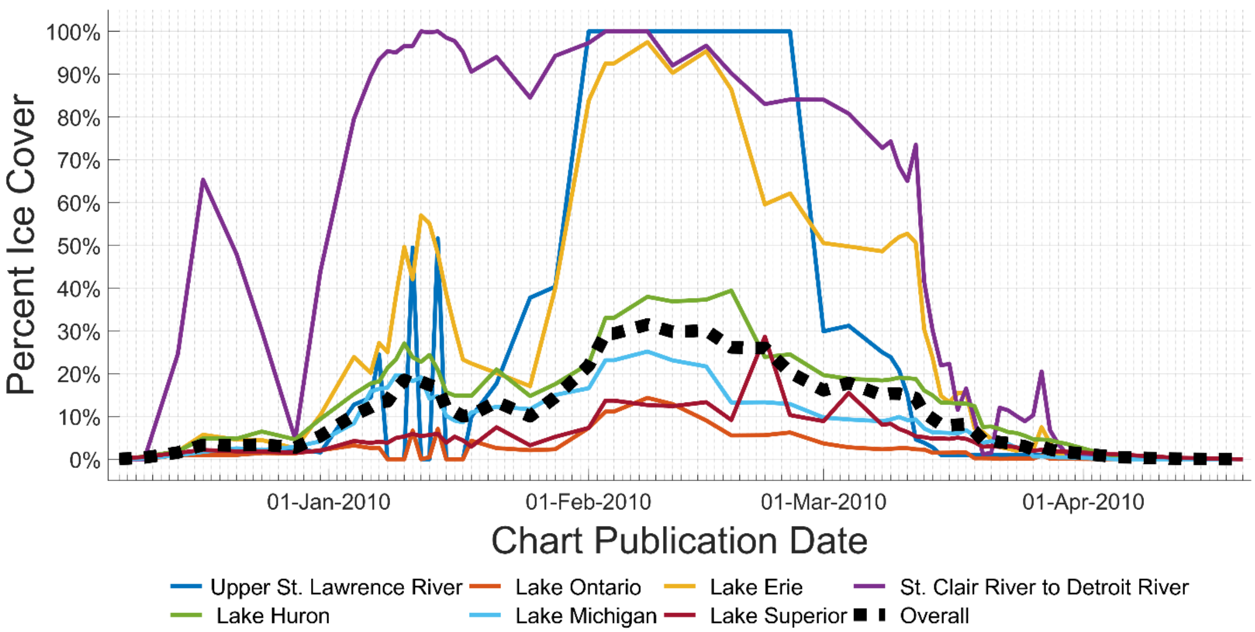

No days with 1/10 ice concentration
15-Jun-2017
15-May-2017
15-Apr-2017
15-Mar-2017
15-Feb-2017
15-Jan-2017
15-Dec-2016
15-Nov-2016
Last Ice of 1/10 Concentration in 2017


No days with 1/10 ice concentration
15-Jun-2018
15-May-2018
15-Apr-2018
15-Mar-2018
15-Feb-2018
15-Jan-2018
15-Dec-2017
15-Nov-2017
Last Ice of 1/10 Concentration in 2018

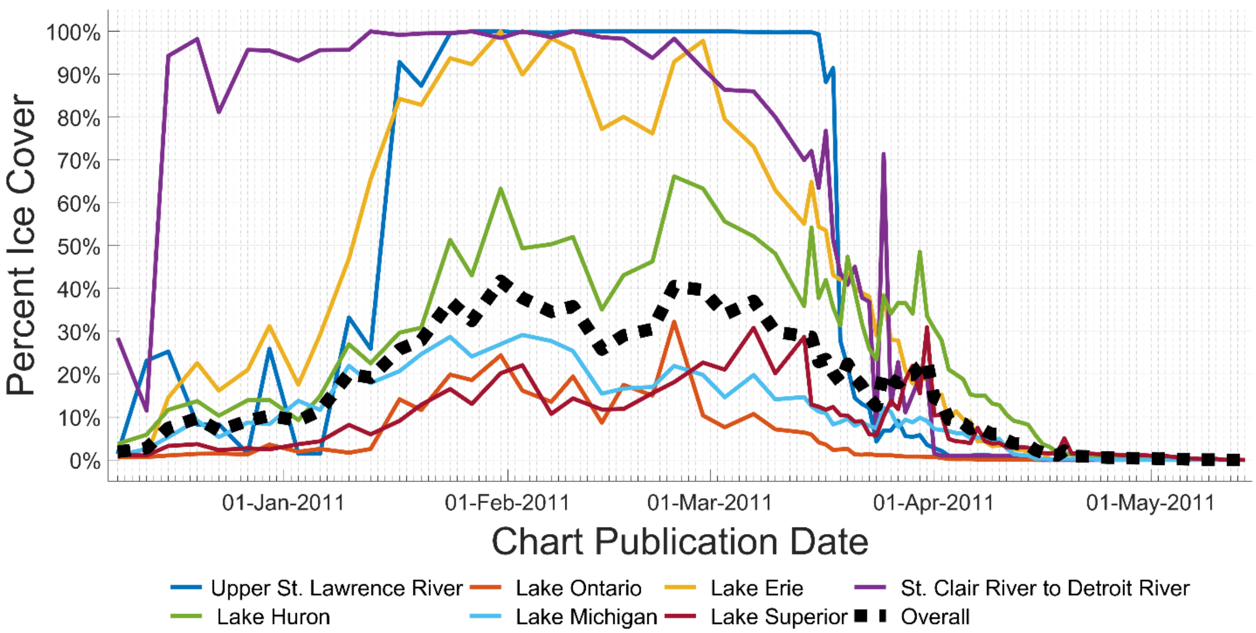

No days with 1/10 ice concentration
15-Jun-2019
15-May-2019
15-Apr-2019
15-Mar-2019
15-Feb-2019
15-Jan-2019
15-Dec-2018
15-Nov-2018
Last Ice of 1/10 Concentration in 2019

Appendix C4 Seasonal Graphs of Regional Ice Extent Progression

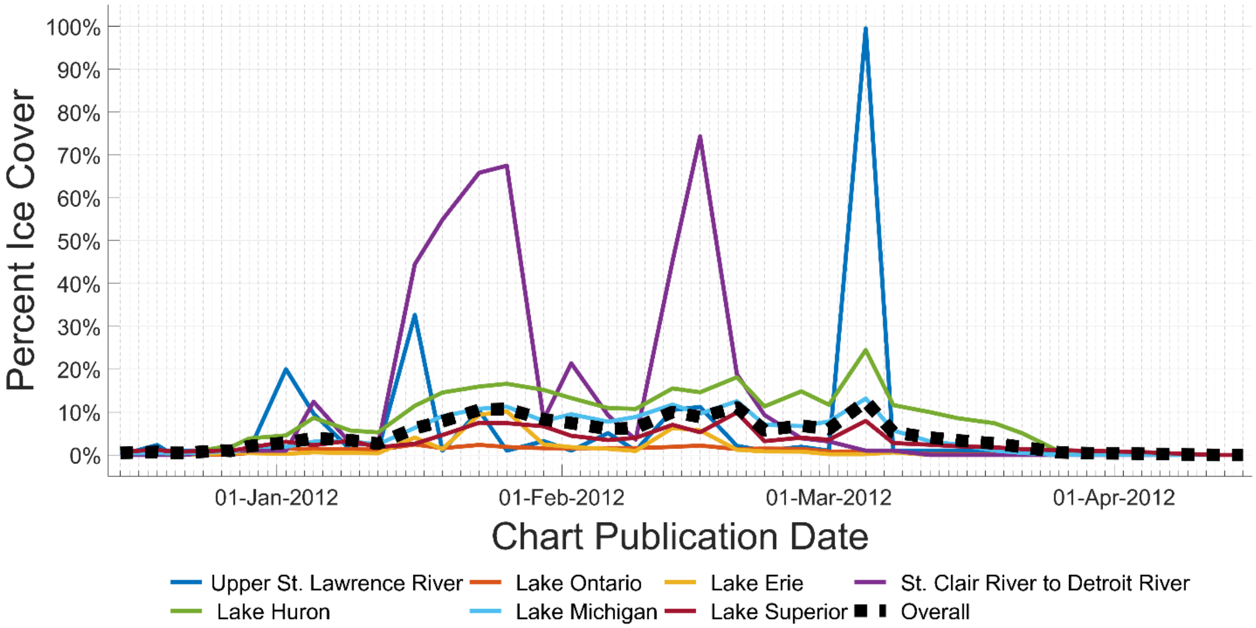
Appendix C4.1 Graph of regional ice extent for the 2010 ice season



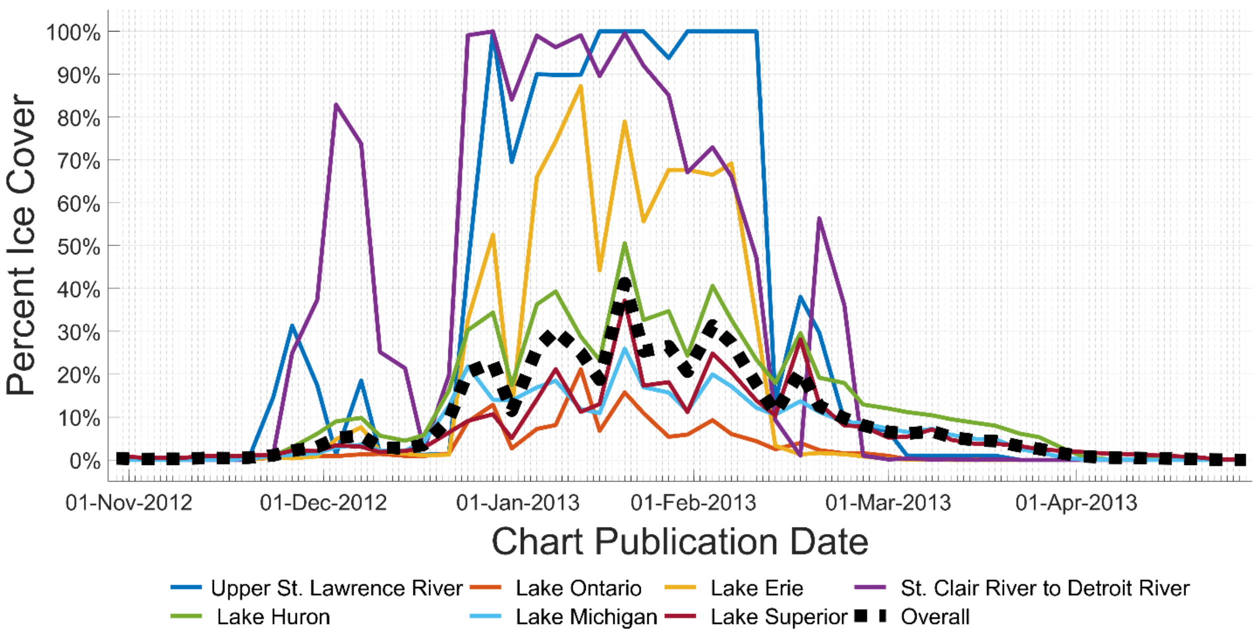
Appendix C4.2 Graph of regional ice extent for the 2011 ice season



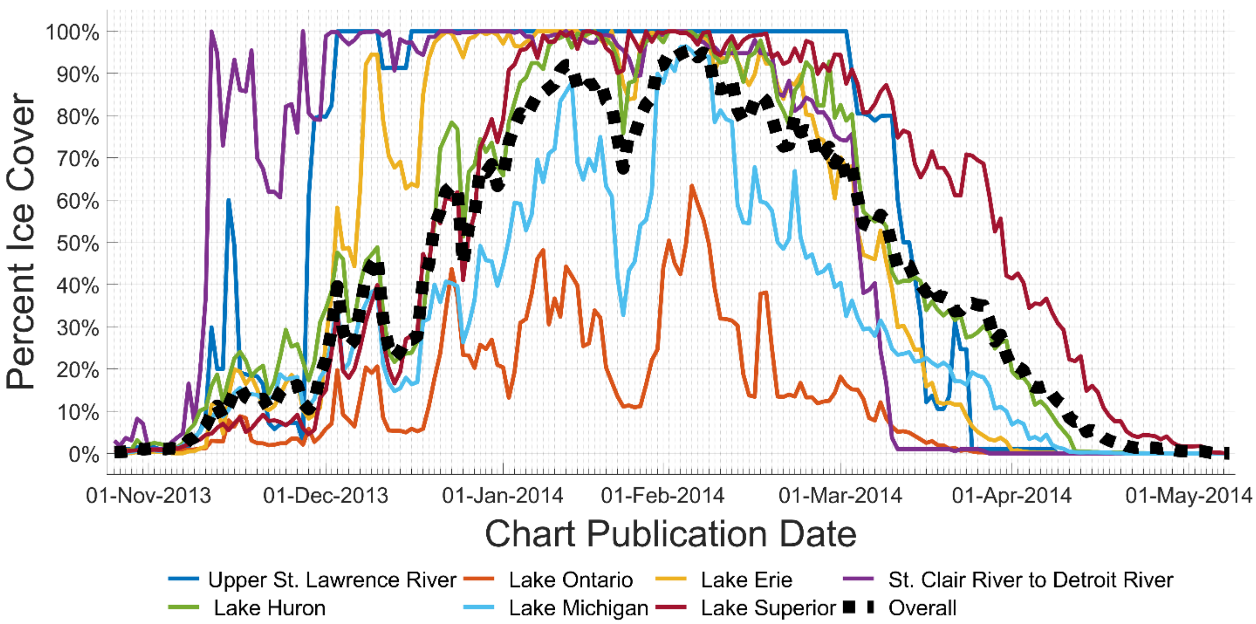
Appendix C4.3 Graph of regional ice extent for the 2012 ice season



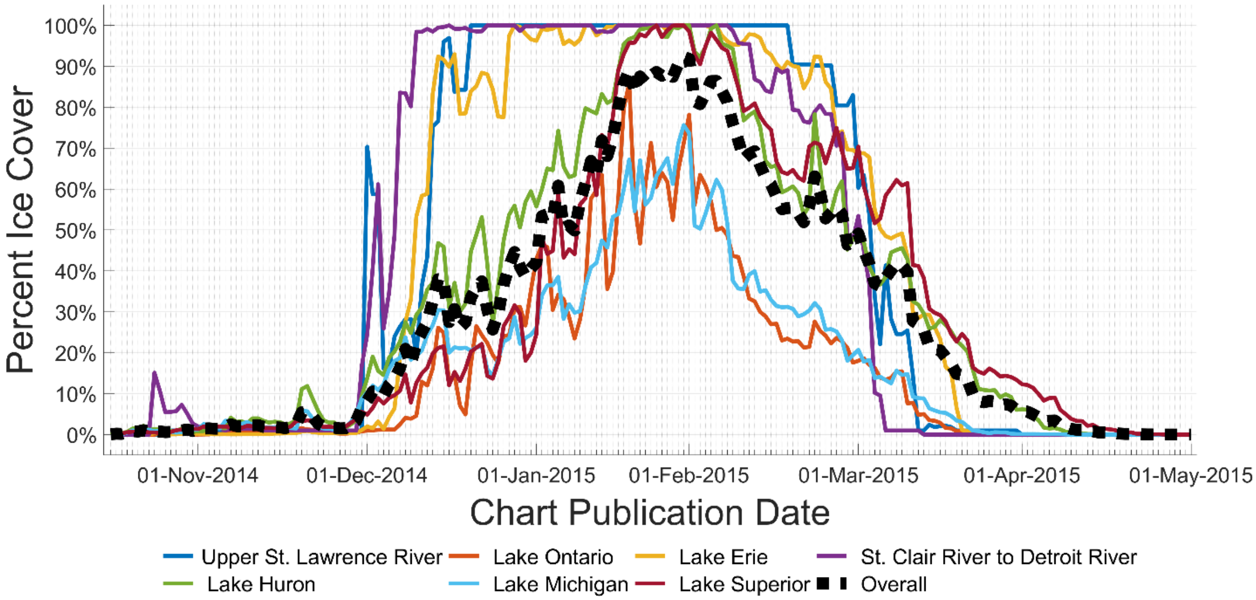
Appendix C4.4 Graph of regional ice extent for the 2013 ice season



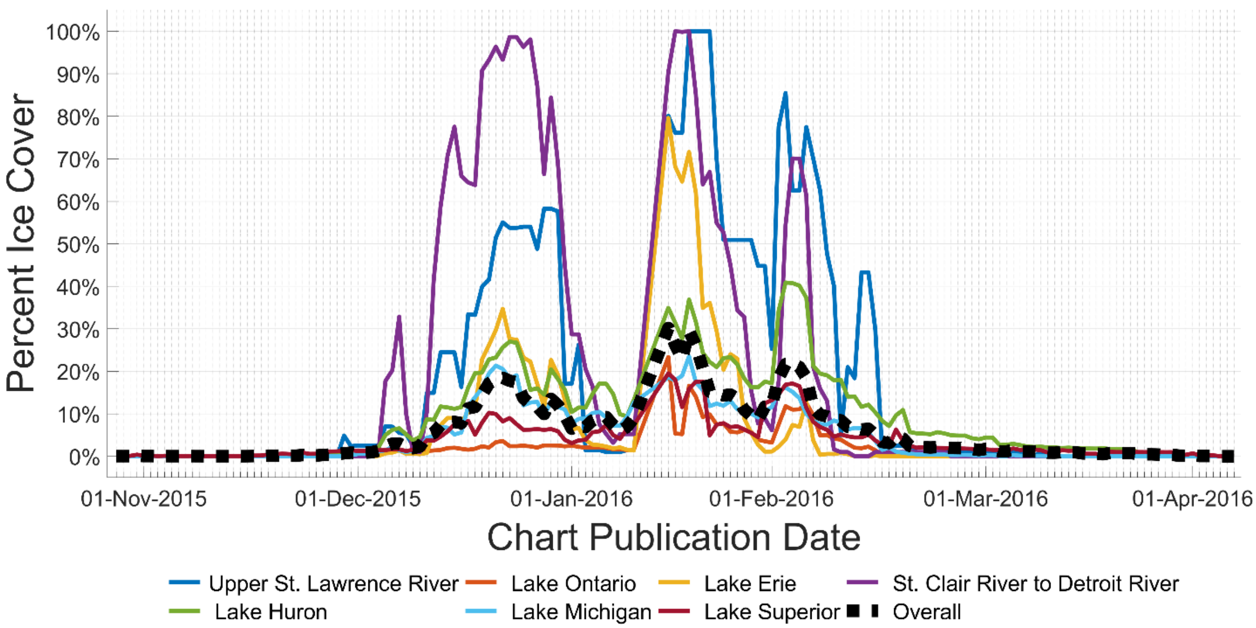
Appendix C4.5 Graph of regional ice extent for the 2014 ice season



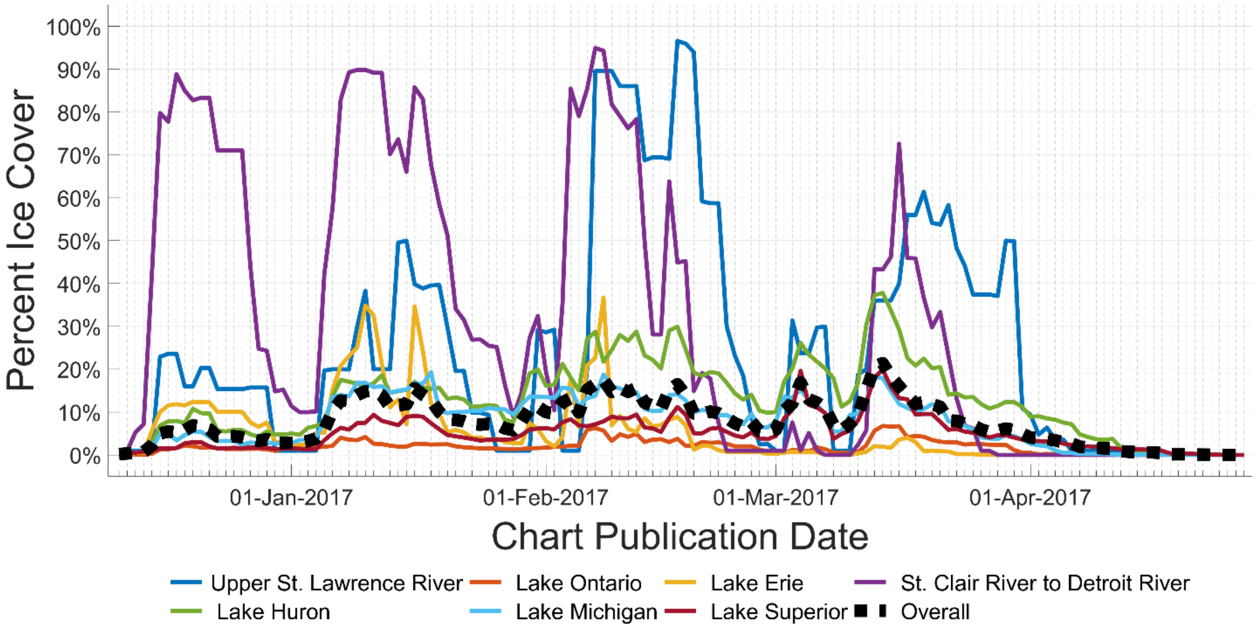
Appendix C4.6 Graph of regional ice extent for the 2015 ice season



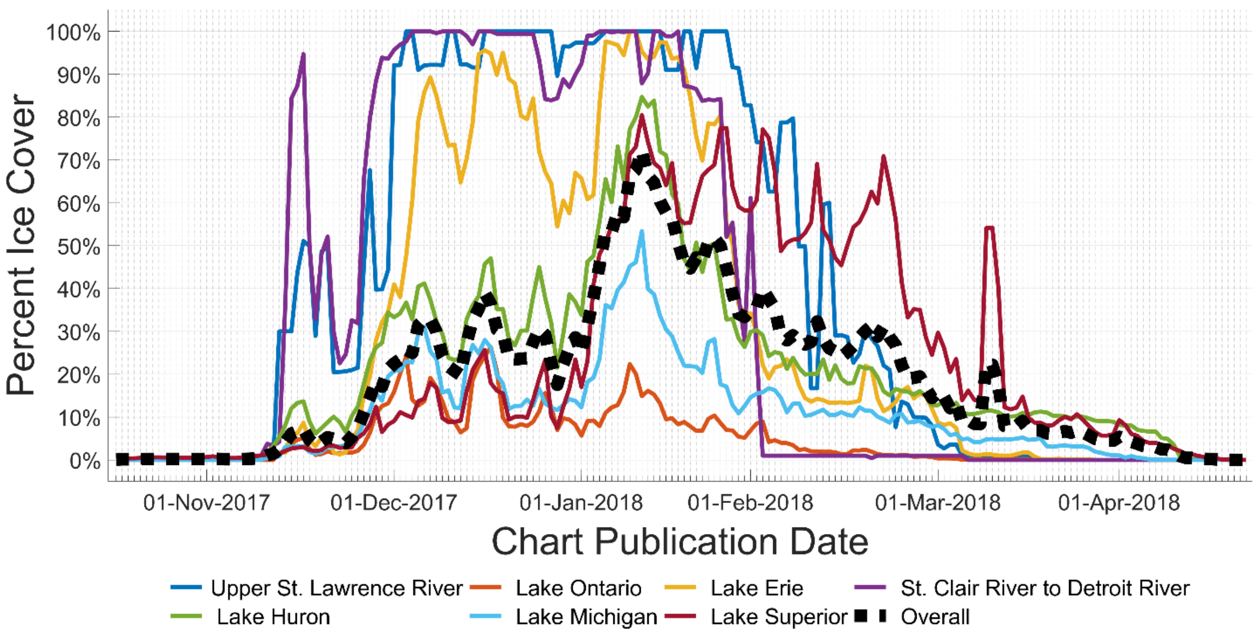
Appendix C4.7 Graph of regional ice extent for the 2016 ice season



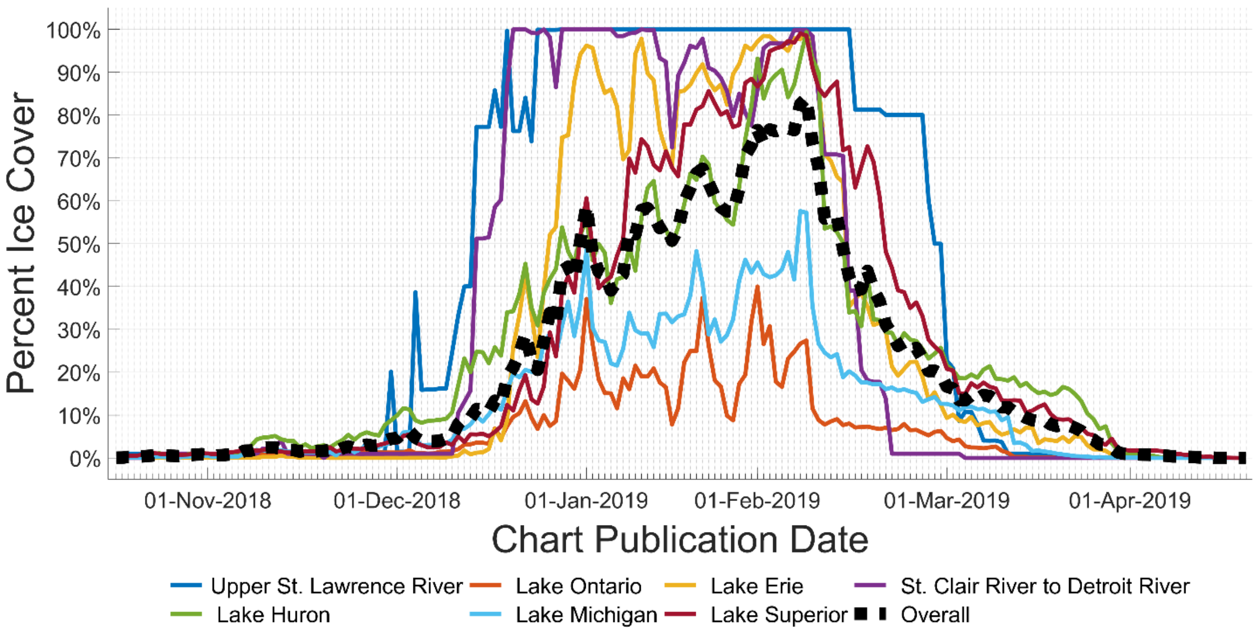
Appendix C4.8 Graph of regional ice extent for the 2017 ice season



Appendix C4.9 Graph of regional ice extent for the 2018 ice season

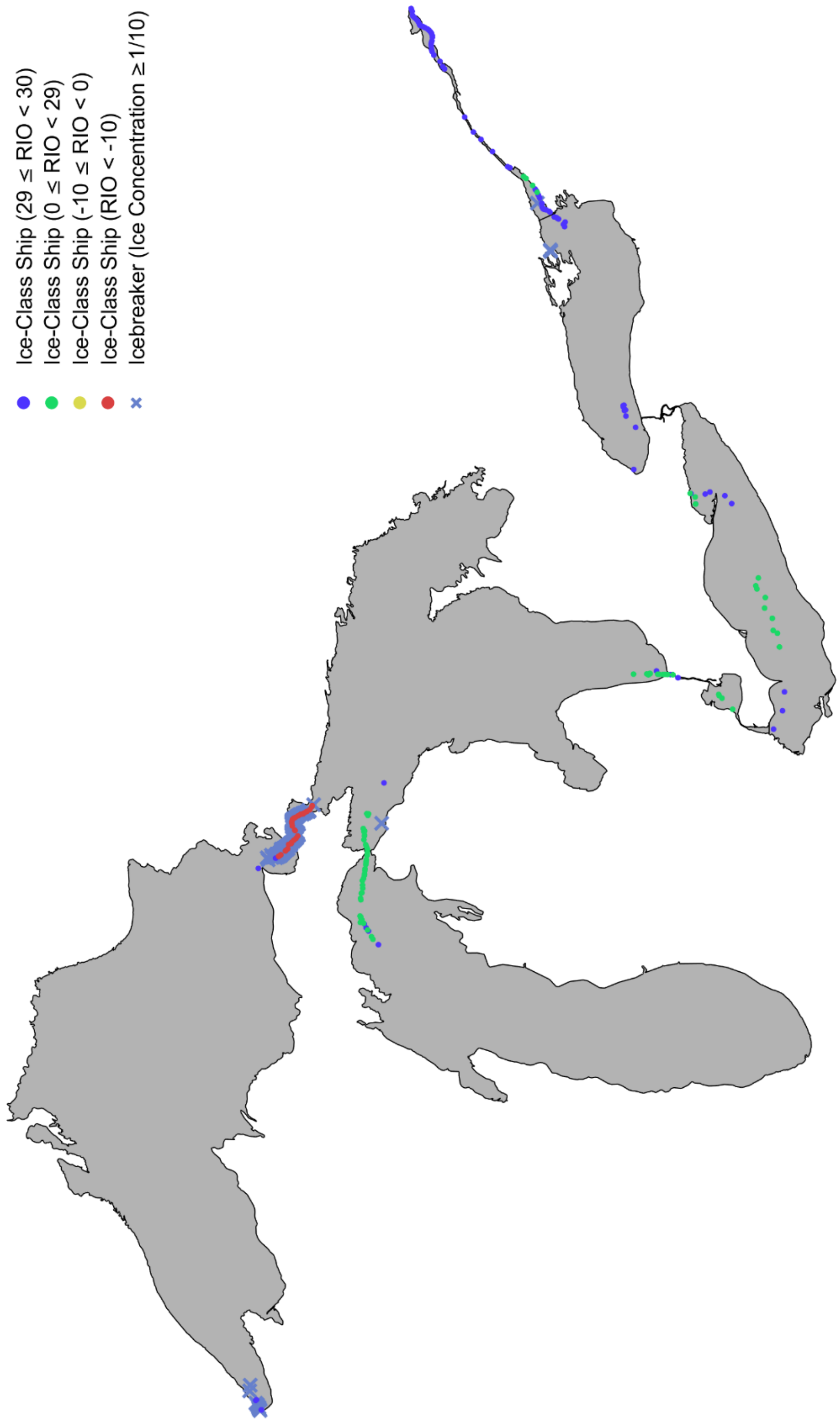


Appendix C4.10 Graph of regional ice extent for the 2019 ice season

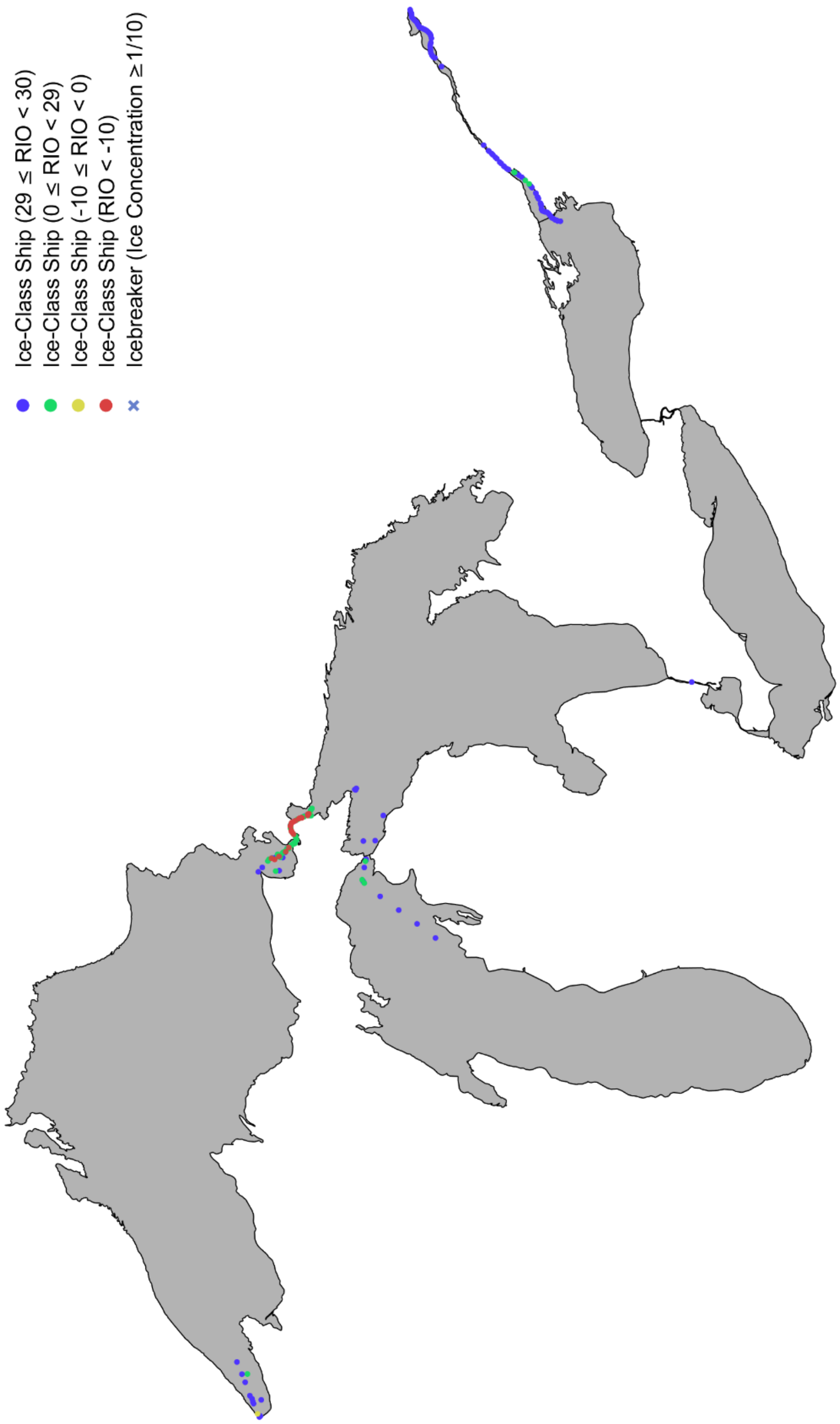


Appendix D Monthly AIS-Record Distributions From 2010-2019

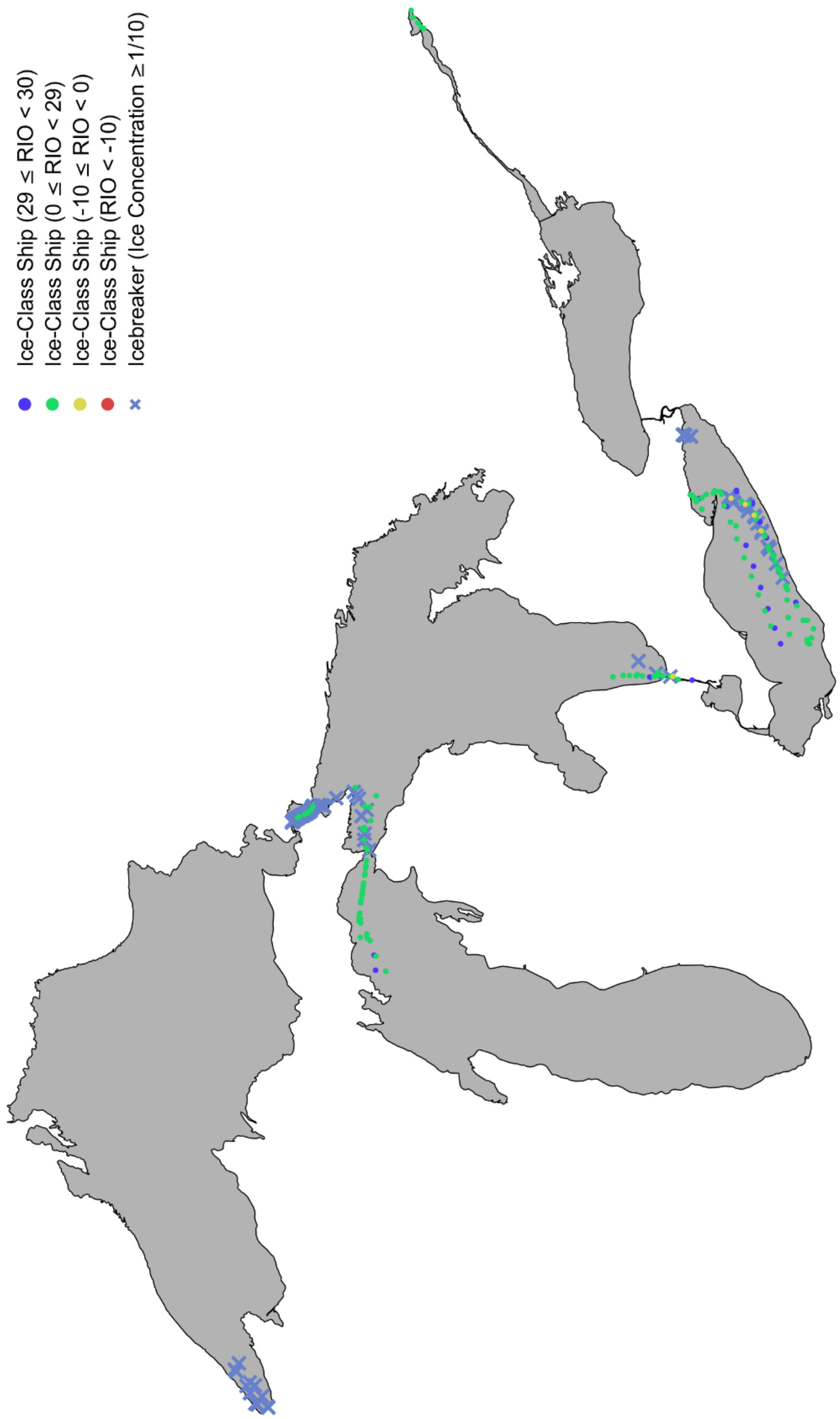
Appendix D1 AIS-Record Distribution for March 2013



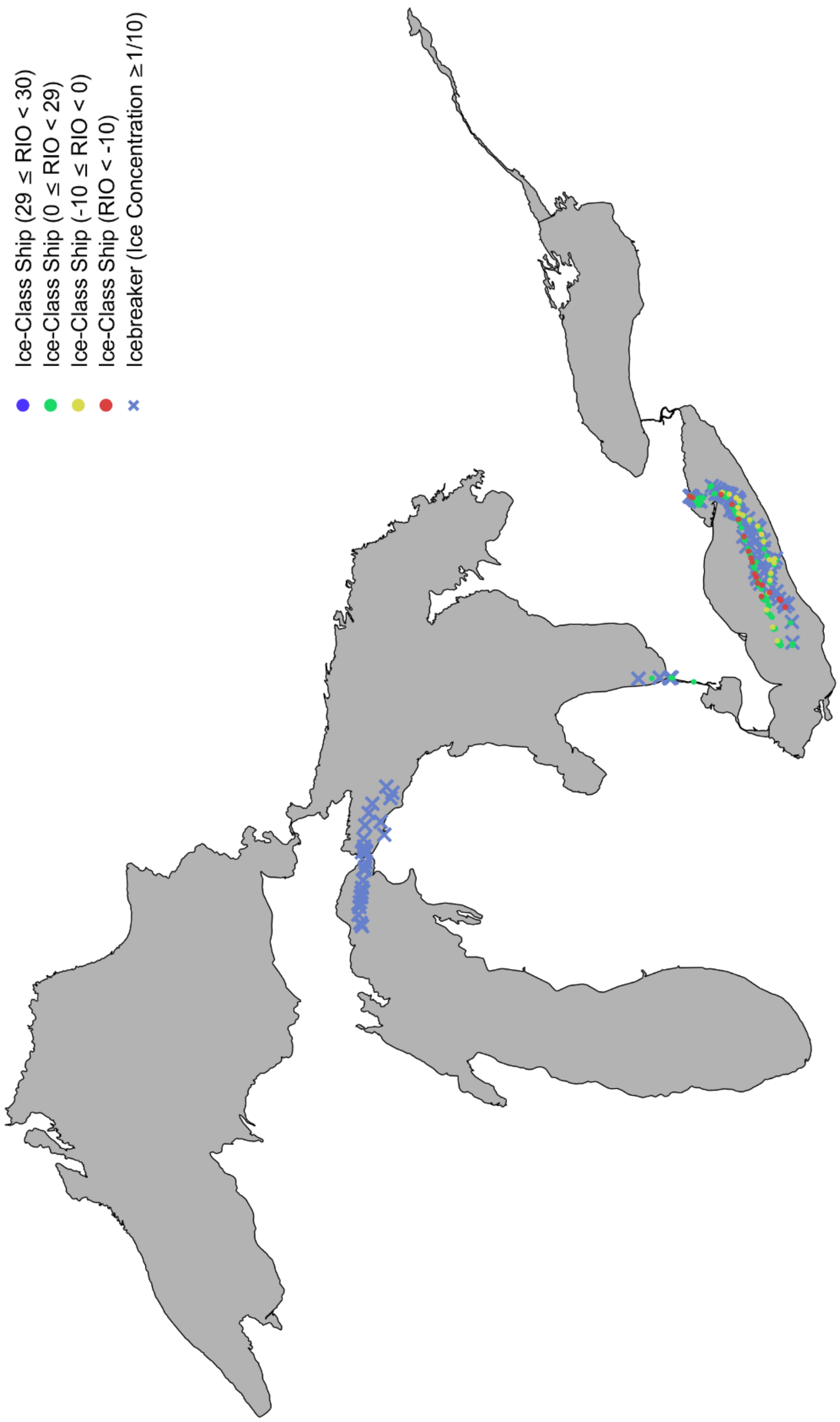
Appendix D2 AIS-Record Distribution for April 2013



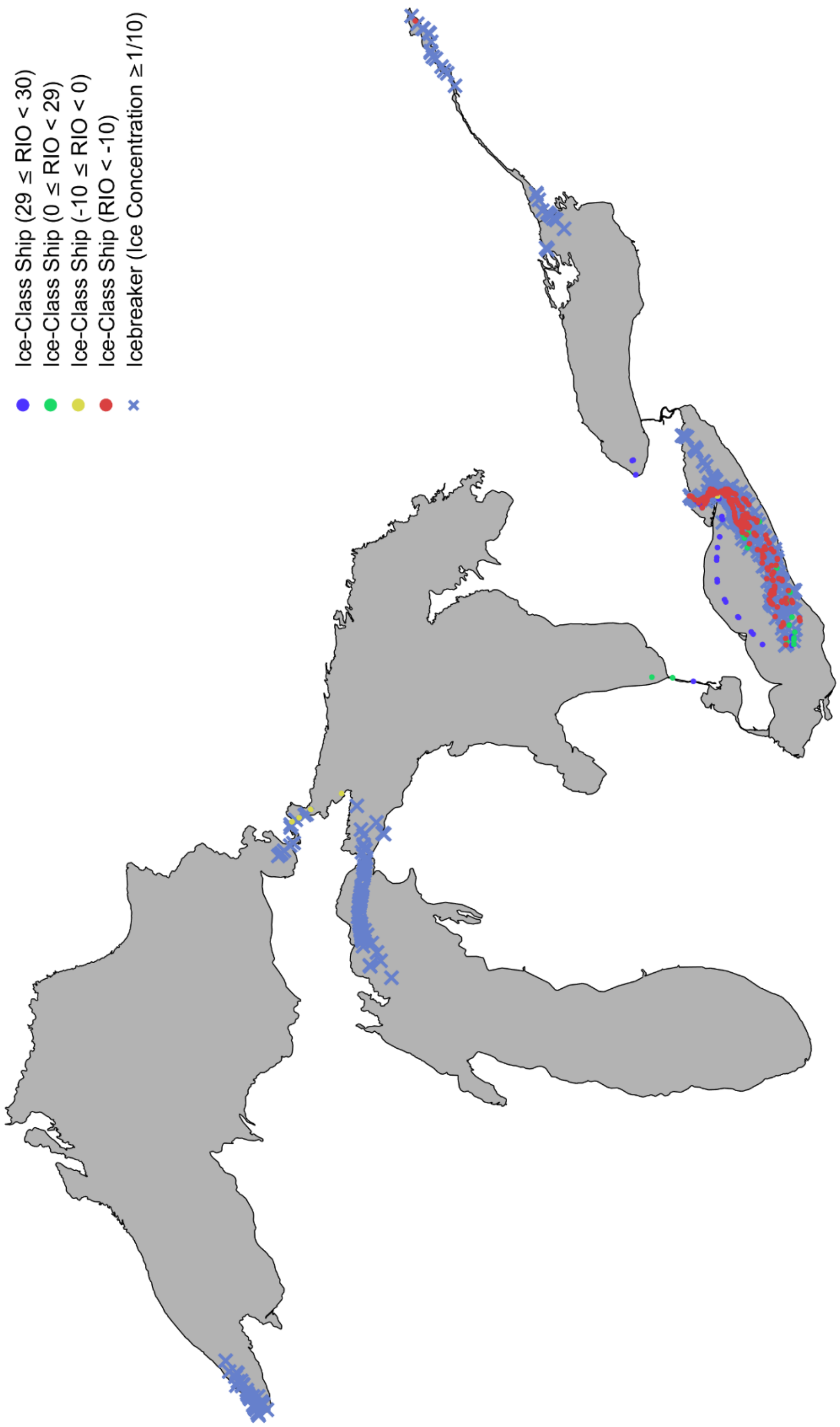
Appendix D3 AIS-Record Distribution for January 2014



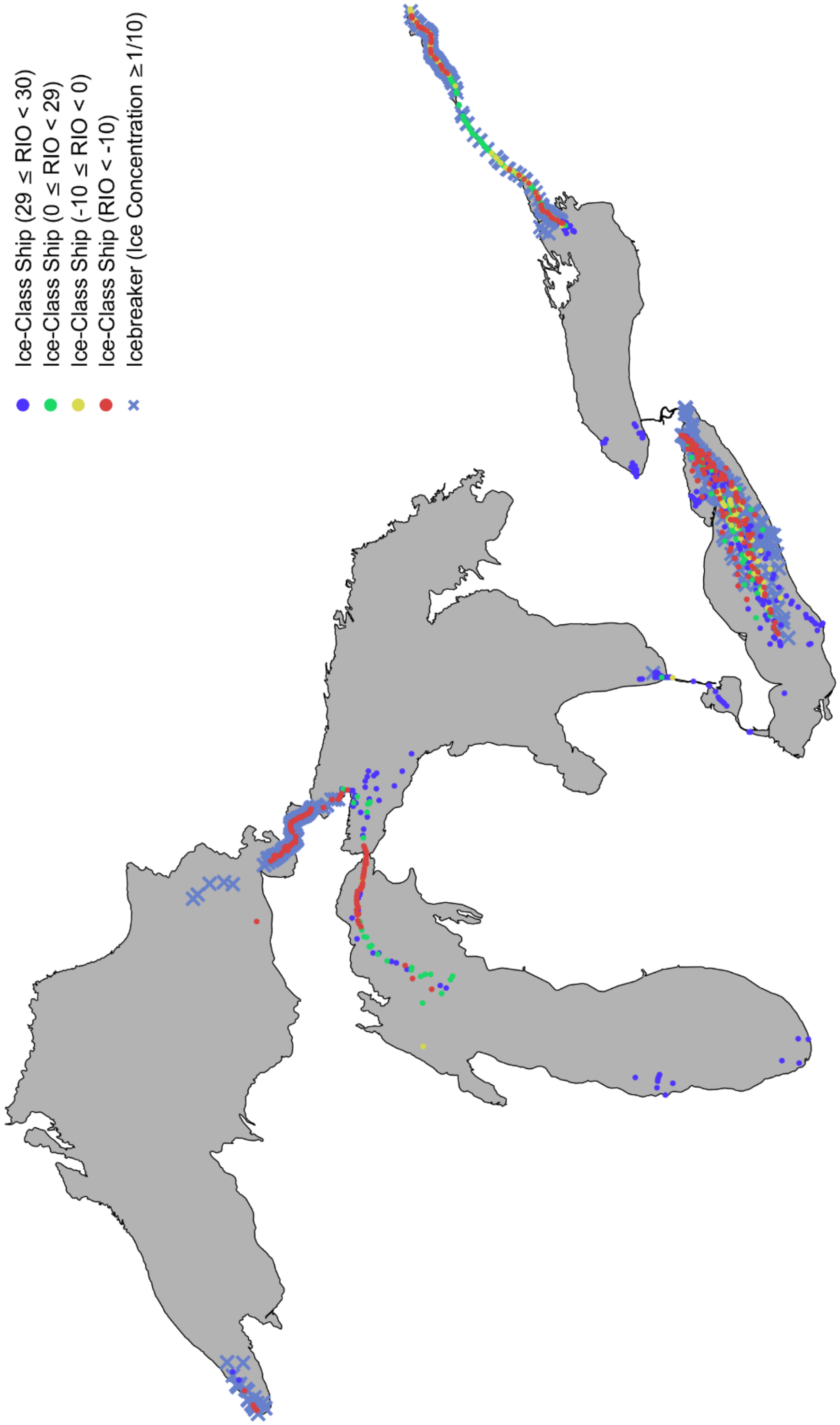
Appendix D4 AIS-Record Distribution for February 2014



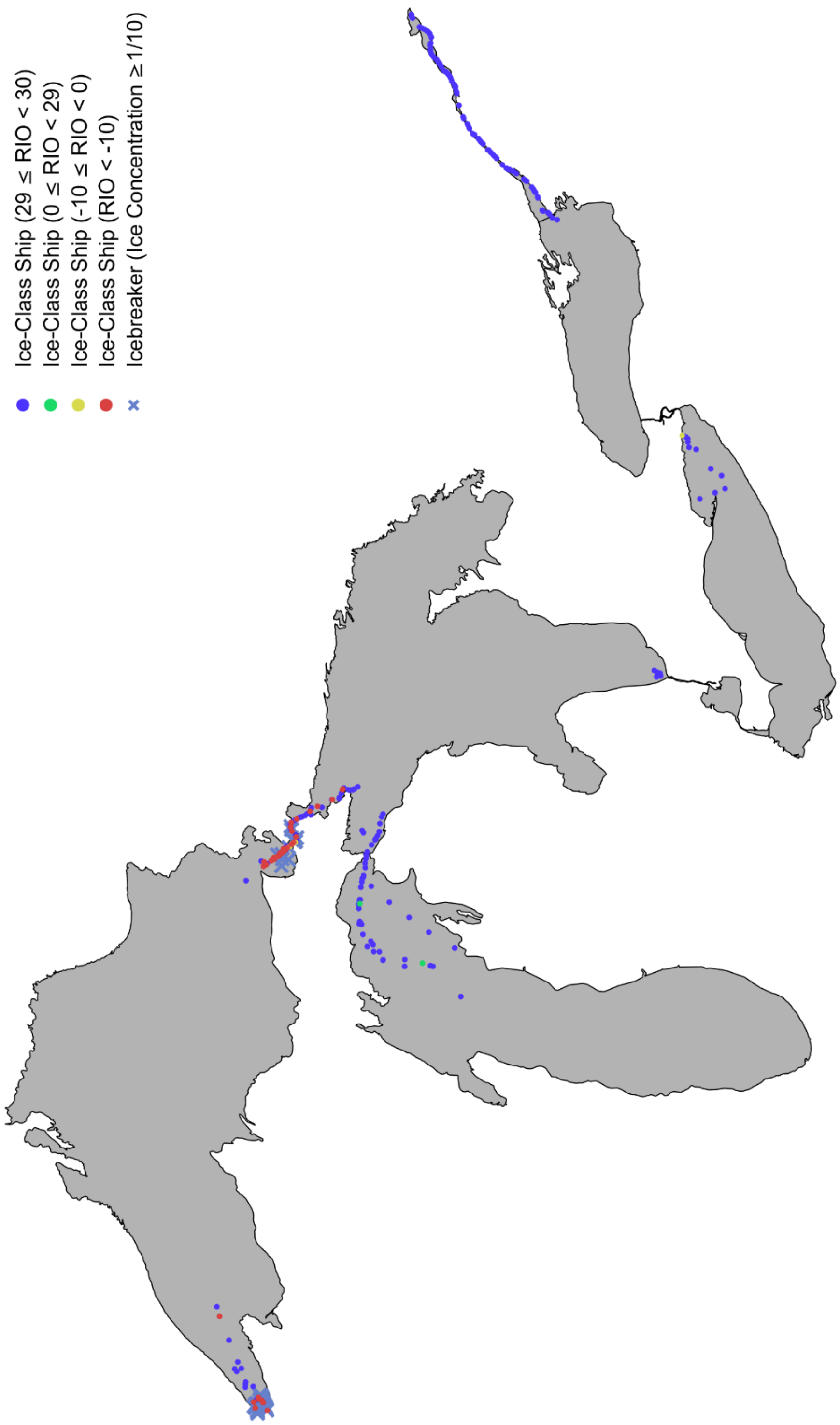
Appendix D5 AIS-Record Distribution for March 2014



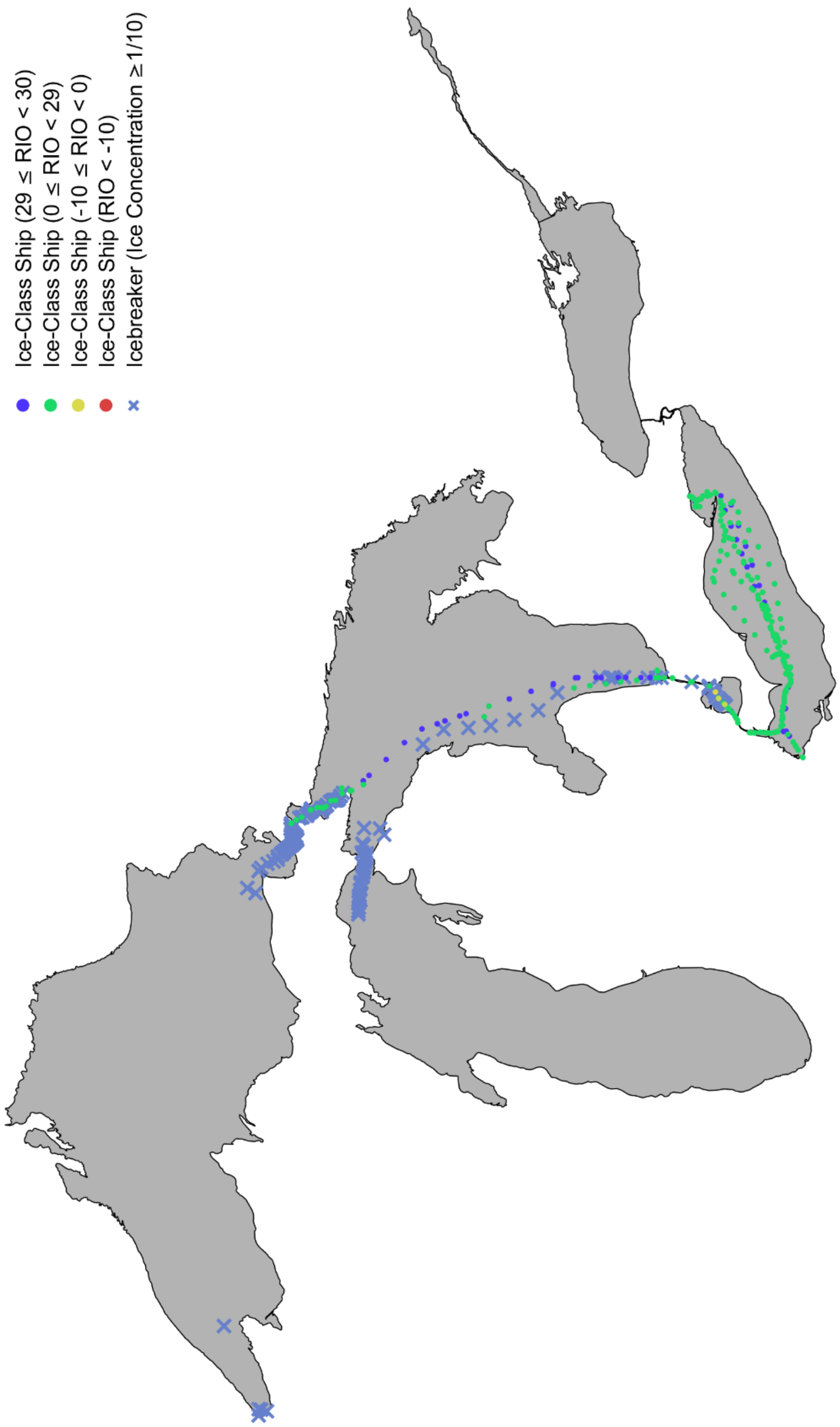
Appendix D6 AIS-Record Distribution for April 2014



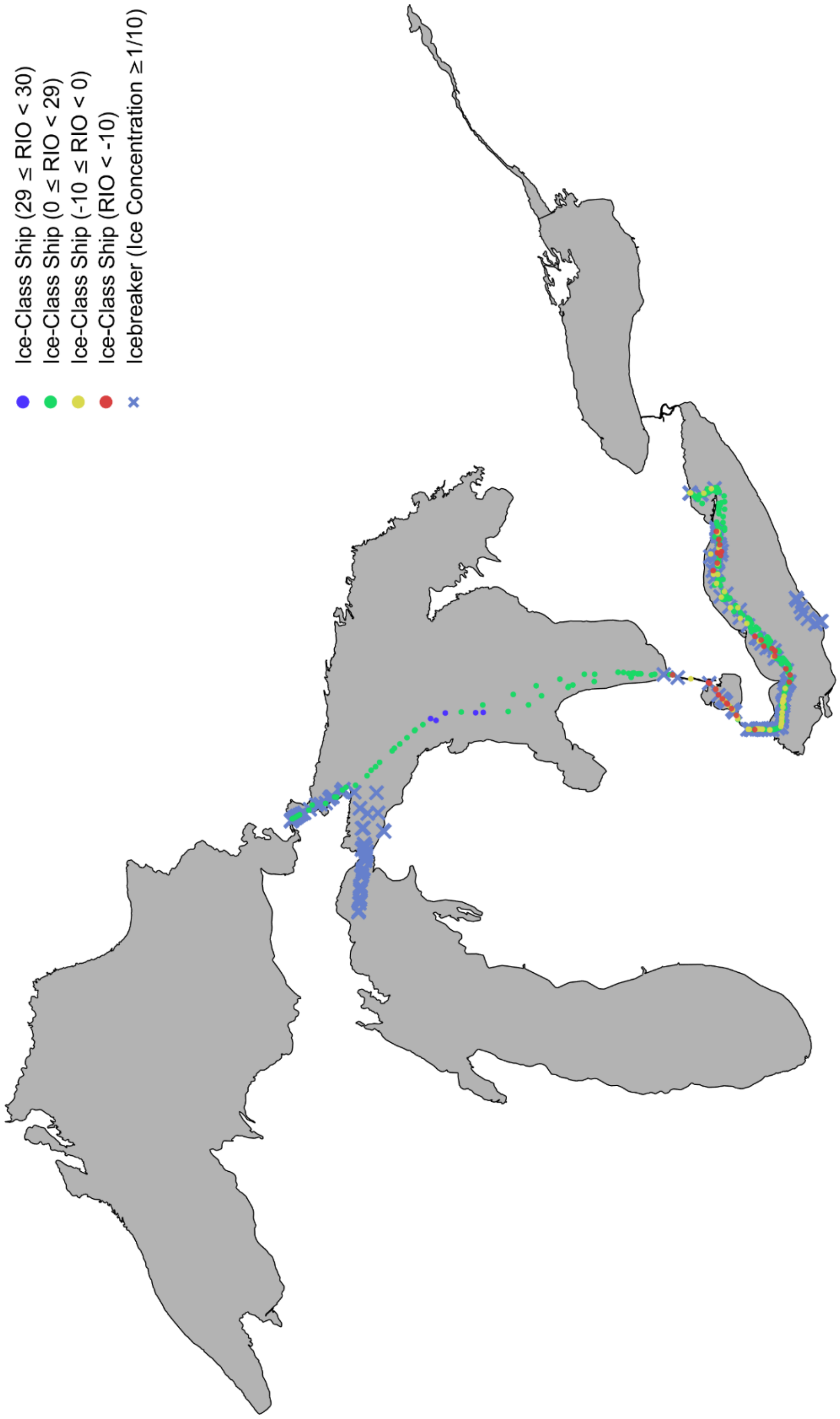
Appendix D7 AIS-Record Distribution for May 2014



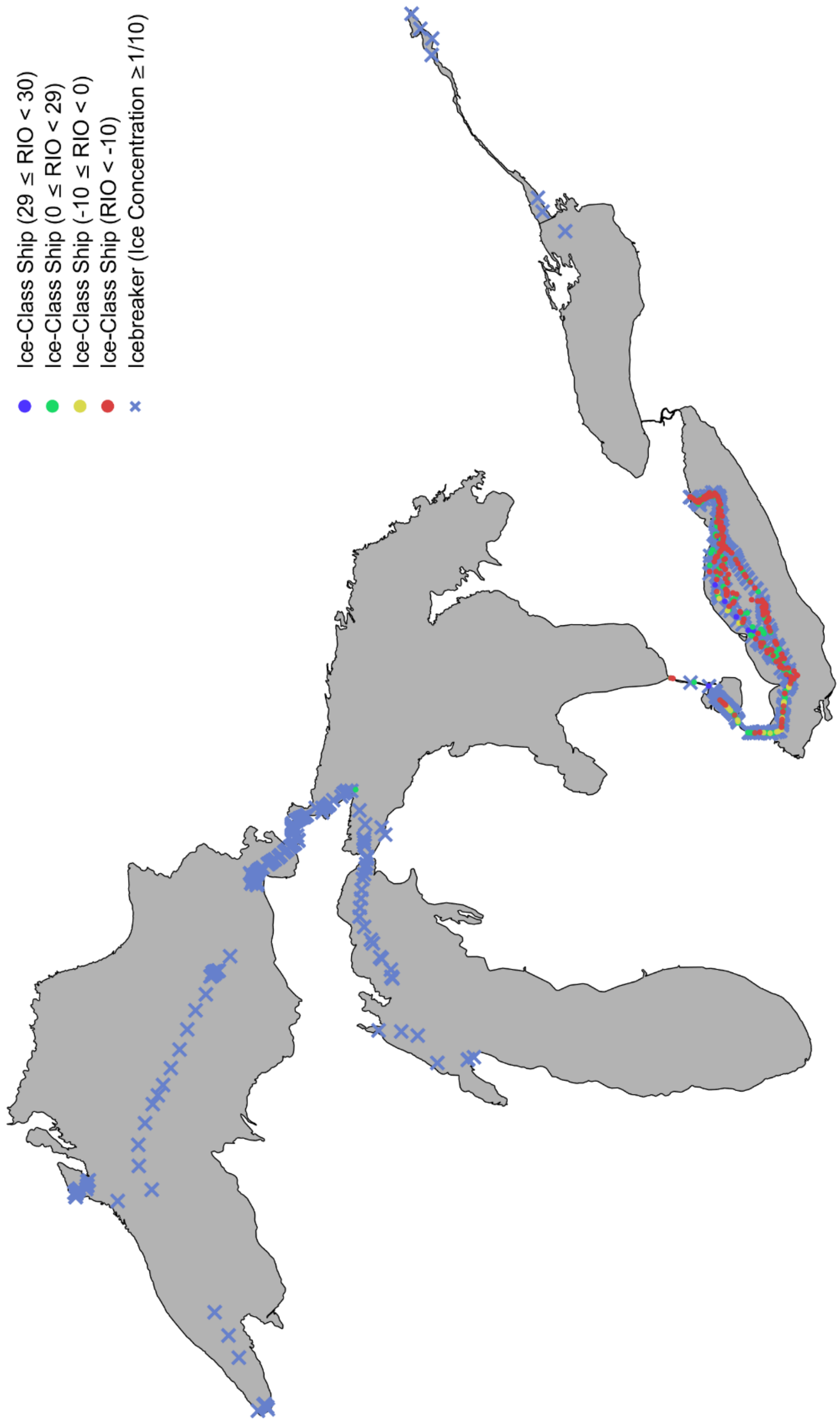
Appendix D8 AIS-Record Distribution for January 2015



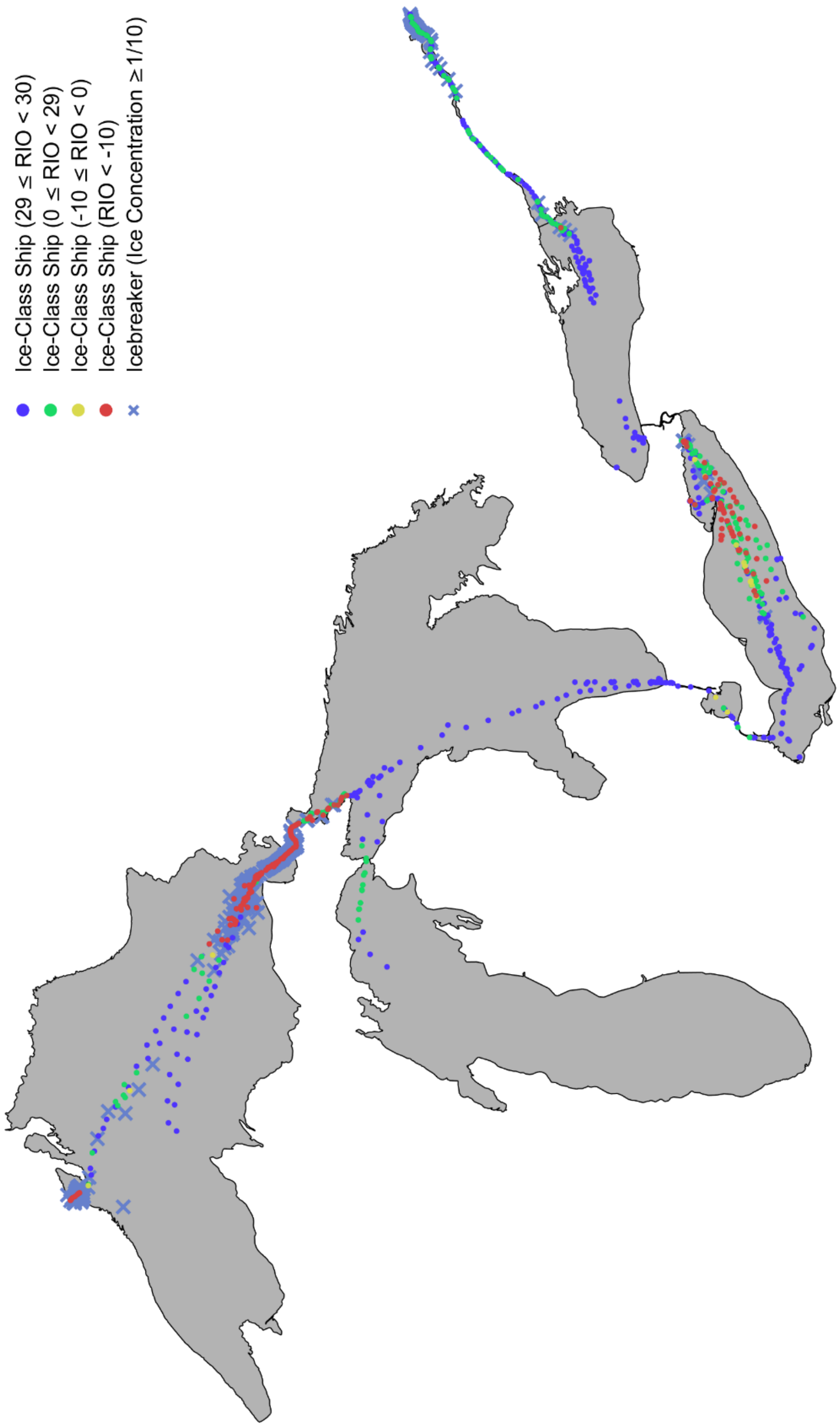
Appendix D9 AIS-Record Distribution for February 2015



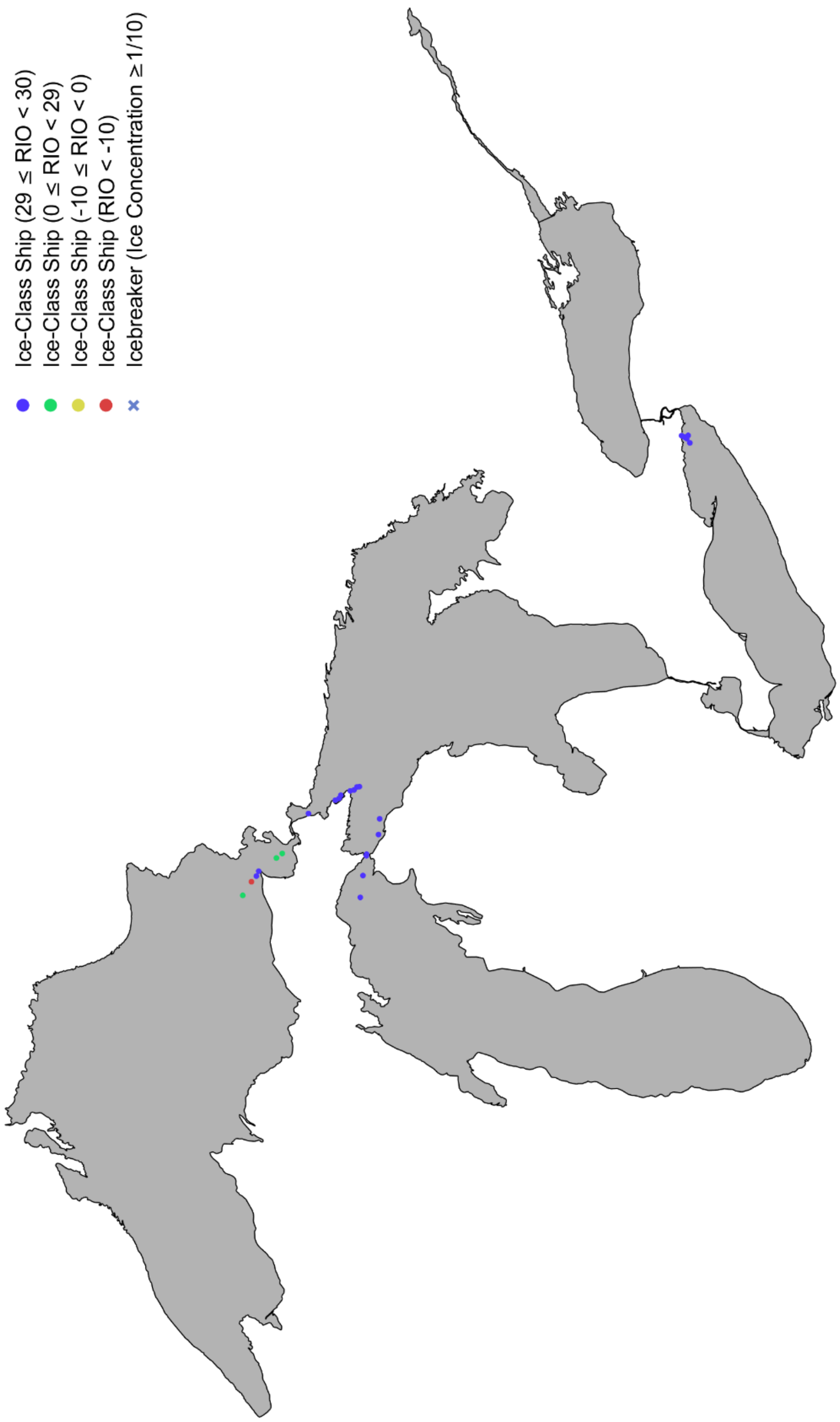
Appendix D10 AIS-Record Distribution for March 2015



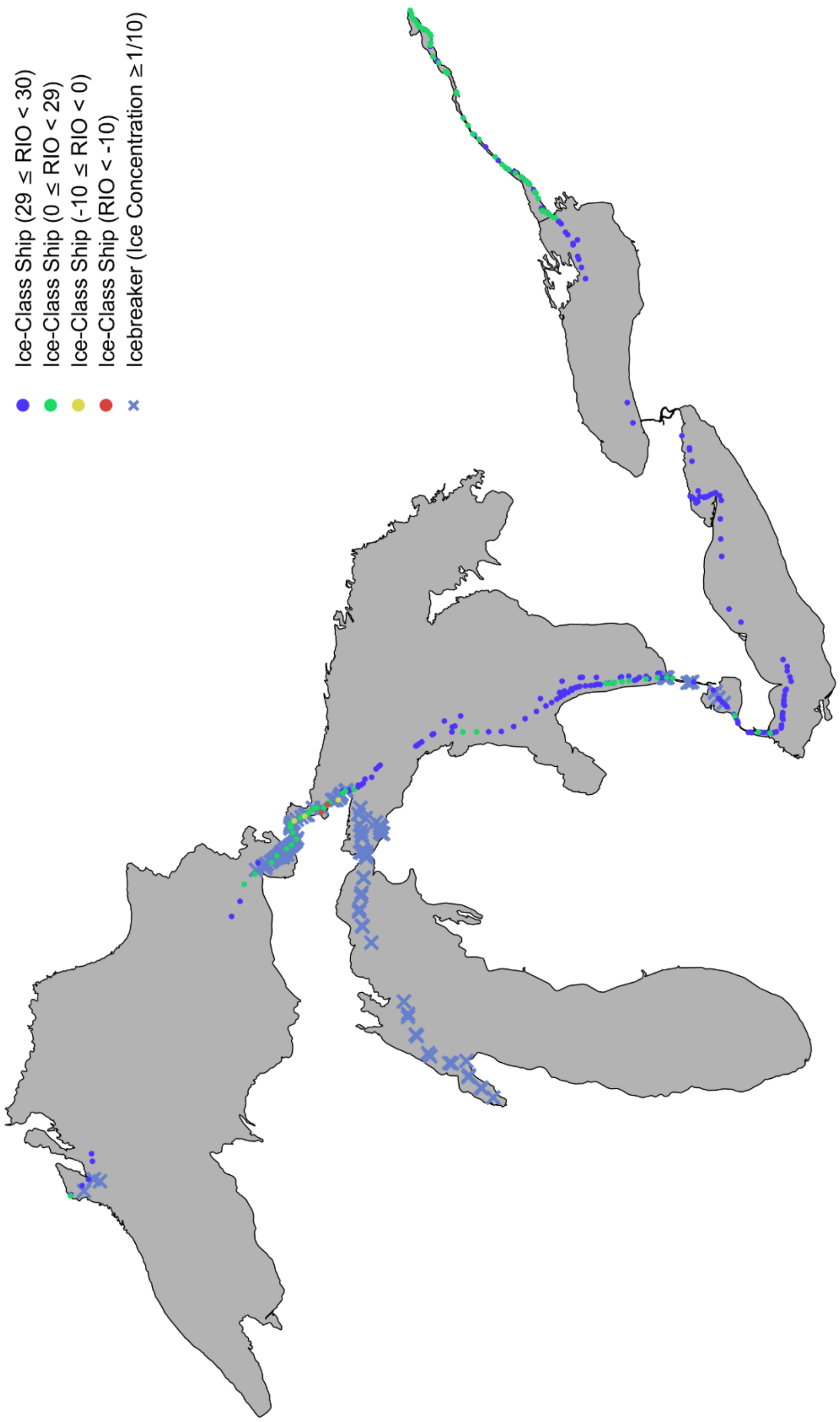
Appendix D11 AIS-Record Distribution for April 2015



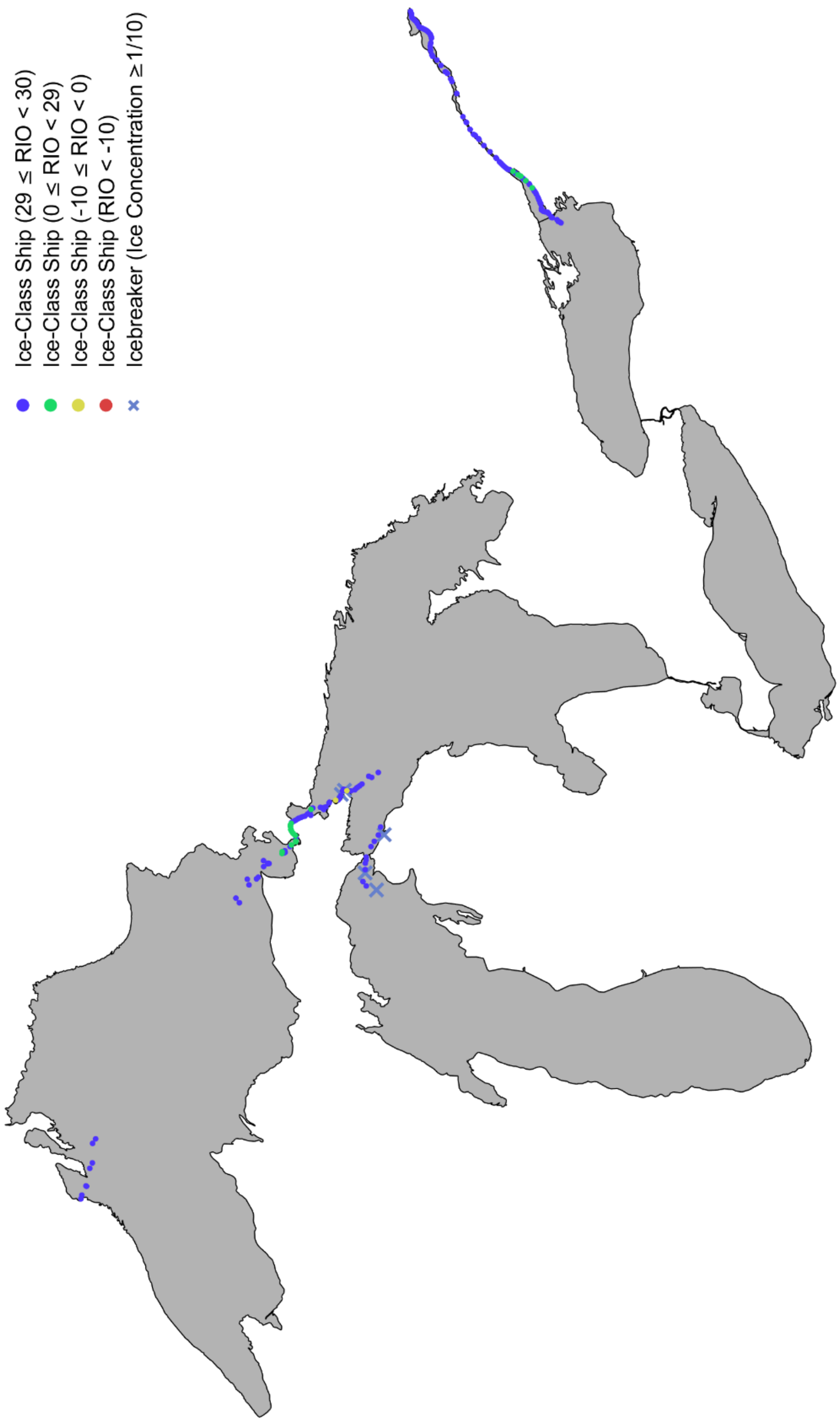
Appendix D12 AIS-Record Distribution for May 2015



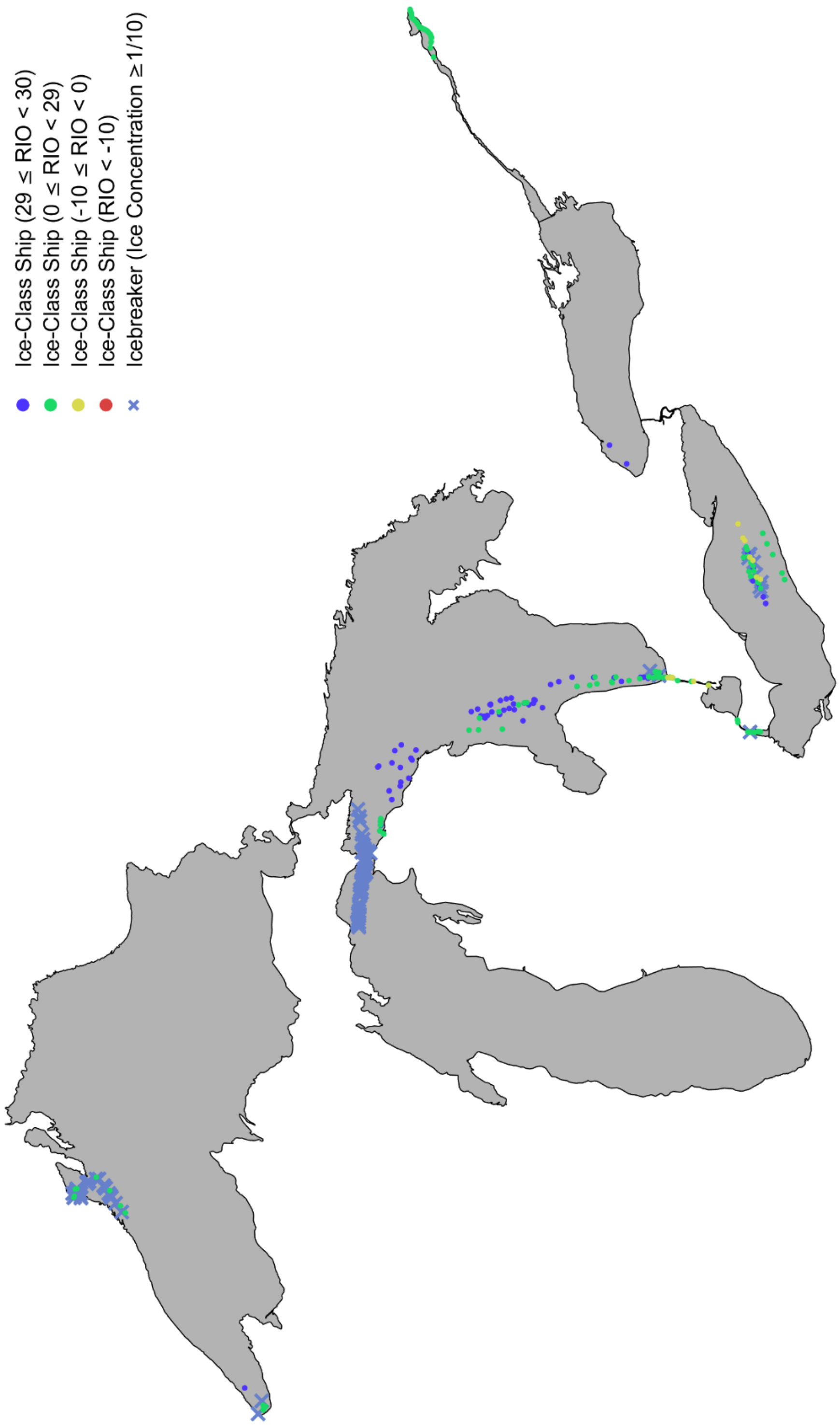
Appendix D13 AIS-Record Distribution for March 2017



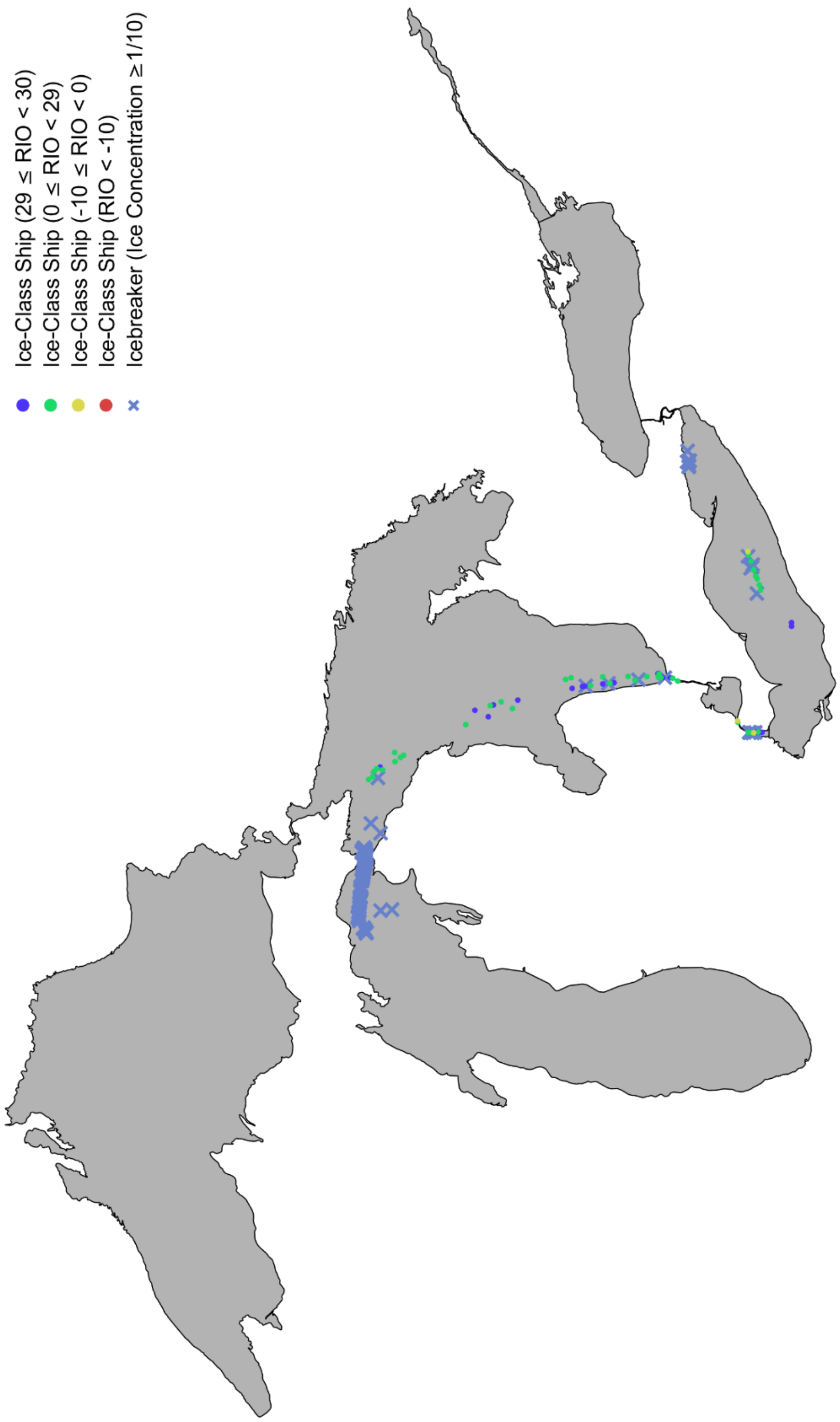
Appendix D14 AIS-Record Distribution for April 2017



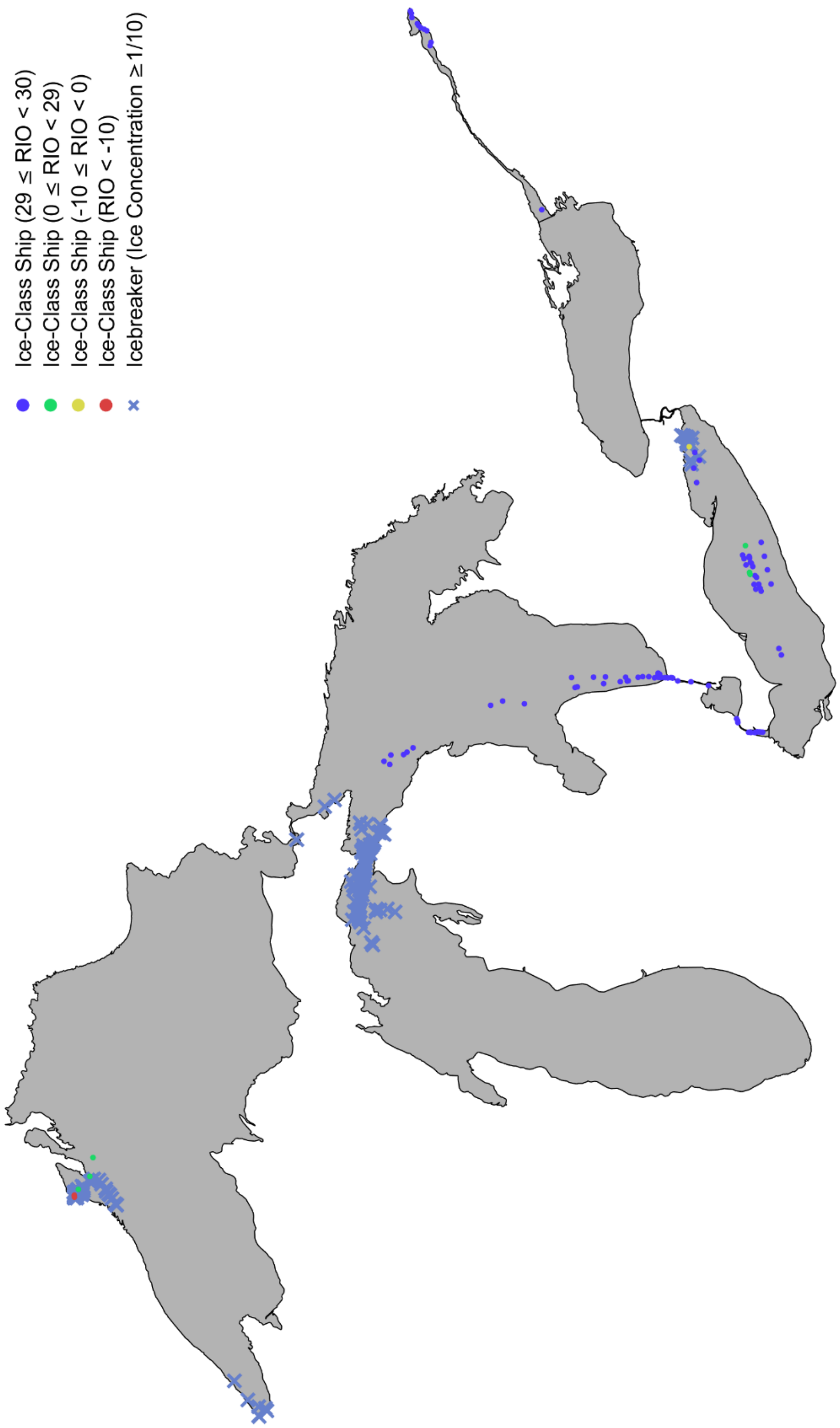
Appendix D15 AIS-Record Distribution for January 2018



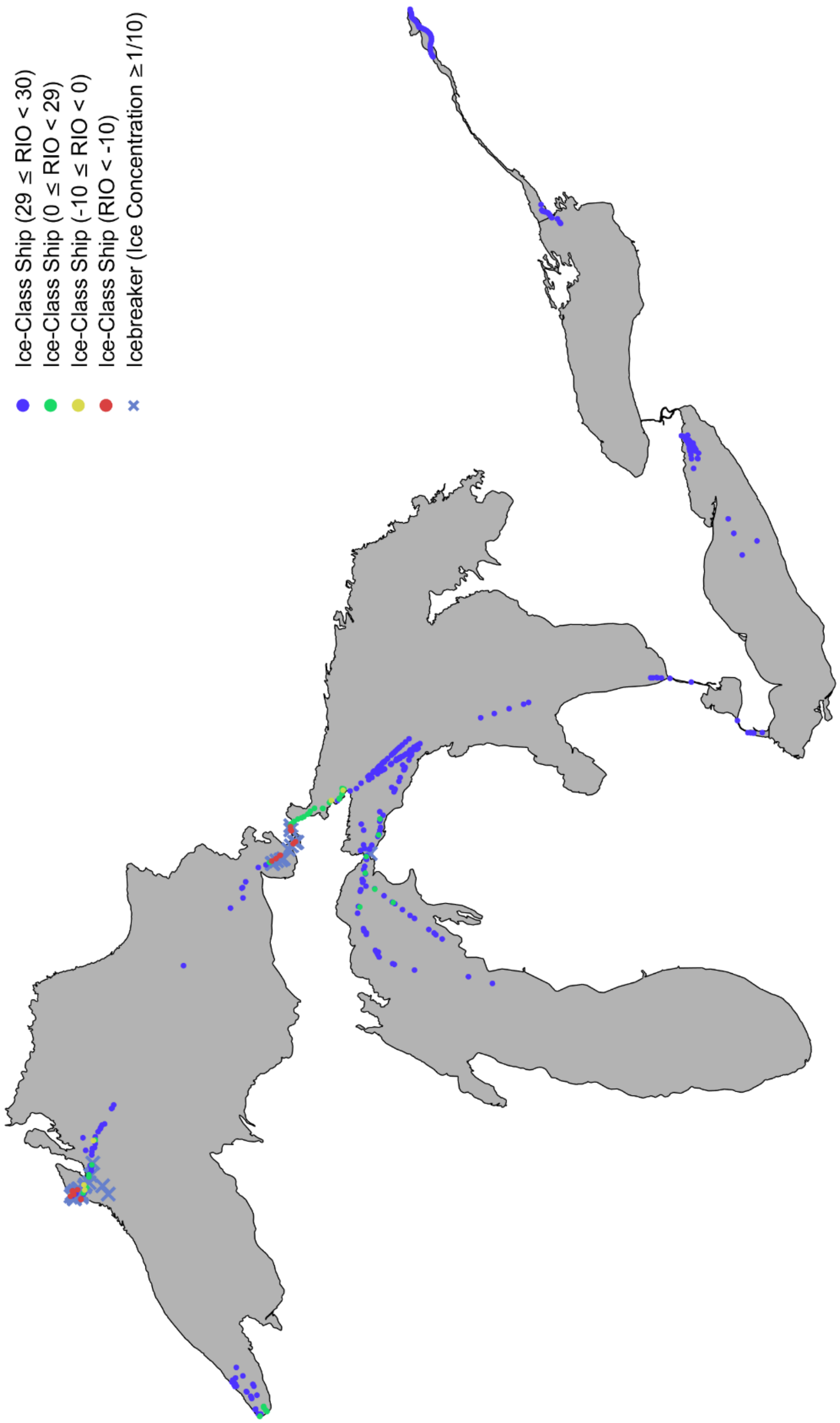
Appendix D16 AIS-Record Distribution for February 2018



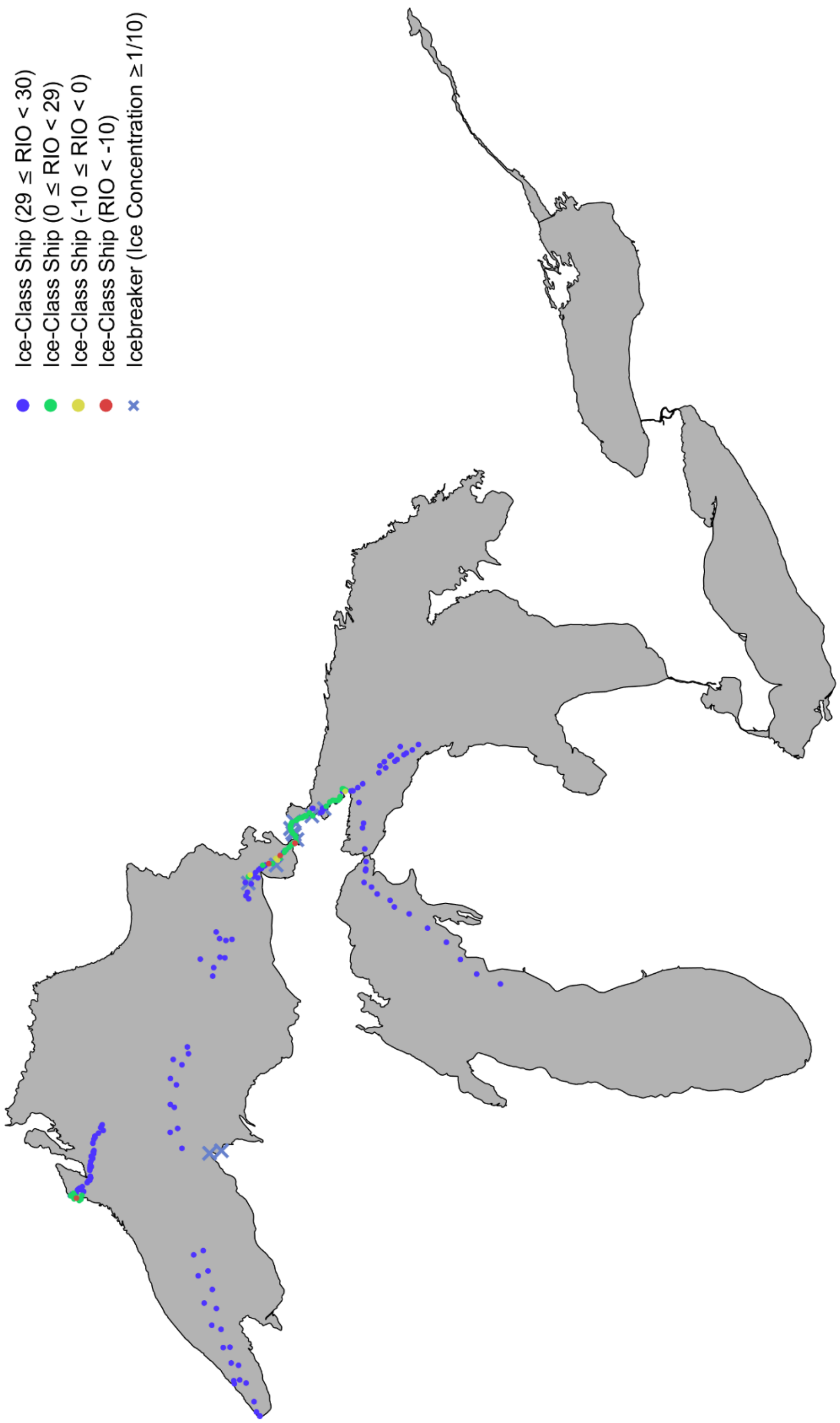
Appendix D17 AIS-Record Distribution for March 2018



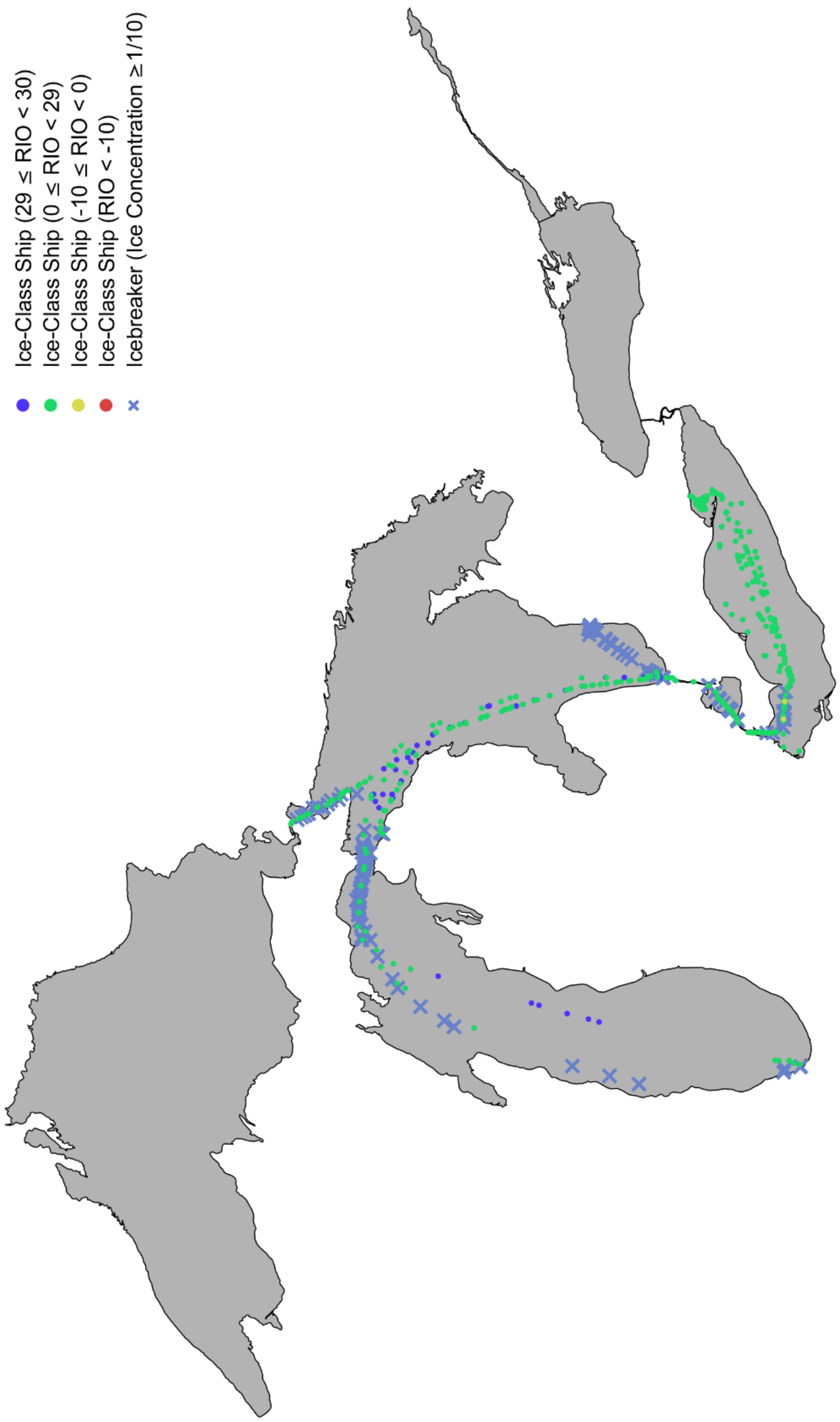
Appendix D18 AIS-Record Distribution for April 2018



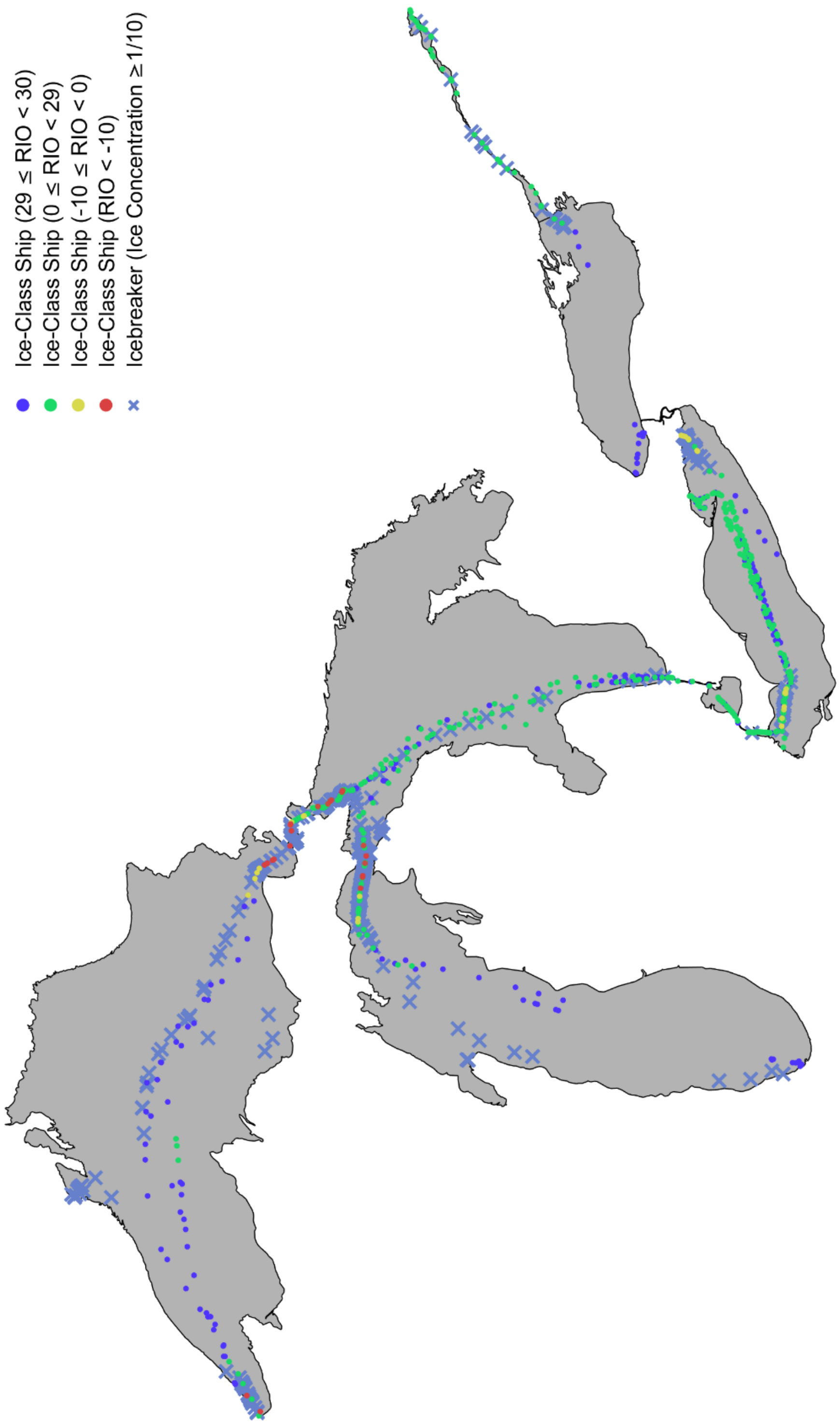
Appendix D19 AIS-Record Distribution for May 2018



Appendix D20 AIS-Record Distribution for February 2019



Appendix D21 AIS-Record Distribution for March 2019



Appendix D22 AIS-Record Distribution for April 2019