Climate change and sea ice:

shipping in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin

by

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Abstract

This thesis examines shipping accessibility in the seasonally ice-covered waters of Hudson Bay, James Bay, Hudson Strait, and Foxe Basin, and discusses the social and environmental implications of shipping in the study area. Shipping accessibility was analyzed for 1980 to 2016 by characterizing the timing of breakup, freeze-up, and the open water season using sea ice concentration thresholds of 15 or 20%, approximating navigable conditions for open water vessels. Research was channeled through three manuscripts. Findings indicate that there is considerable spatiotemporal variation in shipping accessibility in the study area. For example, the open water season currently varies between 64 and 224 days across the area. Shipping accessibility has generally increased since 1980, and spatial variation in the trends has altered the patterns of breakup and freeze-up in the area. Finally, research reveals that shipping has an important social role in the study area that is offset by potential environmental impacts.

Acknowledgements

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- Sections 1, 2, and 5 each contain content from research manuscripts that have either been published or are in the publication process. This is further explained in section 1.2.
- Section 3: Andrews, J., Babb, D., & Barber, D. G. (2017). Climate change and sea ice: Shipping accessibility on the marine transportation corridor through Hudson Bay and Hudson Strait (1980-2014). *Elem Sci Anth*, 5.
- Section 4: Andrews, J., Babb, D., & Barber, D. G. (2017). Climate change and sea ice: shipping in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin (1980-2016). Manuscript submitted for publication.

1. Introduction

The impact of climate change in the far north can be observed from space: sea ice has exhibited negative trends in extent, age, thickness, and duration on annual, seasonal, and monthly timeframes since the beginning of the satellite record (e.g. Stroeve et al., 2012; Vaughan et al., 2013). However, there is considerable variation in time and space within these trends ("spatiotemporal" variation). The decline of sea ice in the Arctic and sub-Arctic (collectively referred to as "Arctic" henceforth) and the resultant increase in marine accessibility create the potential for increased Arctic shipping, but this is not a straightforward cause and effect. First, the spatiotemporal variation in sea ice phenology (timing) and trends yields a shifting patchwork of marine accessibility that is a continuous challenge to assess and predict (e.g. Stroeve & Notz, 2015; Melia, Haines, & Hawkins, 2016). Second, Arctic shipping is not simply a product of marine accessibility - political, regulatory, economic, environmental, and cultural factors can each exert an influence on shipping traffic (e.g. Arctic Council, 2009). Nevertheless, shipping is indeed on the rise in many regions of the Arctic and, with scientists predicting accelerated ice loss throughout much of the northern hemisphere, this trend will likely continue (e.g. Melia et al., 2016). Going forward, inter-disciplinary research will be needed to chronicle and anticipate the changes in marine accessibility and shipping traffic.

Why does Arctic shipping matter? First, with respect to society: Arctic shipping provides essential re-supply services for remote northern communities (e.g. Brooks & Frost, 2012); Arctic shipping enables important economic activity, including trade and resource extraction projects (e.g. Arctic Council, 2009); and trans-Arctic shipping routes provide shorter options for inter-ocean travel (e.g. Melia et al., 2016). Second, with respect to the environment: Arctic shipping represents one of the most environmentally-significant activities in the many non-industrialized regions of the Arctic (e.g. Kelley & Ljubicic, 2012; Siders, Stanley, & Lewis, 2016).

This thesis is focused on shipping in the marine waters of Hudson Bay, James Bay, Hudson Strait, and Foxe Basin in the eastern Canadian Arctic ("the study area" - Figure 1-1). These waters, which stretch nearly 20 degrees of latitude from the sub-Arctic to the Arctic, share a close oceanographic relationship and are frequently grouped for scientific discussion (e.g. Fisheries and Oceans Canada, 2011; Joly, Senneville, Caya, & Saucier, 2011; Hochheim & Barber, 2014), though there is no consensus on the term used to refer to the four regions collectively. The marine waters of the study area are bordered by 39 remote communities and are covered by sea ice for 5 to 10 months of the year.

Figure 1-1. The study area - the waters of Hudson Bay, James Bay, Hudson Strait, and Foxe Basin in the eastern Canadian Arctic. The area is bordered by 39 communities spread amongst five major administrative regions: Nunavut, Nunavik, Eeyou Istchee, Ontario, and Manitoba.

1.1. Research objectives

This thesis presents my efforts to address two related research questions:

1. What is the current shipping accessibility in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin (the "study area"), and how has shipping accessibility changed in recent decades?
2. What are the social and environmental implications of shipping in the study area?

Question 1 was investigated by analyzing the timing of sea ice in the study area. More specifically, the timing of 1) breakup, 2) freeze-up, and 3) the open water season, with these variables defined using sea ice concentration thresholds that approximate navigable conditions for open-water shipping vessels (a designated class of vessel). Question 2 was researched through a review of the relevant literature (academic and "gray") and by speaking with some of those affected by or involved in the shipping industry in the study area (including residents, shippers, regional governments, etc.).

These are dynamic times for the shipping industry in the study area. Shipping traffic is rising as changing environmental and social circumstances present new opportunities and vulnerabilities. Important policy decisions are in the offing. This thesis was motivated by a desire to provide timely and accessible scientific information to stimulate and support the discussion around shipping in the study area. Ultimately, I hope that this research will contribute, in some small way, to the management of an environmentally and socially responsible shipping industry in the area.

1.2. Thesis structure

This is a "Grouped Manuscript Style" thesis. During my Master's degree I have contributed to three research manuscripts (outlined below). The first and second manuscripts listed below present novel research that I conceived, conducted, and reported with the support of David Babb and Dr. David Barber. The third manuscript listed below is an inter-disciplinary review article that was written through a collaborative process with several authors.

Manuscript 1

Andrews, J., Babb, D., & Barber, D. G. (2017). Climate change and sea ice: Shipping accessibility on the marine transportation corridor through Hudson Bay and Hudson Strait (1980-2014). *Elem Sci Anth*, 5.

This manuscript presents a scientific examination of sea ice timing on the marine transportation corridor through Hudson Bay and Hudson Strait to the Port of Churchill. A passive-microwave based dataset was used to characterize the timing of breakup, freeze-up, and the open water season on the corridor between 1980 and 2014. The scientific analysis is accompanied by a description of shipping traffic and the regulatory framework for shipping in Hudson Bay and Hudson Strait.

Manuscript 2

Andrews, J., Babb, D., & Barber, D. G. (2017). Climate change and sea ice: shipping in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin (1980-2016). Manuscript submitted for publication.

This manuscript presents a scientific examination of offshore and local shipping accessibility in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin alongside a discussion of the social and environmental impacts of shipping in the study area. Shipping accessibility was assessed by characterizing the timing of breakup, freeze-up, and the open water season in offshore and local (near-coast) waters. Offshore ice timing was analyzed using passive-microwave based data for 1980 to 2014, local ice timing at Rankin Inlet, Churchill, Kuujjuarapik/Whapmagoostui, and Salluit was examined using Canadian Ice Service ice charts for 1996 to 2016.

Manuscript 3

Ng., A., Andrews, J., Babb, D., Lin, Y., & Becker, A. (in press). Implications of climate change for shipping: Opening up the Arctic seas. *Wiley Interdisciplinary Reviews: Climate Change*

This manuscript presents a combined economic and environmental review of Arctic shipping. David Babb and I contributed the environmental content.

This thesis consists of six sections. Section one provides an introduction to the thesis context, objectives, and structure. Section two presents a review of the relevant literature by combining content from the introductory sections of the three manuscripts listed above. Section three presents the abstract, methods, results, discussion, and conclusions from Manuscript 1. Section four presents the abstract, methods, results, discussion, and conclusions from Manuscript 2. Section five provides a brief discussion of the most pertinent climate model projections for sea ice. Finally, section six presents the key findings of this thesis, outlines the possible implications for policy and management, and suggests avenues for further research.

Sections one, two, and five include content taken from the three manuscripts outlined above. All content included herein from Manuscript 3 was written by me in collaboration with David Babb. Also, throughout sections 1 to 5 any additions or deletions to manuscript content are indicated with square brackets and ellipses, respectively. Finally, where necessary the referencing format, the figure numbering, and the table numbering in the manuscript content have been changed to produce a continuous structure throughout this document.

1.3. The study area

The study area [Hudson Bay, James Bay, Hudson Strait, and Foxe Basin] borders five major administrative regions within Canada: Nunavik and Eeyou Istchee of north-western Quebec, Nunavut, Manitoba, and Ontario. The area is home to 39 formal communities dotted along the coast (Figure 1-1), with a total population of roughly 50,000 (Statistics Canada, 2016). Indigenous people make up the great majority of the population in nearly all of these 39 communities. The majority of residents in the communities of Nunavut and Nunavik are Inuit, and the majority of residents in the coastal communities of Eeyou Istchee and northern Ontario are Cree (Statistics Canada, 2011). Of the 39 communities, only Churchill, Manitoba and the nine communities of James Bay are accessible by rail or road (all-weather or winter). The remaining 29 communities (and roughly 27,000 people) can be accessed only by sea or air.

The marine waters of the study area are covered by sea ice for 5 to 10 months of the year (Hochheim & Barber, 2014). Sea ice is fundamental to the culture and sustenance of the Inuit people in the study area: sea ice is a seasonal extension of their homeland that enables travel and wildlife harvesting (Inuit Circumpolar Council - Canada, 2008; Aporta, 2010). Inuit people have spent generations learning the nuances and subtleties of their local sea ice and the seasonal ice covering forms a familiar, well-travelled topography (Laidler & Elee, 2008; Laidler et al., 2009; Aporta, 2010). Furthermore, many residents of the study area obtain a considerable portion of their food from wildlife harvested on sea ice (Chan et al., 2006; Ford, 2009; Laidler et al., 2009). On the other hand, sea ice is the greatest barrier to shipping in the study area (Kelley & Ljubicic, 2012; Engler & Pelot, 2013). For shippers it is an obstacle and a hazard that prevents access and reduces shipping potential (Aporta, 2011; Brooks & Frost, 2012; Kelley & Ljubicic, 2012). It is important to be mindful of these contrasting perceptions of sea ice.

2. Literature Review

2.1. Broad context - climate change, sea ice, and shipping in the Arctic

In its last report, the Intergovernmental Panel on Climate Change (IPCC) estimated (with high confidence) that the global mean temperature increased 0.85˚C between 1880 and 2012 (IPCC, 2013a). Moreover, temperatures in the polar regions have increased at a significantly greater rate than the lower latitudes due to a number of mechanisms collectively referred to as ‘Polar Amplification’ (Arctic Council, 2004; Cubasch et al., 2013). Warming temperatures in the Arctic have driven a rapid decline in sea ice over the past 50 years and have triggered changes in Arctic weather systems (IPCC, 2013a), with implications for marine transportation.

With respect to shipping, Arctic sea ice is primarily described by referring to ice extent (or area) and ice thickness. It is important to understand the meaning of these variables and how they are observed.

- Ice extent and area both relate to the geographic distribution of sea ice: ice extent refers to the total area with sea ice concentration above a selected threshold (typically 15%), while ice area refers to the total ocean area covered with sea ice (Cavalieri & Parkinson, 2012; Vaughan et al., 2013). Area-based ice measurements are also used to examine the timing of sea ice in areas with non-continuous ice coverage, producing time-related variables such as breakup and freeze-up dates, or melt, open-water, and ice season length. Satellite-based observations, from both visible and microwave-based platforms, provide a continuous data record of the geographic distribution of sea ice, and thus all of the aforementioned variables, for 1979 to the present (Vaughan et al., 2013; Stroeve & Notz, 2015).

- Ice thickness refers to the thickness of ice (and sometimes snow) between the liquid ocean and the atmosphere. Numerous techniques have been used to measure ice thickness in recent decades, including Upward Looking Sonar (ULS) on submarines and moorings, airborne electromagnetic (EM) instruments, and altimetry from aircraft and satellites (Lindsay & Schweiger, 2015; Stroeve & Notz, 2015). Despite the many techniques the current record of sea ice thickness remains incomplete, with gaps in spatial and temporal coverage and relatively high uncertainty (Stroeve & Notz, 2015). For example, satellite altimetry observations are limited to the period between November and April and do not provide measurements during spring and summer when the data could be most applicable to Arctic shipping.

Arctic sea ice is complex and dynamic, with considerable variation over space and time (i.e., "spatiotemporal variation"). Arctic sea ice extent typically varies by roughly 250% over the course of the year, with a maximum extent in March and a minimum in September (Vaughan et al., 2013). Figure 2-1 shows the peripheral Arctic seas with seasonal ice coverage that surround the continuously ice-covered central Arctic…. At any given time, the Arctic ice pack consists of a mixture of first-year ice - ice that has not survived one summer and typically grows to a maximum thickness of two metres, second-year ice - ice that has survived one summer, and multiyear ice - ice that has survived at least two summers and which varies in thickness from roughly 2-10 metres (Haas, Hendricks, Eicken, & Herber, 2010). Older sea ice is concentrated in the central Arctic and is typically thicker because it has undergone multiple winter growth seasons (Tschudi, Stroeve, & Stewart, 2016). Finally, the Arctic ice cover can be further differentiated between 'mobile pack ice' that drifts under the influence of surface winds, ocean currents, the Coriolis force, and tides, and 'landfast ice' that is immobilized by the shore or seafloor.

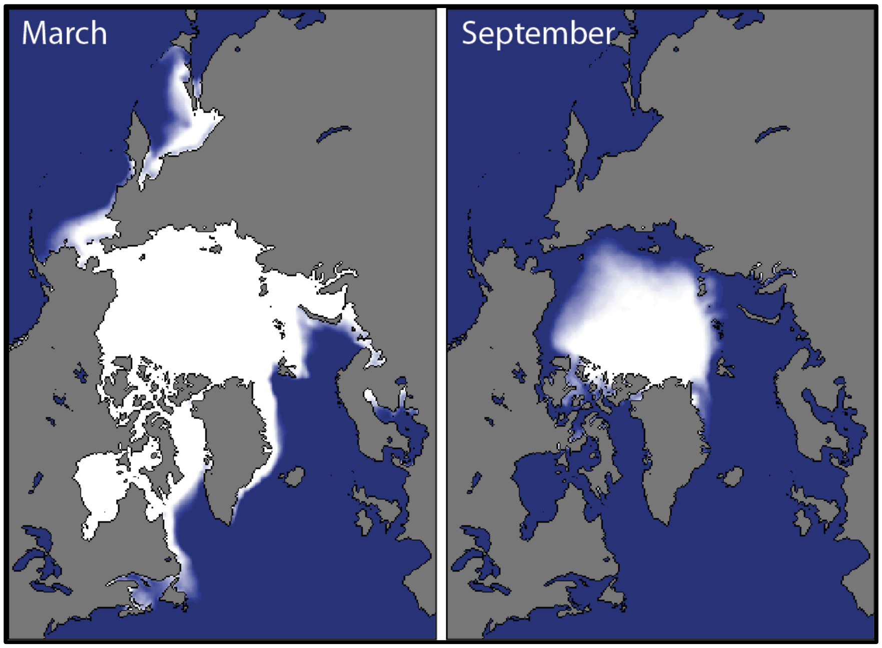

Figure 2-1. The 1981-2010 average maximum (March) and minimum (September) sea ice extent in the northern hemisphere (National Snow and Ice Data Centre, 2016a).

Sea ice is the greatest physical constraint on Arctic shipping. Shippers transiting Arctic waters can either avoid sea ice by confining their activities to the seasonal open water periods in certain Arctic regions, or shippers can travel within sea ice using vessels with some measure of ice-strengthening. A vessel's "ice-strengthening" is the product of many components in the vessel's design (e.g. hull strength, thickness, etc.). The world's shipping fleet contains a broad range of ice-strengthened vessels, varying from "Open Water" vessels capable of travelling in ice up to 15cm thick to "Polar Class" vessels that can travel in sea ice several meters thick (Transport Canada, 2010a). In recent decades, vessels have been built according to numerous different ice-capacity classification systems, resulting in a patchwork of vessel designs and regulations (e.g. Government of Canada, 2017; Canadian Coast Guard, 2012). …However, it is now recommended that new ice-strengthened vessels be built according to international guidelines set out in the "Requirements Concerning Polar Class" by the International Association of Classification Societies (IACS) at the behest of the International Maritime Organization (IACS, 2006 [updated 2016]; Transport Canada, 2009). Ice-strengthened vessels designed according to an earlier classification system may apply for an equivalency in the IACS system.

The Arctic ice pack is undergoing rapid change. Satellite records clearly display negative trends in ice extent, area, and duration (e.g. Comiso, 2012; Vaughan et al., 2013; Stroeve, Markus, Boisvert, Miller, & Barrett, 2014). For example, between 1979 and 2016 the September minimum ice extent declined at a significant rate of -87 200 km^2 or -13.3% per decade (National Snow and Ice Data Center, 2016b). Moreover, the rate of ice loss has accelerated during this period and record minima in ice extent occurred during 2007 and again in 2012 (Vaughan et al., 2013). For context, the September 2012 record minimum ice extent of 3.41 million km^2 was only 54% of the average minimum extent between 1981 and 2010 (Liu, Babanin, Zieger, Young, & Guan, 2016). Underlying the reductions in the spatial extent of sea ice are significant trends towards a thinner and younger ice pack (Kwok and Rothrock, 2009; Maslanik, Stroeve, Fowler, & Emery, 2011; Comiso, 2012; Lindsay & Schweiger, 2015).

Why is Arctic ice declining? Average air temperatures are rising in the Arctic, affecting sea ice formation, growth, persistence, and movement throughout the year (Masson - Delmotte et al., 2013). Also, warmer temperatures and other climate changes appear to drive a series of "feedback loops" that cause accelerated, non-linear Arctic ice loss (Masson - Delmotte et al., 2013; Stroeve et al., 2014). The ice-albedo feedback loop, for example, is a major contributor to Arctic ice loss and can be summarized as follows (Serreze & Barry, 2011; Parkinson, 2014): Reduced sea ice coverage and increased melt raise the proportion of exposed water in an area, which lowers the surface albedo (reflectivity) and increases the absorption of solar radiation. An increase in solar absorption results in further warming of the ocean surface and increased melt of the remaining ice pack, thereby exposing more areas of open water and feeding the cycle. The ice-albedo feedback loop works on a seasonal and an inter-annual timescale: increased melt and warmer surface waters delay fall freeze-up and precondition the subsequent ice pack to be thinner, less extensive, and more susceptible to earlier breakup (Serreze & Barry, 2011). Looking ahead, climate scientists predict (with considerable confidence) that polar warming and sea ice loss will continue, and even accelerate, into the future (e.g. Kirtman et al., 2013).

2.2. Sea ice in the study area

2.2.1. Sea ice phenology

The waters of Hudson Bay, James Bay, Hudson Strait, and Foxe Basin all undergo a complete freeze-and-melt cycle each year (Hochheim & Barber, 2014). Put simply, the study area is seasonally covered with first-year ice, though small extents of second-year ice may be produced in Foxe Basin and migrate into north-eastern Hudson Bay (Gagnon & Gough, 2006; Tivy et al., 2011; Environment and Climate Change Canada, 2013). In recent decades the seasonal timing of ice in the study area has typically run as follows: sea ice grows and melts in a complicated geographic pattern, but growth generally progresses from north to south between September and December and melt generally progresses from south to north between May and August (Environment and Climate Change Canada, 2013; Hochheim & Barber, 2014). Foxe Basin is typically ice free for parts of August and September, Hudson Strait is ice free from July to November/December, and Hudson Bay and James Bay are ice free from July/August until

November/December (Environment and Climate Change Canada, 2013; Hochheim & Barber, 2014). There is, however, considerable spatiotemporal variation within these broad patterns.

First year ice typically varies in thickness from 30 to 120cm (Environment and Climate Change Canada, 2016), and Steward and Lockhart (2005) report an average maximum ice thickness of 160cm in Hudson Bay. The first-year sea ice that covers the study area each year is not uniform. First, the ice can be separated into two categories: landfast ice and mobile pack ice. Roughly put, landfast ice is any relatively immobile and continuous sheet of ice that is grounded or anchored to land in some way (Yu, Stern, Fowler, Fetterer, & Maslanik, 2014). Mobile pack ice is floating sea ice that moves according to ocean currents and winds (Rampal, Weiss, & Marsan, 2009). In the study area, landfast ice typically forms after the pack ice and melts before, and may extend only a short distance or up to tens of kilometres offshore (Environment and Climate Change Canada, 2013). The mobile pack ice of the study area follows distinct movement patterns in different regions. For example, the currents in Hudson Bay flow counter-clockwise and push the mobile ice with them, which can result in dynamic thickening of ice in the eastern Bay during the ice season and raised ice concentrations in the south-west and south during spring breakup (Gagnon & Gough, 2006; Galbraith & Larouche, 2011; Hochheim & Barber, 2014).

The formation, persistence, and melt of sea ice are not simple processes. There is some consensus that, on a broad scale, the timing of sea ice in the study area is largely determined by atmospheric temperatures and wind (Tivy et al., 2011; Hochheim & Barber, 2014; Ogi, Barber, & Rysgaard, 2016). But sea ice is influenced by both the immediate impact of external forces and by the legacy of recent forcing, via the albedo feedback loop and "climate memory" (Gough & Houser, 2005; Stroeve, Crawford, & Stammerjohn, 2016). In the cyclical process of climate memory, the timing of ice at one point in the annual cycle influences the amount of heat stored (or not stored) in the surface waters, which in turn affects ice timing at a subsequent point in the cycle, and so on (Gough & Houser, 2005; Serreze & Barry, 2011; Stroeve et al., 2016). Numerous studies have shown relationships between the timing of breakup and freeze-up in waters of the study area (e.g. Gough & Houser, 2005; Stroeve et al., 2016; Andrews, Babb, & Barber, 2017).

Finally, sea ice is also subject to the local variations in air temperatures, wind, and current, and to other relatively local factors such as freshwater input and precipitation (Gagnon & Gough, 2006; Laidler & Elee, 2008; Galley, Else, Howell, Luckovich, & Barber, 2012). As a consequence, the ice of the study area grows, melts, rafts, and ridges in a variable pattern, producing a heterogeneous first-year ice cover with variable timing and thickness (Hochheim & Barber, 2014; Mussels, Dawson, & Howell, 2016).

2.2.2. Recent trends

The previous paragraphs have described the "typical" timing of sea ice in the study area, but a volume of research indicates that this timing has been changing over recent decades in response to warming temperatures driven by climate change. In a pan-Arctic study using passive-microwave based sea ice data, Parkinson (2014) found significant trends of -10 to -20 days.decade^{-1} in the length of the ice season (ice concentrations >15%) in our study area between 1979 and 2013. Stroeve et al. (2014) used passive-microwave based data to examine changes in the pan-Arctic timing of melt and freeze onset between 1979 and 2013, and reported significant trends for our study area of roughly -3 days.decade^{-1} in melt onset and roughly +6 days.decade^{-1} in melt season length (no significant trends for freeze onset). Tivy et al. (2011) used ice charts from the Canadian Ice Service (CIS) to examine changes in average summer sea ice extent in the Canadian Arctic between 1968 and 2008, and calculated significant trends of -8.9 ± 2.3

%.decade^{-1} for Foxe Basin (Jul - Sep), -16.0 ± 3.4 %.decade^{-1} for Hudson Strait (Jul -Oct), and -10.4 ± 3.1 %.decade^{-1} for Hudson and James Bays (Jul - Oct). Tivy et al. (2011) further reported that within Hudson Bay the trends in summer ice extent were strongest in the northwest, followed by the central Bay, and then the northeast, with no significant trends along the east coast. Finally, the authors remarked that reductions in the ice cover of the "Hudson Bay region" (Hudson Bay and Hudson Strait in this case) are amongst the greatest in the circumpolar Arctic (Tivy et al., 2011).

Several recent articles have looked specifically at the timing of ice in our study area or regions within it. Galbraith and Larouche (2011) used CIS ice charts to examine the timing of ice breakup (below concentrations of 50%) in our study area between 1971 and 2009. Their data had a resolution of one-quarter degree (1/4°) of latitude and longitude, roughly equivalent to 28km north/south and 10-17km east/west in the study area. On a regional scale, the authors reported trends of -4.9 days.decade^{-1} in Foxe Basin, -5.6 in Hudson Strait, and -3.2 in Hudson Bay. Furthermore, the declining trend in breakup date was stronger for 1991-2009 versus 1971-1990 for Foxe Basin (-9.0 vs. -0.9) and Hudson Strait (-13.5 vs. +2.3) but became non-significant for Hudson Bay (Galbraith & Larouche, 2011). On a more local scale, the authors note that the only significant trends in Hudson Bay occurred on the western side, and that the southern coast of the Bay averaged the latest breakup over the time period (Galbraith & Larouche, 2011).

Hochheim and Barber (2014) examined the timing of breakup and freeze-up in our study area between 1980 and 2010 using a passive-microwave based sea ice concentration dataset overlaid on a 25km x 25km pixel grid. The authors defined the open water threshold as the point where 50% of the pixels in an area have ice concentrations below 60% (Hochheim & Barber, 2014). The authors' comparison of the open water seasons of 1996-2010 versus 1980-1995 provided the following results: an average growth of 3.5 weeks for Foxe Basin, with breakup 1.5 weeks earlier and freeze-up 2 weeks later; an average growth of 4.9 weeks for Hudson Strait, with breakup 2.5 weeks earlier and freeze-up 2.4 weeks later; and an average growth of 3.1 weeks for Hudson Bay, with breakup 1.5 weeks earlier and freeze-up 1.6 weeks later (Hochheim & Barber, 2014). The results of Hochheim and Barber (2014) suggest the open water season has been lengthening most quickly in Hudson Strait, in the region at the centre of our study area, and in eastern Hudson Bay.

Kowal, Gough, and Butler (2015) examined sea ice timing in Hudson Bay between 1971 and 2011 using CIS ice chart data for 36 points spaced across the Bay. This research built upon work by Gagnon and Gough (2005) who established the 36 points and examined ice timing for 1971-2003. Kowal et al. (2015) used an ice concentration threshold of 50% to calculate breakup and freeze-up at each point. The authors found that between 1971 and 2011, 23 of 36 points had a significant trend towards earlier breakup and the average trend across all 36 points was -0.49 days.year^{-1}; 34 of 36 points had a significant trend towards later freeze-up and the average trend across all points was 0.46 days.year^{-1}; and 31 of 36 points had a significant trend towards a longer open water season and the average trend across all points was 0.91 days.year^{-1} (Kowal et al., 2015). Breakup trends were least significant in the eastern Bay while freeze-up trends were fairly uniform (Kowal et al., 2015). Finally, the authors results indicate a strengthening in the magnitude and significance of trends for 1971-2011 versus 1971-2003, particularly in the case of freeze-up (Kowal et al., 2015).

The articles discussed above do not provide small-scale analysis of coastal ice conditions and their data are not appropriate for that purpose. Other articles have considered near-shore ice conditions by using sea ice information from finer-resolution data or traditional knowledge (TK).

For example, Laidler et al. (2009) used both of these information sources to examine sea ice changes near Igloolik, a community in northern Foxe Basin. First, the authors used non-gridded data from the CIS ice charts to examine sea ice timing near the community (precise area unspecified): using data for 1982 to 2005 and with "open water" defined using an ice concentration threshold of 5/10, the authors found significant trends of -0.6 days.year^{-1} for breakup, +0.6 days.year^{-1} for freeze-up, and +1.19 days.year^{-1} for the open water season (Laidler et al., 2009). Second, the authors present community members' observations of a considerable constriction of the sea ice season and more volatile ice conditions during fall and spring over recent decades (Laidler et al., 2009). Other articles have presented similar TK-based observations of sea ice change for other communities in the study area, including Cape Dorset (Laidler, Elee, Ikummaq, Joamie, & Aporta, 2010), which lies at the western end of Hudson Strait, and Churchill (Ford et al., 2008).

There are few articles in the scientific literature discussing the phenology or trends in 1) sea ice thickness and 2) landfast ice in our study area. With respect to landfast ice, broader-scale research suggests that the duration of landfast ice is declining in many regions of the Arctic (Galley et al., 2012; Yu et al., 2014). However, in a pan-Arctic study of landfast sea ice based on ice charts from the U.S. National Ice Center, Yu et al. (2014) found no significant trend in winter (Jan-May) landfast ice area nor in the length of the landfast ice season for our study area between 1977 and 2007.

2.3. Shipping in the study area

2.3.1. Shipping regulations

The Canadian government regulates shipping in Hudson Bay and Hudson Strait [and Foxe Basin and James Bay]. Shipping regulations vary between the waters… north of 60°N and the waters south of 60°N. North of 60°N, shipping is regulated by the Arctic Shipping Pollution Prevention Regulations (ASPPR) of the Arctic Waters Pollution Prevention Act (Transport Canada, 2010b). Within the ASPPR is the "Zone/Date System", which regulates the dates during which shipping vessels may operate within one of 16 "Shipping Control Zones" in the Canadian Arctic (Transport Canada, 2010b). The dates of entry and exit for the Shipping Control Zones vary according to vessel type, with longer access windows available to more ice-strengthened vessels (Transport Canada, 2010b). For example, under the Zone/Date System non-ice-strengthened shipping vessels are permitted in the waters of Hudson Bay north of 60°N between July 20 and October 31 [except the north-western Bay, where the dates are July 1 to October 31], and in the waters of Hudson Strait between July 20 and November 5 (Transport Canada, 2010b; Andrews, Babb, McKernan, Horton, & Barber, 2016). The ASPPR were brought into force in 1985 and the regulatory dates of the Zone/Date System were based on the timing of sea ice as understood at that time. These dates appear increasingly out-of-sync with the rapidly changing ice seasons of the Canadian Arctic.

By Transport Canada's own admission, the Zone/Date System "is a fixed system that does not reflect long term trends and inter-annual variability in ice conditions" (Transport Canada, 2010c). As a result, the separate Arctic Ice Regime Shipping System (AIRSS) was developed to enable and regulate shipping in Canadian Arctic waters outside the rigid dates of the Zone/Date System (Transport Canada, 2010c). Under the AIRSS, permission for a vessel to enter a given area is based on a calculation that considers the present ice conditions of the relevant region and the ice capacity of the vessel and its crew (Transport Canada, 2010a; Andrews et al., 2016). Under the AIRSS, non ice-strengthened shipping vessels may travel the waters [of the study area] outside of the windows of the Zone/Date System when conditions permit; however, anecdotal evidence suggests that this rarely happens (Andrews et al., 2016).

Shipping in the waters of Hudson Bay south of 60°N is not regulated by the Arctic Waters Pollution Prevention Act but the region does fall within the Northern Canada Vessel Traffic Service Zone, also known as the NORDREG Zone. The NORDREG Zone encompasses all Canadian waters north of 60°N and all of Hudson Bay, James Bay, and Ungava Bay (Canadian Coast Guard, 2013a). In the NORDREG Zone, vessels with a gross tonnage of over 300 tonnes (e.g., bulk-carriers, fuel tankers, and re-supply vessels) are required to send the Canadian Coast Guard their travel plan prior to entering the Zone, position reports while in the Zone, and a report upon exiting the Zone (Canadian Coast Guard, 2013a).

2.3.2. Shipping traffic

Shipping traffic in the Canadian Arctic is the product of marine re-supply, trade, fishing, tourism, and government and research activity (Engler & Pelot, 2013; Pizzolato, Howell, Derksen, Dawson, & Copland, 2014). Marine re-supply (“sealift”) to communities and resource projects typically contributes the majority of traffic (Arctic Council, 2009; Étienne, Pelot, & Engler, 2013). There is very little shipping in the ice-season in the Canadian Arctic, and thus traffic is confined to the months of the open water and “shoulder” (breakup/freeze-up) seasons (Étienne et al, 2013; Pizzolato et al., 2014; Mussels et al., 2016).

At present there are relatively few publicly available data for traffic volumes in the Canadian Arctic. One source of data is the vessel reports collected by the Canadian Coast Guard (CCG) for the NORDREG Zone... Between 1990 and 2010 vessels travelling through the NORDREG zone were requested to submit position reports to the CCG; since 2010 the submission of position reports has been mandatory for vessels over 300 tonnes (Pizzolato et al., 2014; Andrews et al., 2017). Researchers from the University of Ottawa have undertaken to refine the CCG position reports into a dataset that meets academic standards (see Pizzolato et al., 2014). The CCG/University of Ottawa data indicate that roughly 140 vessels completed between 300 and 350 voyages in the NORDREG Zone each year between 2010 and 2013, up from 100 - 175 voyages per year between 1990 and 2006 (Dawson, Porta, Okuribido-Malcolm, deHann, & Mussels, 2016).

University of Ottawa researchers provided the authors of this paper with the CCG/University of Ottawa shipping traffic data for Hudson Bay, James Bay, Hudson Strait, and Foxe Basin. This particular data has not been released but the methodology is largely explained in Pizzolato et al. (2014) and a product of the dataset has been released to the Polar Data Catalogue (Polar Data Catalogue, n.d.). The CCG/University of Ottawa data for the study area suggest the following [Figure 2-2]: Vessels traffic doubled from roughly 80 voyages per year for 1990-1995 to 160-180 voyages per year between 2010 and 2015. On average between 1990 and 2015, general cargo vessels were responsible for 27% of vessel traffic, bulk carriers were responsible for 23%, and tankers (likely carrying diesel fuel for re-supply) were responsible for 19%. Finally, significant increases in monthly traffic were observed for each month from June to November between 1990 and 2015.

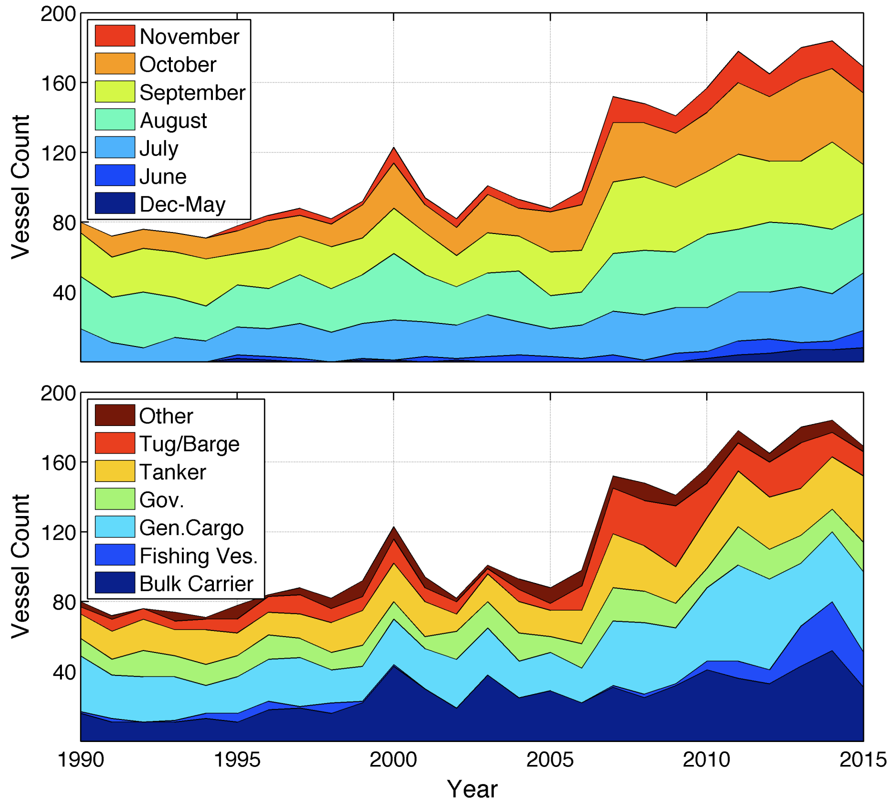

Figure 2-2. Marine traffic in the study area between 1990 and 2015 according to Canadian Coast Guard data processed by researchers at the University of Ottawa (i.e. CCG/University of Ottawa data). Figures show the number of vessels in the study area each year, subdivided according to month (top) or vessel type (bottom).

Vessel traffic is not homogenous within the study area. Traffic data from numerous sources (e.g. Judson, 2010; Étienne et al., 2013; Canadian Coast Guard, 2015; Dawson et al., 2016) and authors' conversations with shipping stakeholders indicate that most shipping traffic accesses and leaves the study area via Hudson Strait. For example, sealift vessels travel from southern Quebec to the study area, make their scheduled stops, and then return to the south. These movement patterns contribute to the concentration of traffic in Hudson Strait, which has the highest traffic volumes in the study area and had average traffic densities nearly twice as high as any other region in the Canadian Arctic between 1991 and 2008 (Judson, 2010). Other relatively busy waters in the study area have historically included the shipping corridor across

Hudson Bay to Churchill and the coastal shipping routes within Hudson Bay, while traffic volumes are typically relatively low in Foxe Basin (Arctic Council, 2009; Judson 2010; Étienne et al, 2013; Oceans North Canada, 2016).

Vessel movement patterns in the study area are necessary context for an analysis of shipping accessibility. Because nearly all traffic accesses the area via Hudson Strait, the shipping accessibility of a particular community or resource project will typically hinge on both the local ice conditions (local accessibility) and the ice conditions from that locality through the study area to the eastern end of Hudson Strait (regional accessibility).

Finally, it is worth mentioning that detailed and timely shipping data for the Canadian Arctic may soon become more readily available. For example, technological and regulatory advancements in vessel monitoring may provide new insights via the Automatic Identification System (AIS) and the Long Range Identification and Tracking (LRIT) of ships (see Canadian Coast Guard, 2013b; Étienne et al., 2013; Eguíluz, Fernández-Gracia, Irigoien, & Duarte, 2016).

2.3.3. Socio-economic impact

Although shipping traffic in the study area is relatively low and is confined to the ice-free and shoulder seasons, shipping nonetheless plays an important socio-economic role in the area. As discussed, most of the communities in the region (29 communities, roughly 27,000 people) can be accessed only by sea or air. As a result, marine re-supply ("sealift") provides these communities with essential supplies that are too heavy or too costly to be flown in, such as fuel, housing materials, construction supplies, vehicles, non-perishable food items, etc…(Inuit Circumpolar Council - Canada, 2008; Arctic Council, 2009; Brooks & Frost, 2012; Andrews et al., 2016). Sealift cargo rates are highly expensive for northern communities (Brooks & Frost, 2012) but they are substantially cheaper than airlift cargo rates. For example, in a report for the

Government of Nunavut, the Mariport Group Ltd (2005) writes that airplane freight rates in the territory can be as much as ten times more expensive than sealift. Any reduction in provisioning costs would likely be very welcome - the expense of the current provisioning system contributes to the high food costs and high cost of living that are extremely problematic for Canada's Arctic communities (Chan et al., 2006; Brooks & Frost, 2012; Government of Canada, 2015).

Shipping enables the two mining projects currently in production in the study area: the Raglan nickel mine that ships from Deception Bay, near Salluit, and the Meadowbank gold mine that ships from Baker Lake (Gavrilchuk & Lesage, 2014; Mussels, Dawson, & Howell, 2017). In addition to sealift and mine support, commercial shipping is important to the fishing, tourism, and research industries in the study area, and government shipping is necessary for security and emergency services (Engler & Pelot, 2013; Mussels et al., 2016). Also, prior to 2016 the Port of Churchill was an important economic contributor to the town of Churchill and provided sealift services for communities on the west coast of Hudson Bay, but the Port was put up for sale in 2015 and shipping operations were stopped in 2016 (further discussed in sections 3.2.2. and 4.2.2. below).

Shipping volumes have been growing in the study area and are projected to continue doing so (Judson, 2010; Étienne et al., 2013). The communities of the study area are experiencing rapid population growth and this will drive growing demand for sealift services (Engler & Pelot, 2013; Statistics Canada, 2016; Andrews et al., 2016). Numerous mining projects currently in the development or construction stages will require shipping through the study area in the coming years in order to progress. These projects include Nunavik Nickel (Ni, Cu, Pd, Pt), the Eldor project (rare earth metals), and Hopes Advance Bay (Fe, Te, V) in Nunavik; Amaruq (Au) and Meliadine (Au) in western Hudson Bay; Roche Bay (Fe) near Hall

Beach in Foxe Basin; and Duncan Lake (Fe) near the east coast of James Bay (Agnico Eagle, n.d.; Gavrilchuk & Lesage, 2014; Natural Resources Canada, 2016). A report from the Government of Canada (2015) suggests that if the sealift and resource potential of the study area were fully developed they could yield a return of well over $10 billion dollars, far exceeding the required investment. It remains to be seen whether the necessary investment will occur, however. Finally, the tourism industry is expected to continue growing, perhaps (but not necessarily) bringing more cruise ship and pleasure craft traffic to the study area (Stewart, Tivy, Howell, Dawson, & Draper, 2010; Kelley & Ljubicic, 2012; Engler & Pelot, 2013; Lassere & Têtu, 2015; Dawson, Johnston, & Stewart, 2017).

2.3.4. Environmental impact

There is relatively little industrial activity in the study area at present and shipping could be the most environmentally-significant activity for the marine environment. Shipping can impact the marine environment in numerous ways. Key mechanisms include: 1) contaminant pollution (e.g. oil spills, bilge release), 2) noise pollution, 3) introduction of invasive species, 4) disturbance of marine mammals, and 5) disruption of sea ice (see Inuit Circumpolar Council - Canada, 2008; Kelley & Ljubicic, 2012; Siders et al., 2016; Zerehi, 2016; Andrews et al., 2016). The potential environmental consequences of shipping in the study area are made considerably more severe by the limited (or non-existent) shipping infrastructure, the difficulties of shipping in ice-infested waters, the relatively low quality charts and navigational aids for the area, and the lack of monitoring, vessel support, and emergency response capacity (Kelley & Ljubicic, 2012; Commissioner of the Environment and Sustainable Development, 2014; Government of Canada, 2015; Andrews et al., 2016). These factors also affect the economic feasibility and human risk of shipping in the study area (Commissioner of the Environment and Sustainable Development, 2014; Government of Canada, 2015).

The environment of the study area is a fundamental component of the culture and well-being of its people. The Inuit people of the area are reliant on marine wildlife for a large proportion of their diet and nutrition (Priest & Usher, 2004; Poppel, Kruse, Duhaim, & Abryutina, 2007; Ford, 2009; Laidler et al., 2010; Wallace, 2014). But this is not simply a case of hunting for food - the marine environment, including sea ice, is an absolutely integral part of the Inuit homeland and identity (Inuit Circumpolar Council- Canada, 2008; Laidler et al., 2010; Aporta, 2010). Also, the coastal waters and estuaries of James Bay and northern Ontario are highly important to the Cree people of that area, supporting game species (especially migratory waterfowl) and enabling traditional activities (Feit, Morrison, & Wilson, 1995; Ohmagari & Berkes, 1997). The marine environment and the people of the study area should not be considered separately, and any major environmental impact in the study area would also be a major social impact.

3. Manuscript 1 - Climate change and sea ice: shipping accessibility on the marine transportation corridor through Hudson Bay and Hudson Strait (1980-2014)

Andrews, J., Babb, D., & Barber, D. G. (2017). Climate change and sea ice: Shipping accessibility on the marine transportation corridor through Hudson Bay and Hudson Strait (1980-2014). *Elem Sci Anth*, 5.

3.1. Abstract

Shipping traffic has been increasing in Hudson Strait and Hudson Bay and the shipping route through these waters to the Port of Churchill may soon become a federally-designated transportation corridor. A dataset on passive-microwave based sea ice concentration was used to characterize the timing of the ice on the shipping corridor to the Port between 1980 and 2014. Efforts were made to produce results in a readily accessible format for stakeholders of the shipping industry; for example, open water was defined using a sea ice concentration threshold of ≤ 15% and results are presented in terms of real dates instead of anomalies. Between 1980 and 2014, the average breakup date on the corridor was July 4, the average freeze-up date was November 25, and the average length of the open water season was 145 days. However, each of these three variables exhibited significant long-term trends and spatial variability over the 34-year time period. Regression analysis revealed significant linear trends towards earlier breakup (-0.66 days year^{-1}), later freeze-up (+0.52 days year^{-1}), and a longer open water season (+1.14 days year^{-1}) along the shipping corridor between 1980 and 2014. Moreover, the section of the corridor passing through Hudson Strait displayed significantly stronger trends than the two sections in Hudson Bay (i.e., “Hudson Islands” and “Hudson Bay”). As a result, sea ice timing in the

Hudson Strait section of the corridor has diverged from the timing in the Hudson Bay sections. For example, the 2010-2014 median length of the open water season was 177 days in Hudson Strait and 153 days in the Hudson Bay sections. Finally, significant linear relationships were observed amongst breakup, freeze-up, and the length of the open water season for all sections of the corridor; correlation analysis suggests that these relationships have greatest impact in Hudson Strait.

3.2. Further background

[Most of the introduction for this manuscript was covered in sections 1 and 2 above. This section (3.2) presents the remaining introductory material.]

3.2.1. The Northern Marine Transportation Corridor Initiative

Anticipating increased shipping in the Canadian Arctic, Transport Canada and the Canadian Coast Guard have proposed the Northern Marine Transportation Corridors initiative. Under this initiative, navigational aids (such as navigation buoys, modern charts and surveys, accurate bathymetric data, emergency support, etc.) would be concentrated along various high-traffic routes, or "corridors", where possible (Dawson et al., 2016; Oceans North Canada, 2016). The present initiative does not call for mandatory use of the corridors once they are in place but rather suggests that the potentially easier and safer travel along the corridors would incentivize their use (Dawson et al., 2016; Oceans North Canada, 2016). While the location of these corridors has not been decided definitively, it appears likely that the shipping route through Hudson Strait and Hudson Bay to the Port of Churchill will be designated a primary corridor, the top designation in the initiative (Dawson et al., 2016; Oceans North Canada, 2016).

3.2.2. The Port of Churchill

The Port of Churchill is an international port located at 58°N on the west coast of Hudson Bay. The Port has four loading berths, including one tanker berth, which are capable of handling vessels as large as the 60,000-80,000 tonne "Panamax" class (Andrews et al., 2016). The Port has been privately owned since 1997. Over the past decade, the Port has typically exported roughly 400,000 to 500,000 tonnes of grain and 10,000 tonnes of re-supply freight per year, though export volumes have varied considerably from year to year (Andrews et al., 2016). Grain is typically shipped to international destinations via the Atlantic while re-supply freight is destined for the Kivalliq region of Nunavut (Andrews et al., 2016). The Port has not regularly handled imports. Between 2009 and 2014 the Port's grain-shipping season typically ran from early August to late October (averaging 11.2 weeks), with the earliest shipment departing on July 28, 2010, and the latest shipment leaving the Port on November 2, 2014 (Andrews et al., 2016). Between 2009 and 2014, an average of 18 grain-shipping vessels visited the Port each year; these grain-shipping vessels are not typically ice strengthened (Andrews et al., 2016). The future of the Port is currently uncertain, as it was put up for sale by its current owners in 2015 and was closed for business in July 2016 (Kives, 2016). At present, negotiations are ongoing between the Port's current owner, the Manitoba Provincial government, the Canadian federal government, and local indigenous leaders, and a variety of scenarios are being considered for continuation of the Port's operations (Kavanagh, 2016; Gilmore, 2016).

Within the context of the changing sea ice patterns and growing shipping traffic in Hudson Bay and Hudson Strait, and of the potential for a designated shipping corridor to the Port of Churchill, this paper presents our efforts to accurately characterize the behavior of sea ice in the Bay and Strait along the corridor to the Port. More specifically, this paper examines the present timing of breakup and freeze-up along the shipping corridor, considers how the timing may have changed between 1980 and 2014, and discusses the factors that may be influencing ice along the corridor.

3.3. Methods

Sea ice concentration data were retrieved from the "Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data" (Cavalieri, Parkinson, Gloersen, & Zwally, 1996 [updated yearly]) dataset hosted by the National Snow and Ice Data Centre (NSIDC). These data are generated using the NASA Team algorithm and are updated yearly; the data have been used in a considerable number of published sea ice analyses (e.g., Stammerjohn, Martinson, Smith, Yuan, & Rind, 2008; Meier, Stroeve, Barrett, & Fetterer, 2012; Parkinson, 2014).

The Cavalieri et al. (1996) data are presented on a stereographic grid with a spatial resolution of 25 km by 25 km. A daily ice concentration value is available for each 25 km by 25 km "pixel" for each day of the year (Cavalieri et al., 1996). For the sake of analysis, it was necessary to geographically define the shipping corridor to the Port of Churchill. Based on the proposed coordinates of the official "Transportation Corridor" to the Port (courtesy of the Canadian Hydrographic Service) and shipping tracks from recent years (as shown by Judson 2010; Andrews et al., 2016; Oceans North Canada, 2016) the shipping corridor was geographically defined from the mouth of Hudson Strait to the Port of Churchill (Figure 3-1). The colored squares in Figure 3-1 indicate the location of the 25 km by 25 km pixels that were included in the analysis. Pixels that contact the shore do not have ice concentration data and so were not included in the corridor, meaning that a band of marine waters extending up to 35 km from the shore (greatest distance within a 25x25km square) was not included in the analysis. A total of 281 pixels were included in the corridor, and the corridor was further subdivided into three sections for the sake of analysis: “Hudson Bay” (148 pixels), “Hudson Islands” (43 pixels), and “Hudson Strait” (90 pixels) as per Figure 3-1.

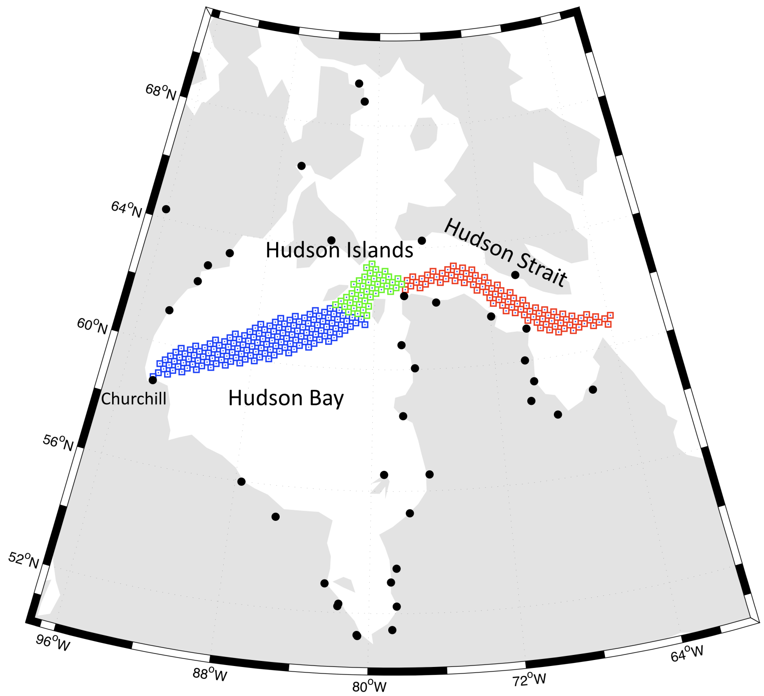

Figure 3-1. Hudson Bay, Hudson Strait, and the shipping corridor to the Port of Churchill. Hudson Bay, Hudson Strait, and Foxe Basin in the eastern Canadian Arctic are shown. The shipping corridor to the Port of Churchill is indicated with colored squares, subdivided into three sections for analysis: “Hudson Bay” (blue), “Hudson Strait” (red), and “Hudson Islands” (green), which is bordered by Nottingham, Southampton, Coats, and Mansel islands. Both the Hudson Bay and Hudson Islands sections fall within the traditional boundaries of Hudson Bay. Black dots indicate the location of communities in the area.

The purpose of this analysis was to examine sea ice concentrations in the context of shipping. Therefore breakup and freeze-up were defined using a 15% concentration threshold. The majority of shipping at the Port of Churchill is conducted using non-ice strengthened vessels (Andrews et al., 2016), and it was decided that sea ice concentrations of 15% or below represented an accurate assessment of “open water” for these vessels. The Arctic Ice Regime

Shipping System (AIRSS) defines ice concentrations below 10% as open water, while concentrations of 10-30% are considered “very open drift” (Transport Canada, 2010a). Ice concentrations of ≤ 15% have been used as shipping-enabling thresholds elsewhere in the literature. For example, Bensassi, Stroeve, Martínez-Zarzoso, and Barrett (2016) used a 15% concentration threshold to track the “navigable” periods of the Northern Sea Route. Parkinson (2014) and Stammerjohn et al. (2008) also used 15% sea ice concentration as the open water threshold in their analyses. Note that ≤ 15% is a lower concentration threshold than those used by Kowal et al. (2015) or Hochheim and Barber (2014) to define breakup and freeze-up.

Although passive microwave imagery provide the most consistent, long-term data for sea ice concentration in the Arctic (Comiso, Parkinson, Gersten, and Stock, 2008), there are some limitations to the Cavalieri et al. (1996) dataset that may be relevant to this study. First, passive-microwave based ice concentration data are subject to uncertainty. Cavalieri et al. (1996) estimate that the dataset’s sea ice concentration is within 5% of the actual sea ice concentration in winter and 15% in the summer, with uncertainty rising in thinner ice packs or where melt-ponds are present. Based on a comparison of ice charts from the Canadian Ice Service with the Cavalieri et al. (1996) dataset, Agnew and Howell (2003) estimated that the passive microwave results underestimated sea ice concentration in marginal ice zones by 7 to 45% during fall freeze-up and 20 to 35% during summer melt. However, Agnew and Howell (2003) made their comparison using sea ice concentrations above 20% and Stammerjohn et al. (2008) contend that passive microwave methods are considerably more accurate at estimating sea ice concentrations of 15% or below (such as used in this study) due to the contrast in emissivity between open water and sea ice. Moreover, the Cavalieri et al. (1996) dataset has been improved continuously since the Agnew and Howell study in 2003, and both Stammerjohn et al. (2008) and Strong (2012) successfully used the data to identify the ice edge and marginal ice zone, respectively. Finally, the results for the Hudson Bay area produced using NSIDC passive-microwave based datasets tend to be in good agreement with results produced using sea ice concentration datasets from other sources (e.g. Hochheim and Barber 2010).

Second, it has been suggested that the Cavalieri et al. (1996) data produce inaccurate ice concentration estimates for near-shore pixels (termed land-to-ocean spillover). The NASA Team algorithm has been adjusted to minimize this error (Cavalieri et al. 1996), and the results from this research show no evidence of systematic deviation between near-shore and offshore pixels.

3.3.1. Breakup, freeze-up and open water season determination

For the sake of analysis, breakup was defined as the first of at least three consecutive days with ice concentrations less than or equal to 15% while freeze-up was defined as the first of at least three consecutive days with ice concentrations greater than 15%. The 3-day window ensured that transient ice motion and short-term variations in ice concentration did not affect our analysis. The open water season was defined as the days between breakup and freeze-up. The breakup date, freeze-up date, and the length of the open water season were determined for every pixel for each year from 1980 to 2014. Breakup and freeze-up dates were kept in day of year (doy) format throughout the analysis but were converted to calendar dates in the displayed results where appropriate.

Sea ice timing on the corridor was examined by analyzing pixels individually and as a group. First, linear regression was used to examine the trends in breakup, freeze-up, and the length of the open water season for each pixel of the corridor between 1980 and 2014. Second, analysis was conducted for the corridor and each corridor section using 1980-2014 datasets comprised of the annual median value of the pixels in each grouping. Statistical analysis revealed that each dataset follows a normal distribution and that no dataset exhibits significant autocorrelation. Multiple types of regression analyses were applied to the datasets, and linear regression yielded the best fits and the most statistically rigorous results in all cases. Finally, spectral analysis was used to test all datasets for underlying patterns or cycles but none was found.

Although Hochheim and Barber (2014) chose to generate and use anomaly data for their analysis in an effort to minimize bias, an anomaly method was not used in this analysis and absolute concentrations were used instead. The use of absolute concentrations allows the precise identification of breakup and freeze-up dates for each year, and it was decided that results with tangible calendar dates would be more applicable in this shipping-related context.

3.3.2. Following-year Difference

In this paper, the term "following-year difference" will be used to refer to the difference in breakup date, freeze-up date, or the length of the open water season between one year and the subsequent year. Following-year difference was analyzed in order to examine the year-to-year variation in ice timing on the corridor; the standard deviations in the 1980-2014 time series were also used to comment on year-to-year variability. Two methods were used to examine following-year difference. First, the following-year difference in each variable was calculated for every pixel from 1981 to 2014; these data were used to consider variations in following-year difference within the corridor… Second, the following-year difference in each of the twelve 1980-2014 time series was calculated, producing 1981-2014 time series for following-year difference. These time series were analyzed using linear regression.

3.4. Results

3.4.1. Sea ice on the shipping corridor: current timing and 1980-2014 trends

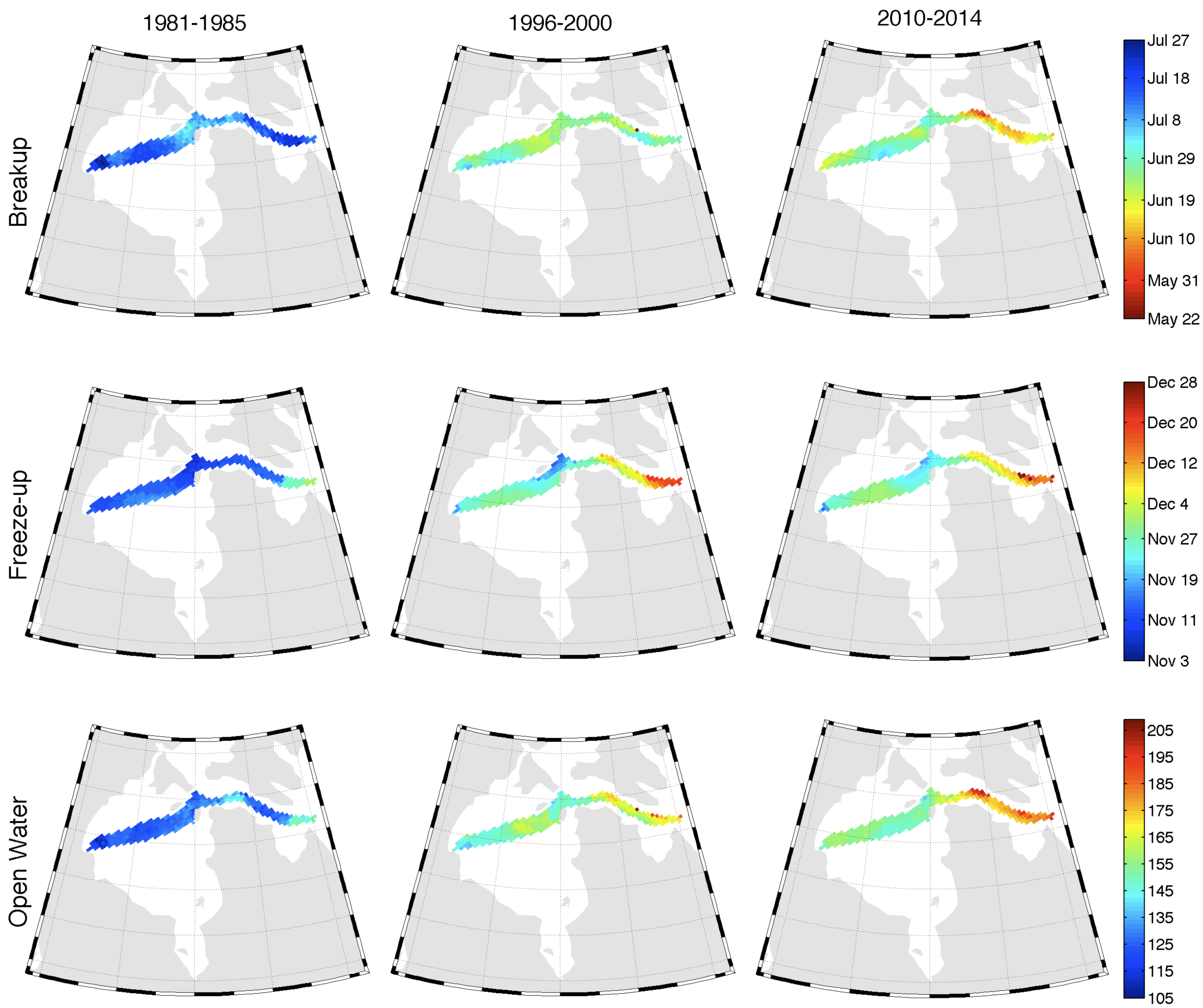

Figure 3-2. Sea ice timing along the shipping corridor to the Port of Churchill.
The timing of breakup, freeze-up, and the open water season are compared for the periods 1981-1985, 1996-2000, and 2010-2014. Maps were generated by calculating the five-year median value for each pixel in the corridor and then assigning a color to that pixel's location on the map. The 5-year window was used to capture inter-annual variation.

Figure 3-2 [above] displays the timing of breakup, freeze-up, and the open water season along the shipping corridor for 1981-1985, 1996-2000, and 2010-2014. The median values for 2010-2014 provide the best insight from this dataset into the current timing of sea ice on the corridor. Breakup on the corridor now typically takes place between June 1 and July 6 (median = June 26), freeze-up typically takes place between November 18 and December 27 (median = November 26), and the length of the open water season varies between 146 and 200 days (median = 156). Figure 3-2 also clearly displays the change in ice timing on the corridor in recent decades and the considerable spatial variability in ice timing within the corridor. These two points are addressed in sequence below.

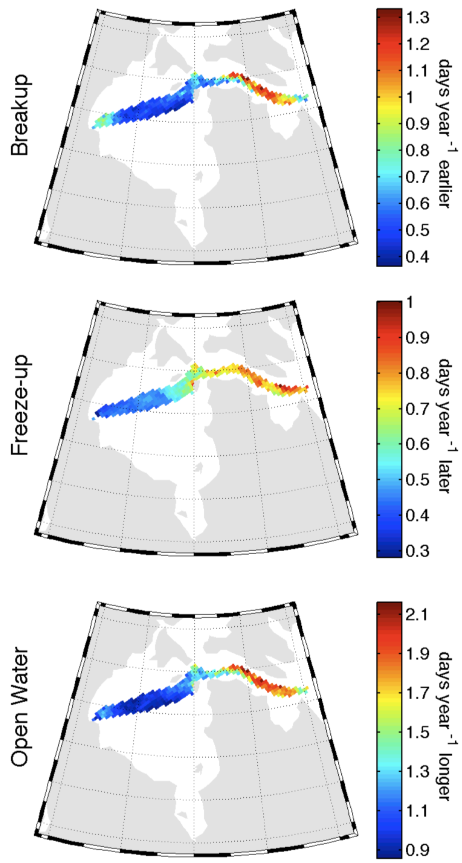

Figure 3-3. 1980-2014 trends in breakup, freeze-up, and open water for the pixels of the corridor. The 1980-2014 trends in breakup date, freeze-up date, and open water season length are shown for the pixels of the shipping corridor. Trend values are the slope of the linear regression line for each pixel and only significant trends (p-value < 0.05) are shown.

Figure 3-3 [above] displays the significant trends calculated for all three variables for every pixel of the shipping corridor. The magnitude of these trends ranged from -0.35 to -1.35 days year^{-1} for breakup (median = -0.60), from 0.15 to 1.10 days year^{-1} for freeze-up (median = 0.58), and from 0.85 to 2.20 days year^{-1} for open water season (median = 1.16). All pixels exhibited significant trends for each variable except for two of the pixels nearest to Churchill that did not exhibit significant trends for freeze-up.

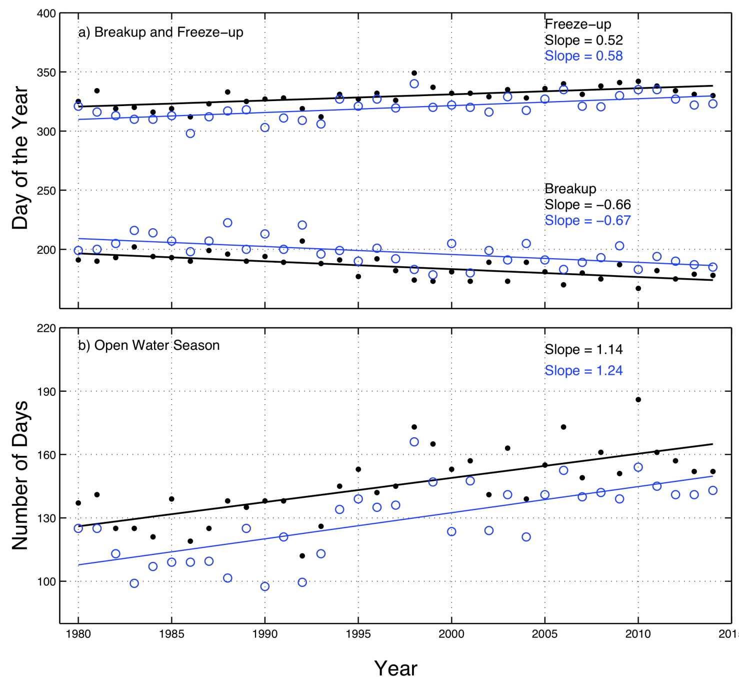

Figure 3-4. 1980-2014 breakup, freeze-up, and open water season for the shipping corridor. These time series show breakup, freeze-up, and the length of the open water season on the shipping corridor to the Port of Churchill between 1980 and 2014. The annual median values for the 281 pixels on the shipping corridor are indicated by solid black circles; the annual median values for the 10% of pixels with the most restrictive ice timing in each year are indicated by open blue circles. Plotted lines are linear regressions; the slopes of all regression lines are significant at the 99% confidence level ($p < 0.01$). Goodness-of-fit tests indicate that the residuals of each regression line are normally distributed. Slope units are days year^{-1}.

The 1980-2014 time series based on the annual median values of the corridor pixels provide further insight into the changes in ice timing on the corridor (Figure 3-4 [above]): between 1980 and 2014, median breakup date varied between June 16 and July 26 with a mean date of July 4 (doy 185 ± 9.64), median freeze-up date varied between November 8 and December 15 with a mean date of November 25 (doy 329 ± 8.5), and the median length of the open water season varied between 112 and 186 days with a mean length of 145 days (± 16.69). Linear regression suggests that between 1980 and 2014 breakup became earlier at a rate of 0.66 days per year, freeze-up became later at a rate of 0.52 days per year, and the open water season lengthened at a rate of 1.14 days per year with all three trends significant at the 99% confidence level. Finally, Figure 3-4 also shows that the median ice timing of the 10% of pixels with the most restrictive ice timing in each year (latest breakup, earliest freeze-up, and shortest open water season) followed very similar trends to the corridor as a whole, with trends of -0.67, 0.58, and 1.24 days year^{-1} for breakup, freeze-up, and the open water season, respectively.

3.4.2. Spatial variability in ice timing within the corridor

As indicated by the 2010-2014 median values displayed in Figure 3-2, the section of the shipping corridor passing through Hudson Strait typically exhibits an earlier breakup (June 17), a later freeze-up (December 8), and a longer open water season (177 days) than the rest of the corridor (Table 3-1). The Hudson Islands and Hudson Bay appear to share similar ice timing, with median breakup only one day apart (June 29 vs. June 30), median freeze-up 5 days apart (November 29 vs. November 24), and an equal median open water season length (153 days). A comparison of the 2010-2014 sea ice timing on the three sections of the corridor is presented in Table 3-1.

Table 3-1. Median values for the 2010-2014 timing of sea ice on the shipping corridor by section.

Corridor section	Breakup date		Freeze-up date		Days of open water season	
	Across all pixels (range)	Of regression line [a] values	Across all pixels (range)	Of regression line [a] values	Across all pixels (range)	Of regression line[a] values
Hudson Bay	June 29 (June 16-July 6)	June 29	Nov. 29 (Nov. 18-Dec. 3)	Dec. 1	153 (146-159)	156
Hudson Islands	June 30 (June 23-July 6)	June 22	Nov. 24 (Nov. 18-Dec. 3)	Nov. 29	153 (146-173)	161
Hudson Strait	June 17 (June 1-June 22)	June 17	Dec. 8 (Nov. 26-Dec. 27)	Dec. 14	177 (160-200)	184

[a] Regression lines displayed in Figures 5 and 6.

The 1980-2014 time series for the three different sections of the shipping corridor (Figures 3-5 and 3-6 [below]) also display some interesting variations in ice timing within the corridor. For example, both the Hudson Islands and Hudson Strait exhibited relatively low values for open water season length in 1990 but the length of the open water season in Hudson Bay was greater than average that year. Also, both the Hudson Islands and Hudson Strait exhibited their maximum values for open water season length in 2010 (195 and 214 days respectively) driven by late freeze-up, but the length of the open water season and freeze-up date in Hudson Bay that year were only slightly greater than average. On the other hand, the datasets for open water season length for all three sections exhibited local maxima in 1998. These examples suggest that the factors influencing ice timing may be different, or differently weighted, both between regions and between years.

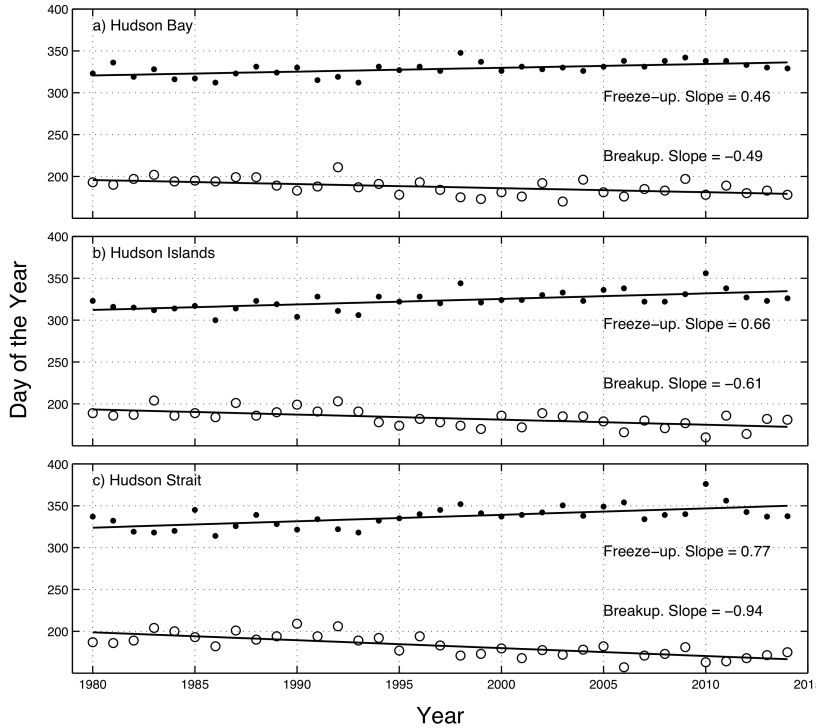

Figure 3-5. 1980-2014 breakup and freeze-up timing for the three sections of the shipping corridor. This time series shows breakup (open circles) and freeze-up (solid circles) on the Hudson Bay, Hudson Islands, and Hudson Strait sections of the corridor between 1980 and 2014, where data points indicate the annual median values of all pixels in a corridor section. The slope of each regression line is significant at the 99% confidence level. Slope units are days year^{-1}. Characteristics of the datasets and regression lines are displayed in Table 3-2.

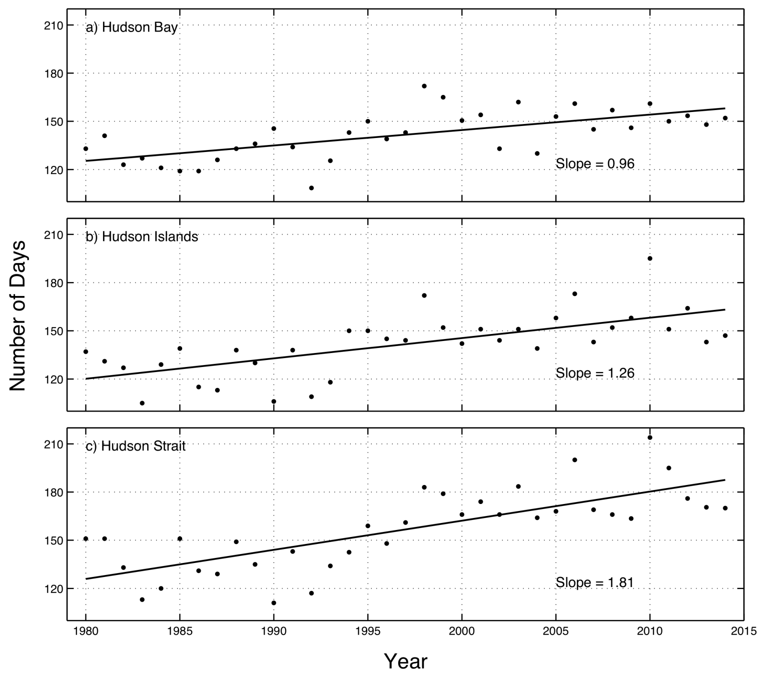

Figure 3-6. 1980-2014 open water season length for the three sections of the shipping corridor. This time series shows the length of the open water season on the Hudson Bay, Hudson Islands, and Hudson Strait sections of the corridor between 1980 and 2014, where data points indicate the annual median values of all pixels in a corridor section. The slope of each regression line is significant at the 99% confidence level. Slope units are days year^{-1}. Characteristics of the datasets and regression lines are displayed in Table 3-2.

Table 3-2. Characteristics of the 1980-2014 datasets and their regression lines for the three sections of the corridor.

Characteristic	Breakup (HB, HI, HS)[b]	Freeze-up (HB, HI, HS)[b]	Open water season (HB, HI, HS)[b]
Mean day of year (date) ± standard deviation	187 (July 6) ± 9.32, 183 (July 2) ± 10.39, 183 (July 2) ± 13.00,	328 (Nov. 24) ± 8.39, 323 (Nov. 19) ± 11.18, 337 (Dec. 3) ± 12.80,	142 ± 15.13 days, 142 ± 19.49 days, 157 ± 24.71 days,
Median following-year difference (days $year^{-1}$)	±8, ±9, ±8.75	±5.5, ±7.5, ±7.75	±10.25, ±12.5, ±16.75
Regression line slope (days $year^{-1}$)	-0.49, -0.61, -0.94[c]	0.46, 0.66, 0.77[c]	0.96, 1.26, 1.81[c]
Regression line p-value	<0.001, <0.001, <0.001	<0.001, <0.001, <0.001	<0.001, <0.001, <0.001
Regression line Pearson correlation coefficient (R)	-0.53, -0.60, -0.74	0.56, 0.60, 0.61	0.65, 0.67, 0.75
HB vs. HS regression slopes (days $year^{-1}$) and significance result [p-value] [d]	-0.49 vs. -0.94** [0.0244]	0.46 vs. 0.77* [0.140]	0.96 vs. 1.81** [0.014]
HB vs. HI regression slopes (days $year^{-1}$) and significance result [p-value] [d]	--0.49 vs. -0.61 [0.530]	0.46 vs. 0.66 [0.302]	0.96 vs. 1.26 [0.340]
HI vs. HS regression slopes (days $year^{-1}$) and significance result [p-value] [d]	-0.61 vs. -0.94* [0.104]	0.66 vs. 0.77 [0.630]	1.26 vs. 1.81* [0.144]

[a] Datasets and regression lines displayed in Figures 5 and 6.
[b] HB is Hudson Bay, HI is Hudson Islands, and HS is Hudson Strait.
[c] The slope of each regression line is significant at the 99% confidence level ($p < 0.01$) at least. The residuals of each regression line are normally distributed and do not exhibit significant autocorrelation.
[d] One asterisk (*) indicates slopes are significantly different at the 85% confidence level ($p < 0.15$); two asterisks (**) indicate slopes are significantly different at the 95% confidence level ($p < 0.05$).

Figure 3-3 displays the considerable spatial variation in the sea ice trends within the shipping corridor and indicates that ice timing may be changing at a greater rate in Hudson Strait than in the other sections of the corridor. This difference is supported by the results from the linear regression of the 1980 to 2014 time series for the three different sections (Table 3-2): Hudson Strait exhibited significantly stronger trends than both Hudson Bay and the Hudson Islands for breakup and the length of the open water season, and significantly stronger trends than Hudson Bay for freeze-up (Figures 3-5 and 3-6). However, it should be mentioned that in all cases there was greater confidence in the difference in trends between Hudson Strait and Hudson Bay than the difference between Hudson Strait and the Hudson Islands ($p < 0.05$ vs. $p < 0.15$, respectively). The slopes of the regression lines for Hudson Bay and the Hudson Islands were not significantly different for any of the three variables.

3.4.3. Following-year Difference

The median values for following-year difference in the 1980-2014 time series for breakup, freeze-up, and open water season are shown in Table 3-2 [above]. Between 1981 and 2014, median following-year difference was lowest for freeze-up (± 5.5-7.75 days per year), followed by breakup (± 8-9 days per year), and highest for the length of the open water season (± 10.25-16.75 days per year). These values suggest that year-to-year variation is highest in open water season length, followed by breakup and then by freeze-up. This pattern is supported by the standard deviation of the 1980-2014 time series for the corridor as a whole: ± 16.69 for open water season, ± 9.64 for breakup, and ± 8.50 for freeze-up. Also, in most cases median following-year difference was lowest in Hudson Bay, followed by the Hudson Islands, and then by Hudson Strait. Standard deviation in the 1980-2014 datasets followed the same order in all three variables: lowest for Hudson Bay, followed by the Hudson Islands, and then by Hudson Strait (Table 3-2).

Figure 3-7 shows the median following-year difference within the shipping corridor for 2005-2014, the most recent ten years of data in the dataset used for this analysis. Figure 7 suggests that the magnitude of year-to-year variation in breakup, freeze-up, and open water season is quite variable within the corridor: The 2005-2014 median following-year difference in breakup date varied between 2 and 24 days $year^{-1}$ on the corridor and values were highest near Churchill and in the central part of the corridor (eastern Hudson Bay, Hudson Islands, and western HS). Following-year difference in freeze-up date varied between 2.5 and 14.5 days year^{-1} and values were highest in the Hudson Islands and eastern Hudson Strait and relatively low in Hudson Bay. Finally, the following-year difference in the length of the open water season varied between 4.5 and 37.5 days year^{-1} and the greatest values were also in the central part of the corridor.

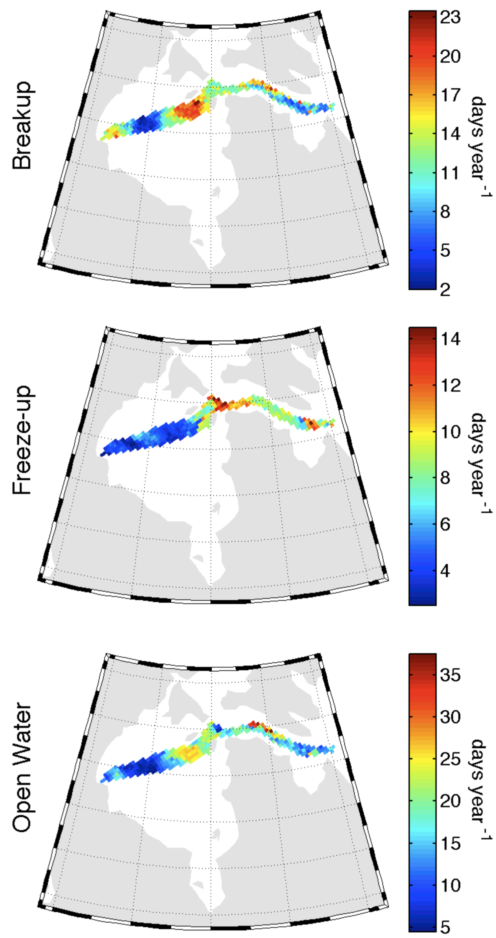

Figure 3-7. 2005-2014 Following-year Difference along the shipping corridor.
Median following-year difference in breakup, freeze-up, and the length of the open water season is shown for 2005-2014. Maps were generated by calculating the ten-year median value for each pixel in the corridor and then assigning a color to that pixel's location on the map.

No long-term trend or variability was observed in the twelve 1981-2014 datasets for following-year difference. Furthermore, analysis on the pixel level revealed few long-term trends between 1981 and 2014: the central corridor exhibited some significant trends in breakup (+0.38 to 0.55 days year^{-1}) and significant trends in freeze-up were exhibited throughout the western third of the corridor (-0.38 to -0.12 days year^{-1}) but little else.

3.4.4. Relationships amongst breakup, freeze-up, and the length of the open water season

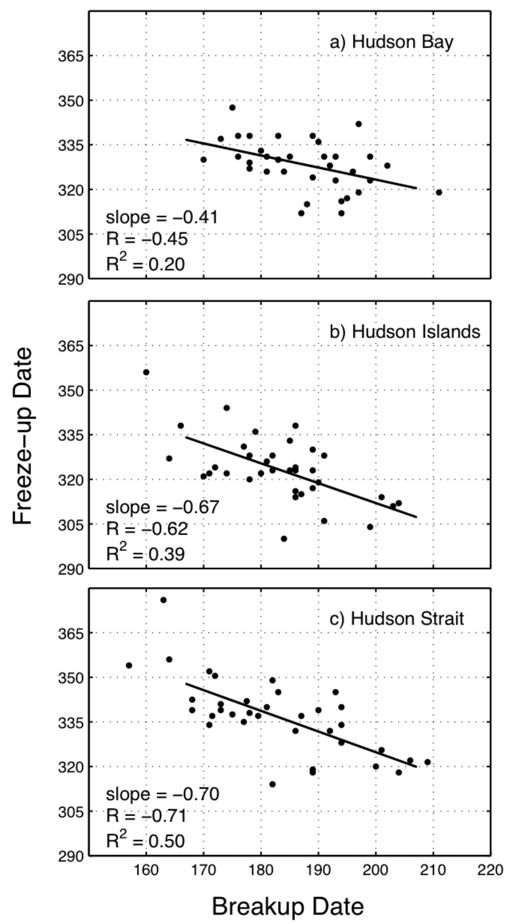

Figure 3-8. Freeze-up date as a function of breakup date for the three sections of the corridor. Median freeze-up date is shown as a function of median breakup date for 1980-2014. The slope of each regression line is significant at the 99% confidence level ($p < 0.01$). Slope units are days day^{-1}. Characteristics of the datasets and regression lines are displayed in Table 3-3.

Table 3-3. Characteristics of relationships among breakup, freeze-up, and open water season length.

Characteristic	**Freeze-up (Y) as a function of breakup (X)** (HB, HI, HS)[a]	**Break-up (Y) as a function of freeze-up the previous year (X)** (HB, HI, HS)[a]	**Breakup (Y) as a function of open water season length the previous year (X)** (HB, HI, HS)[a]
Regression line slope (days-Y per day-X)	-0.41, -0.67, -0.70	-0.55, -0.42, -0.74	-0.23, -0.24, -0.39
Regression line p-value[b]	<0.01, <0.01, <0.001	<0.01, <0.01, <0.001	<0.05, <0.01, <0.001
Regression line R^2 value	0.20, 0.39, 0.50	0.24, 0.20, 0.54	0.14, 0.21, 0.55
Regression line Pearson correlation coefficient (R)	-0.45, -0.62, -0.71	-0.49, -0.45, -0.73	-0.38, -0.45, -0.74
HB vs. HS regression slopes (days day^{-1}) and significance result [p-value] [c]	-0.41 vs. -0.70* [0.134]	-0.55 vs. -0.74 [0.354]	-0.23 vs. -0.39 [0.187]
HB vs. HI regression slopes (days day^{-1}) and significance result [p-value] [c]	-0.41 vs. -0.67 [0.204]	-0.55 vs. -0.42 [0.577]	-0.23 vs. -0.39 [0.964]
HI vs. HS regression slopes (days day^{-1}) and significance result [p-value] [c]	-0.67 vs. -0.70 [0.886]	-0.42 vs. -0.74* [0.089]	-0.24 vs. -0.39* [0.148]

[a] HB is Hudson Bay, HI is Hudson Islands, and HS is Hudson Strait.
[b] The slope of each regression line is significant at the 95% confidence level ($p < 0.05$) at least. The residuals of each regression line are normally distributed and do not exhibit significant autocorrelation.
[c] An asterisk (*) indicates slopes are significantly different at the 85% confidence level ($p < 0.15$).

The relationships amongst breakup, freeze-up, and the open water season were examined by applying correlation analysis to three relationships: first, the relationship between breakup and freeze-up in the same year; second, the relationship between freeze-up and breakup the following year; third, the relationship between the length of the open water season and breakup the following year (Table 3-3). Linear regression yielded significant slopes ($p < 0.05$) in all three relationships for each corridor section. The relationship analysis indicates that breakup one day earlier corresponds to freeze-up 0.41-0.70 days later (Figure 3-8), that freeze-up one day later corresponds to breakup 0.42-0.74 days earlier the next year (Figure 3-9), and that a one day longer open water season corresponds to breakup 0.23-0.39 days earlier the next year (Table 3-

3). Interestingly, the strengths of the correlations varied markedly amongst the different sections of the corridor. For all three relationships the correlation between the independent and dependent variables (examined using Pearson Correlation Coefficient, R) and the proportion of variance accounted for by the independent variable (coefficient of determination, R^2) were greater for Hudson Strait (R = -0.71 to -0.74; R^2 = 0.50 to 0.55) than for the Hudson Islands (R = -0.45 to -0.62; R^2 = 0.20 to 0.39) and Hudson Bay (R = -0.38 to -0.49; R^2 = 0.14 to 0.24).

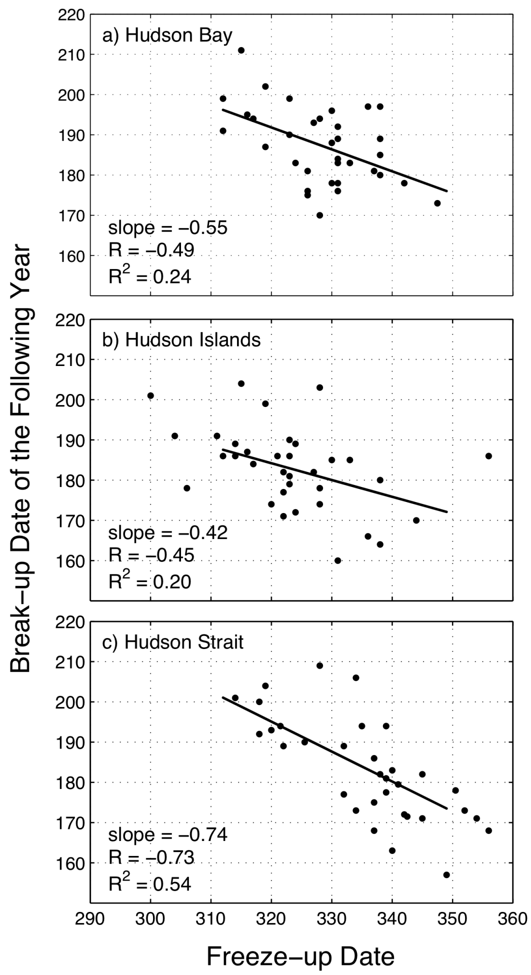

Figure 3-9. Break-up as a function of freeze-up the year before (1981-2014).
The relationship between median freeze-up date (x-axis) and median breakup date of the following year (y-axis) is shown for 1981 to 2014. The slope of each regression line is significant at the 99% confidence level ($p < 0.01$). Slope units are days day^{-1}. Characteristics of the datasets and regression lines are displayed in Table 3-3.

3.5. Discussion

The regulated dates for the shipping corridor through Hudson Bay and Hudson Strait to the Port of Churchill do not appear to be in good agreement with the current timing of sea ice on the corridor. The Zone/Date System of the Arctic Waters Pollution Prevention Act restricts non ice-strengthened shipping vessels to July 20-October 31 in Hudson Bay and the Hudson Islands and to July 20-November 5 in Hudson Strait (Transport Canada, 2010c), though vessels can travel outside these dates using the Arctic Ice Regime Shipping System (Transport Canada, 2010a). Marine insurers, meanwhile, often raise the price of insurance for shipping vessels travelling to the Port of Churchill outside the dates of an August 15 to October 15 window (Andrews et al., 2016). According to our analysis, the annual median ice timing of the most ice-restricted 10% of the corridor exhibited an average breakup date of July 16 and an average freeze-up date of November 15 between 1980 and 2014 (Figure 3-4), and both of these values fall outside the regulation dates. Moreover, the recent timing of sea ice on the corridor appears to be even farther from the regulatory dates: 2010-2014 median breakup dates for the pixels in the corridor ranged from June 1 to July 6 and median freeze-up dates ranged from November 18 to December 27 (Table 3-1). Between 2010 and 2014, Hudson Bay and the Hudson Islands were typically ice-free between late June and late November, while Hudson Strait was typically ice-free between June 17 and December 8. However, when applying our results to examine marine accessibility it is important to remember that a band of marine waters extending up to 35 km from the shore was not captured in our analysis.

The trends in ice timing in Hudson Bay presented in this paper are in close agreement with those presented by Kowal et al. (2015), and the similarity in the results provides some validation of the sea ice concentration estimates in the passive-microwave based dataset used in this analysis. Our findings suggest that between 1980 and 2014 the median breakup date for Hudson Bay became earlier at a rate of 0.49 days year^{-1}, the median freeze-up date became later at a rate of 0.46 days year^{-1}, and the open water season lengthened at a rate of 0.96 days year^{-1} (Table 3-2). Based on an analysis of data from the CIS ice charts for 1970 to 2011, Kowal et al. (2015) reported average trends of 0.49 days year^{-1} towards earlier breakup, 0.46 days year^{-1} towards later freeze-up, and 0.91 days year^{-1} towards a longer ice-free period. The striking similarity in the results produced by the two different data sources (passive microwave vs. CIS ice charts) suggests that the Cavalieri et al. (1996) passive-microwave based dataset used in this analysis is producing reliable information about the changes in sea ice timing in the Hudson Bay area.

The results from this analysis and the results presented by Hochheim and Barber (2014) both suggest that the timing of ice within the different regions of the shipping corridor is diverging. Both analyses indicate that Hudson Strait is exhibiting significantly stronger trends towards earlier breakup, later freeze-up, and a longer open water season. During the 1981 to 1985 period the overall median breakup date in Hudson Strait was later than or the same as the Hudson Islands and Hudson Bay (July 15 vs. July 7 and July 15), and although median freeze-up was later in the Strait than in the other sections (Nov. 16 vs. Nov. 11 and 15), the median length of the open water season was only slightly longer (132 days vs. 129 and 125). The Strait experienced significantly stronger trends in ice timing than the other two sections over the years between 1980 and 2014 and this shows in the 2010-2014 median values: median breakup date in Hudson Strait was considerably earlier than the other sections (June 17 vs. June 30 and 29), median freeze-up date was considerably later, and the median open water season was over 20 days longer (177 days vs. 153 days). The timing of ice on the corridor was once fairly uniform but the Hudson Strait section is now behaving very differently than the other two regions. Moreover, the timing of ice in Hudson Strait will continue to diverge from the timing of ice in the Hudson Islands and Hudson Bay if current trends persist. The physical mechanisms driving this difference are currently being investigated, with a particular focus on the intrusion of Atlantic layer waters into the Strait and the possible effects of freshwater export.

Spectral analysis did not reveal significant periodicity or cyclical behavior in any of the 1980-2014 time series, which was somewhat unexpected. The timing of sea ice in Hudson Bay and Hudson Strait is thought to be determined largely by surface air temperatures and wind forcing (Tivy et al., 2011; Hochheim & Barber, 2014; Kowal et al., 2015). Several studies have hypothesized that the timing of ice in the Bay and Strait could be closely linked to cyclical variations in ice forcing caused by atmospheric or oceanic oscillations such as the North Atlantic Oscillation, El Niño, and the Atlantic Multidecadal Oscillation (Tivy et al., 2011). However, no conclusive indication of cyclical behavior in ice timing that could have been caused by these oscillations was observed in this analysis. It is possible that the methods used to generate the time series were not appropriate for examining cyclical behavior. It is also possible that the 1980 to 2014 time frame was too short to yield a statistically significant indication of cyclical behavior.

Our analysis suggests that year-to-year variation in ice timing on the corridor, examined via following-year difference and standard deviation, is typically greater for breakup than for freeze-up and is greatest in Hudson Strait, followed by the Hudson Islands, and then by Hudson Bay. The results of Gagnon and Gough (2005) agree with the first part of this conclusion, as the authors reported standard deviations of 10.5 to 22.7 days for breakup in Hudson Bay, 7.5 to 10.5 days for freeze-up, and concluded that differences between years are generally larger for breakup. However, Stroeve et al. (2014) reported a tendency for greater year-to-year variation in freeze-up than for breakup in the Arctic as a whole between 1979 and 2013. Assuming our conclusions are correct, it is not clear why the ice along the corridor may exhibit opposing behavior to the tendency of the Arctic as a whole. Nevertheless, the apparent contradiction does not reduce the potential usefulness of our analysis of year-to-year variation for stakeholders of the shipping industry: though the results in Figure 3-7 and Table 3-2 do not provide a predictive tool, they do provide a quantitative assessment of the typical variation within breakup, freeze-up, and the length of the open water season along the corridor.

The significant relationships amongst breakup, freeze-up, and the length of the open water season (Table 3-3) are not surprising, but the varying strengths of the coefficient of determination (R^2) in these relationships suggest the timing of ice is influenced in different ways on different sections of the corridor. It is theoretically appropriate that earlier breakup and longer open water seasons could result in increased warming of surface waters and delayed freeze-up (Gough & Houser, 2005); in fact, this effect has been demonstrated experimentally (e.g., Stroeve et al., 2014). Similarly, it is also to be expected that later freeze-up could leave less time for ice to form during the cold-weather season, resulting in a weaker ice pack that could break up more quickly (Stroeve et al., 2012). Gough and Houser (2005) describe these phenomena as a climate "memory", whereby the timing of ice at one point in the sea ice cycle influences the quantity of heat stored in the surface (mixed) layer, which affects ice timing at ensuing points in the cycle. Interestingly, the results of correlation analysis suggest that this climate memory may be relatively more important in Hudson Strait than in the Hudson Islands and Hudson Bay: in Hudson Bay and the Hudson Islands the significant relationships amongst breakup, freeze-up, and the length of the open water season all produced R^2 values below 0.40 with most below 0.25, while the same analysis yielded R^2 values of 0.50 to 0.55 for Hudson Strait. The meaningfulness of this difference in R^2 values may be best illustrated by an example: variation in the breakup date in Hudson Bay appears to account for only 20% of the variation in freeze-up date in the Bay, while variation in breakup date in Hudson Strait appears to account for 50% of the variation in freeze-up date in the Strait. These results are in partial agreement with Houser and Gough (2003), who concluded that variations in sea ice timing in Hudson Strait were largely (rather than just 50-55%) driven by the legacy of ice timing the year before.

Although the values of the coefficient of determination (R^2) for the relationships between breakup, freeze-up, and the open water season suggest that no single relationship is responsible for more than 55% of the variation in any single variable, the relationships may nonetheless provide some usefulness as predictive tools. This usefulness is because some of the relationships do show high correlation. In other words, though causation remains somewhat unclear, correlation is strong in some cases, particularly in Hudson Strait, where all three relationships yielded correlation coefficients with magnitudes greater than 0.70. These relatively strong correlation values may not enable quantitative prediction but they do enable qualitative prediction that could be useful to stakeholders in the shipping industry. For example, breakup and freeze-up in Hudson Strait have a correlation coefficient of $R = 0.71$; thus once the Hudson Strait breakup date for a given year is known, the significant regression line ($p < 0.001$) for the relationship can provide some insight into the likely timing of freeze-up in the Strait that year. A similar method was used with moderate success by Gough and Houser (2005) to predict the timing of sea ice in Hudson Strait for 2000 to 2003.

3.6. Conclusions

Shipping traffic is rising in the Canadian Arctic as climate change leads to longer periods of open water in the north. Hudson Strait and Hudson Bay are amongst the busiest water bodies in the Canadian Arctic, and the shipping corridor through the Strait and Bay to the Port of Churchill is being considered for designation as a Northern Marine Transportation Corridor. The primary objective of this research was to characterize the timing of sea ice along the shipping corridor in a format that would be applicable to stakeholders in the shipping industry.

This analysis indicates that the shipping corridor to the Port can now be divided into two sections, each with considerably different ice timing, and that this timing will continue to diverge. The "Hudson Islands" and "Hudson Bay" sections of the shipping corridor defined for this analysis, which both fall within the traditional geographic definition of Hudson Bay, exhibited similar ice timing for 2010-2014: median breakup dates of June 30 and 29, median freeze-up dates of November 29 and 24, and median open water season lengths of 153 days. The "Hudson Strait" section of the corridor, meanwhile, had quite different sea ice timing during the 2010-2014 period: median breakup of June 17, median freeze-up of December 8, and a median open water season length of 177 days. The timing of ice on the corridor was much more homogenous at the beginning of the dataset (1981-1985), but in recent decades Hudson Strait has exhibited significantly stronger trends in breakup date, freeze-up date, and open water season length than the other sections of the corridor. If these trends persist into the future the timing of ice for the different sections of the corridor will continue to diverge.

Analysis suggests that year-to-year variation in breakup, freeze-up, and the length of the open water season varies quite substantially between variables and amongst different sections of the corridor. First, breakup date consistently exhibited higher following-year difference and standard deviation than freeze-up date. Second, Hudson Strait consistently exhibited the highest standard deviation and following-year difference. Interestingly, no sections of the corridor displayed long-term trends in following-year difference between 1981 and 2014.

Significant relationships were discovered amongst breakup, freeze-up, and the length of the open water season on each corridor section and for the corridor as a whole. These results fit well with the existing concept of a climate "memory", which explains how the timing of the ice-free season and the ice-covered season can influence one another. Interestingly, correlation analysis suggests that local variation in ice timing and climate memory have a much stronger impact on ice timing in Hudson Strait than in Hudson Bay. Finally, the significant relationships and strong correlations amongst breakup, freeze-up, and the length of the open water season could potentially provide useful predictions for ice timing in some circumstances.

4. Manuscript 2 - Climate change and sea ice: shipping in Hudson Bay, Hudson Strait, and Foxe Basin (1980-2016)

Andrews, J., Babb, D., & Barber, D. G. (2017). Climate change and sea ice: shipping in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin (1980-2016). Manuscript submitted for publication.

4.1. Abstract

The seasonally ice-covered waters of Hudson Bay, James Bay, Foxe Basin, and Hudson Strait ("the study area") are bordered by 39 communities with a total population of roughly 50,000 people, most of whom are Inuit or Cree. Sea ice is a cornerstone of the environment and culture of the study area but is also the main barrier to shipping traffic, which has been growing in the area. This study investigates shipping accessibility in the study area by characterizing the timing of breakup, freeze-up, and the open water season in offshore and local waters. Offshore ice timing was analyzed using passive-microwave based data for 1980 to 2014, local ice timing near Rankin Inlet, Churchill, Kuujjuarapik/Whapmagoostui, and Salluit was examined using Canadian Ice Service ice charts for 1996 to 2016. Open water was defined using sea ice concentration thresholds of ≤15% (offshore) or <20% (local) in an attempt to represent accessible conditions for open-water shipping vessels. The results for the offshore and local waters both display considerable spatial variability. For the offshore waters, breakup currently occurs between May 17th and August 19th and freeze-up occurs between October 22nd and December 30th, with overall trends (1980-2014) of +0.58 days.year^{-1} towards an earlier breakup, +0.47 days.year^{-1} towards a later freeze-up, and +0.97 days.year^{-1} towards a longer open water season. Also, significant relationships amongst breakup and freeze-up were observed. For the

local waters, the 1996-2016 average open water season at the four communities varied between 112.7 days (Churchill) and 154.7 days (Kuuj/Whap). Ultimately, shipping accessibility to Rankin Inlet, Churchill, and Salluit appears to be limited by their local ice timing, while accessibility to Kuuj/Whap appears to be limited by ice timing in north-eastern Hudson Bay.

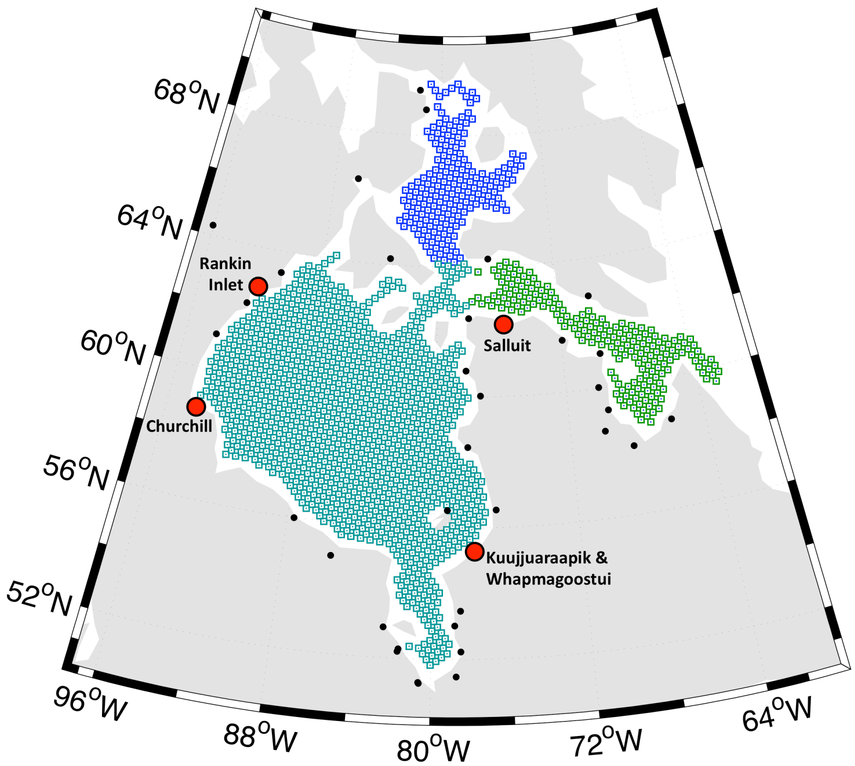

Figure 4-1. The study area.

The marine waters of Hudson Bay, James Bay, Hudson Strait, and Foxe Basin in the eastern Canadian Arctic. Coloured squares show the approximate location of the 25km x 25km pixels of the sea ice dataset. The area was divided into three regions for further analysis: "Hudson Bay" (light blue - includes James Bay), Hudson Strait (green), and Foxe Basin (dark blue). The four communities examined using Canadian Ice Service ice charts are indicated with red circles, while the remainder of the communities in the area are indicated with black dots.

4.2. Further background

[Most of the introduction for this manuscript was covered in sections 1 and 2 above. This section (4.2) presents the remaining introductory material.]

The communities of Rankin Inlet, Churchill, Kuujjuarapik/Whapmagoostui, and Salluit were selected for an analysis of local sea ice conditions. These communities were chosen in an attempt to provide a cross-section of the 39 communities in the study area with respect to sea ice and shipping. (Note: Kuujjuarapik and Whapmagoostui are neighbouring communities with some shared infrastructure. In this article they are sometimes referred to as a single community for the sake of convenience - thus “four” study communities.)

4.2.1. Rankin Inlet

Rankin Inlet, Nunavut (62˚N, 92.1˚W) is a community of roughly 2,850 people in north-western Hudson Bay (Statistics Canada, 2016). The community is located on a point at the base of a broad inlet that opens to the east. Rankin Inlet is the administrative centre for the Kivalliq region of Nunavut. The Meliadine Gold Mine, roughly 25km from the community, is slated to begin production in the coming years and will be shipping to and from Rankin Inlet (Agnico Eagle Ltd, 2012; Canadian Northern Economic Development Agency, 2013; Gavrilchuk & Lesage, 2014). The community currently has no permanent marine infrastructure and sealift is unloaded onto the beach via barge. Some minor shipping infrastructure upgrades are slated to accompany the Meliadine project (Agnico Eagle Ltd, 2012). For several years the Government of Nunavut and the federal government have discussed developing a deep-water port at the community (Brooks & Frost, 2012; Gavrilchuk & Lesage, 2014), but there appear to be no concrete plans and no timeline for this project. With respect to sea ice, charts from Environment and Climate Change Canada (2013) indicate that the open water season near the community (approximately sea ice concentration ≤ 10%) typically ran from early July to early November between 1981 and 2010.

4.2.2. Churchill

Churchill, Manitoba (58.7˚N, 94.2˚W) is a community of roughly 900 people located at the mouth of the Churchill River on western Hudson Bay (Statistics Canada, 2016). The Port of Churchill is the only deep-water port in the Canadian Arctic and is equipped with four loading berths capable of handling vessels of 60-80,000 tonnes (Andrews et al., 2016). Churchill is connected to the south via the Hudson Bay Railway. Both the Port and the Railway have been privately owned since 1997, but both assets were put up for sale in 2015 and operations at the Port were stopped in 2016 (Andrews et al., 2016; Robertson, 2017). Prior to its closure the Port typically handled exports of grain and re-supply freight, shipping grain exclusively in open water (non ice-strengthened) vessels (Andrews et al., 2016). In the decade up to 2014 the Port typically exported 400,000 - 600,000 tonnes of grain and roughly 10,000 tonnes of re-supply freight each year (Andrews et al., 2016). Grain was exported to international destinations in 15-20 shipments per year during a shipping season that typically ran from August to October; re-supply freight was sent to communities in western Hudson Bay (Andrews et al., 2016). According to figures from Environment and Climate Change Canada (2013), the open water season near the community typically ran from early July to early November between 1981 and 2010.

4.2.3. Kuujjuarapik/Whapmagoostui ("Kuuj/Whap")

The neighbouring communities of Kuujjuarapik and Whapmagoostui (55.3˚N, 77.8˚W) are located in south-eastern Hudson Bay at the mouth of the Great Whale River. Kuujjuarapik is a village in Nunavik with a population of roughly 690 people; Whapmagoostui is a village in the Cree territory of Eeyou Istchee with a population of roughly 985 people (Statistics Canada, 2016). The two communities share the use of some infrastructure, including a relatively new marine breakwater and boat ramp (Quebec, 2015). The Government of Quebec has considered developing a deep-water port at Kuuj/Whap; the project was formally included in the initial Plan Nord of 2012 but was not in the revised version of 2015 (Gavrilchuk & Lesage, 2014; Quebec, 2015; Government of Canada, 2015). There has also been discussion of building a road to the community from the south, which could be used to bring exports from the planned Duncan Lake Mine (Gavrilchuk & Lesage, 2014; Quebec, 2015). The current government appetite for these projects is not clear and no detailed development plans or timelines could be found. According to figures from Environment and Climate Change Canada (2013), the open water season near the community typically ran from early July to early December between 1981 and 2010.

4.2.4. Salluit

Salluit, Nunavik (62.2˚N, 75.6˚W) is a community of roughly 1,485 people located in Sugluk Inlet on the south side of Hudson Strait (Statistics Canada, 2016). The community has a new marine breakwater and a boat ramp (Quebec, 2015). According to figures from Environment and Climate Change Canada (2013), the open water season near the community typically ran from early July to early December between 1981 and 2010. Sugluk Inlet lies roughly 20km west of Deception Bay, where there is a port associated with the Raglan Nickel mine.

Climate change is driving a longer open water season in the study area. This could be a challenge for the Inuit people - declining sea ice will mean less time for hunting and travel over the ice, and ice-use may become more hazardous (Ford et al., 2008). Shipping traffic appears to have doubled in the study area between 1990 and 2015, and longer open water seasons and growing socio-economic demand will provide further stimulus for this trend. There are potential benefits to increased shipping: for example, increased sealift could lead to a lower cost of living, while shipping-enabled growth in the tourism, fishing, and mining sectors could bring welcome employment and economic growth. However, these potential benefits are stacked against the environmental impact of shipping. A careful approach will be needed for an environmentally responsible and socially beneficial shipping industry in the study area. Scientific research will be an important component of this approach. In this context, this paper presents our efforts to characterize the offshore and local timing of sea ice in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin between 1980 and 2016. More specifically, our research examines the timing of breakup, freeze-up, and the open water season both offshore and near the four communities of Rankin Inlet, Churchill, Kuujjuarapik/Whapmagoostui, and Salluit.

4.3. Methods

4.3.1. Offshore sea ice analysis

Offshore shipping accessibility was examined using the "Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data" dataset (Cavalieri et al., 1996, updated yearly) hosted by the National Snow and Ice Data Centre (NSIDC). This dataset provides daily sea ice concentrations on a 25km x 25km grid for 1980 to 2014. The study area defined in this analysis includes 1,559 of the 25x25km "pixels" (Figure 4-1). The area was also subdivided into three regions for further analysis: Hudson Bay (1181 pixels), Hudson Strait (197 pixels), and Foxe Basin (181 pixels). Note: the "Hudson Bay" region defined for this offshore analysis includes James Bay.

As can be seen in Figure 4-1, pixels directly bordering the coast were not included in the analysis. This was done for two reasons: 1) in order to minimize the influence of near-shore landfast ice or any other highly local, coastline ice in our desired offshore results, and 2) to avoid the erroneous data that can sometimes arise in passive-microwave datasets for near-shore locations. Because no pixels bordering the coast were included in the dataset, the offshore analysis excludes coastal marine waters up to a maximum of 71km from shore: Pixels have dimensions of 25x25km (and a diagonal of ~35.4km) and a pixel containing any land is labeled as "coast". Thus some pixels labeled as "coast" in the dataset may include marine waters up to 35.4km offshore. As a result, pixels bordering the "coast" may actually border a region nearly 35.4km from shore; the exclusion of these pixels therefore results in a data-less zone of up to 71km (<35.4 + 35.4) from shore.

The timing of open water conditions at each pixel from 1980 - 2014 was determined using the following method: for each year, breakup was recorded as the first of three consecutive days with ice concentrations ≤15%, freeze-up was recorded as the first of three consecutive days with ice concentrations >15%, and the open water season was the number of days between breakup and freeze-up. The three-day window used for breakup and freeze-up insured that transient ice motion and other short-term variations in ice concentration did not affect our analysis; longer time windows were experimented with (e.g. 7 days) but they made no appreciable difference to the results. The 15% concentration threshold for open water conditions was selected as the best representation of navigable conditions for open-water shipping vessels. Linear regression was used to examine trends in the timing of breakup, freeze-up, and the open water season for each pixel for 1980 to 2014. Linear regression was also used to examine the relationships between breakup and freeze-up dates for each pixel.

The Cavalieri et al. (1996) dataset used here and other similar passive-microwave based datasets have been used extensively for sea ice analyses similar to the research we are presenting in this paper (e.g. Stammerjohn et al., 2008; Cavalieri & Parkinson, 2012; Hochheim & Barber, 2014; Parkinson, 2014; Stroeve et al., 2016; Andrews et al., 2017). A more thorough discussion of the strengths and weaknesses of the Cavalieri et al. (1996) dataset in our context can be found in Andrews et al. (2017). Finally, the 15% ice concentration threshold used in our research has been similarly applied as a navigability threshold in several publications (e.g. Bensassi et al., 2016; Andrews et al., 2017) and more generally as an open water threshold in others (e.g. Stammerjohn et al., 2008; Parkinson, 2014; Stroeve et al., 2016).

4.3.2. Local sea ice analysis

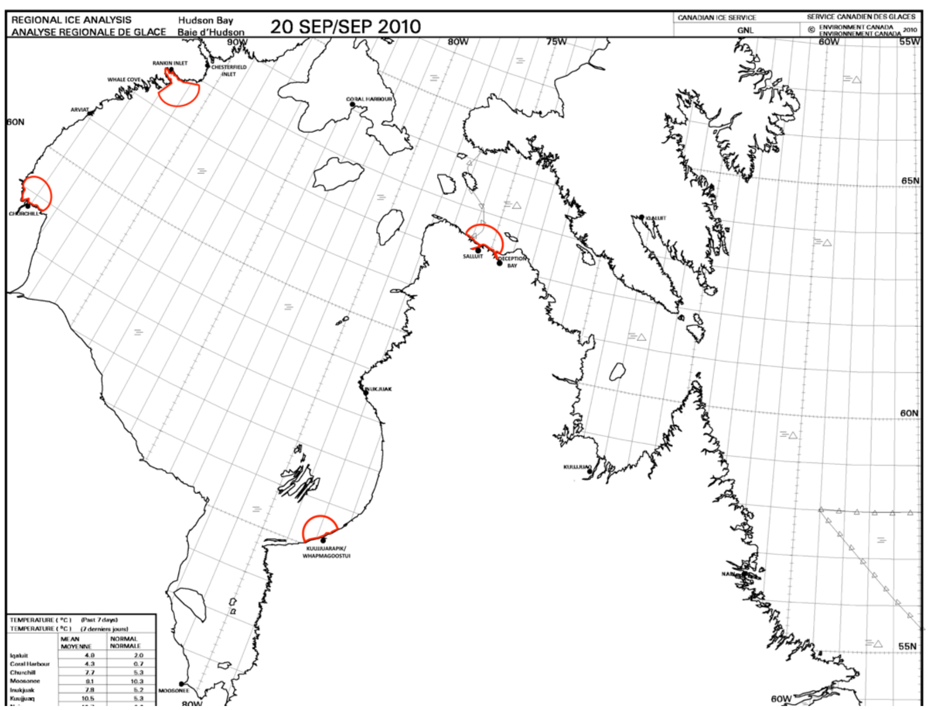

Figure 4-2. The community areas for local sea ice analysis.
A modified Canadian Ice Service ice chart for the “Hudson Bay region” showing the marine area examined for Rankin Inlet, Churchill, Kuujjuarapik/Whapmagoostui, and Salluit. Modified from Government of Canada (n.d.).

The timing of sea ice near Rankin Inlet, Churchill, Kuuj/Whap, and Salluit, was examined for 1996 to 2016 using ice charts created by the Canadian Ice Service (CIS) for the "Hudson Bay region" (Government of Canada, n.d.). The CIS ice charts present the geographic distribution of sea ice within a region, with the ice grouped into "polygons" (i.e. areas) of equal ice concentration. Each polygon is labelled with information on the sea ice within it, including the ice concentration, stage of development, and form. But there is another layer of information: polygons often contain variation in the sea ice within them, and in these cases the different sub-areas of sea ice within each polygon are described. The CIS charts present ice concentrations in tenths (/10ths). Since 1982 the charts have been labelled using the ice "Egg Code" maintained by the World Meteorological Organization (Environment and Climate Change Canada, 2016).

The ice data from CIS charts have been used for numerous quantitative analyses published in the scientific literature but there are some important qualifiers and caveats that should be discussed. Put briefly, CIS ice charts have been created since the 1960s by ice experts using the best-available information from surface observations, aerial observations, and satellite data (both visual and microwave based). However, "best-available" has changed since the 1960s and so has the demand for ice charts. As a result, the methodology used to create the charts and the frequency of their production has changed considerably over the decades. With respect to methodology, two points in particular are worth elaborating: the proportion of ice chart content derived from 1) satellite observations and 2) "now-casting". First, the proportion of ice chart data based on satellite observations grew from 15% prior to 1978, to 50-55% from 1978 to 1995, and finally to 80% in 1996 with the introduction of RADARSAT (Canadian Ice Service, 2006). Second, the CIS has often used a process called "now-casting" to produce ice charts when timely ice observations are not available. When now-casting, CIS experts estimate ice conditions at the time of the chart's creation by extrapolating from earlier observations (Canadian Ice Service, 2006). The ice estimates based upon now-casting carry considerable uncertainty (Tivy et al., 2011). Prior to 1996, an average of 50% of the data in Arctic ice charts were the product of now-casting based on observations taken an average of 5 or more days prior to a chart's creation (Canadian Ice Service, 2006). Since 1996, with the introduction of RADARSAT and the more timely availability of data, an average of only 20% of data in the Arctic charts has been produced through now-casting from observations only 1 day prior to a chart's creation (Canadian Ice Service, 2006).

Tivy et al. (2011) thoroughly examined the quality of the CIS sea ice data to assess their validity for statistical analysis. The authors discuss now-casting and technological changes and note a further important source of error: the quality of ice observations has not typically been homogenous across all Arctic regions (or ice chart areas) at any given time. As a result there is variability in the quality of data within each ice chart, and the highest-quality data are typically found near communities and shipping routes. For example, the authors of this paper observed that the region near Deception Bay (and the shipping route for the Raglan nickel mine) appears to have more detailed data than surrounding areas in the ice charts for 2011 to 2016.

The CIS's changing methodology has resulted in an archive of ice data that vary in quality both within and between charts, which affects the data's suitability for statistical analyses. Nonetheless, after a thorough consideration of uncertainty and error, Tivy et al. (2011) rank the CIS data for our study area as "fair" to "excellent" on their "Quality Index", which was created to "portray the variability in data quality over space and time". Furthermore, the CIS ice chart data has been used for numerous studies examining multi-decadal trends in ice conditions within our study area. For example, Tivy et al. (2011), Galbraith and Larouche (2011), and

Kowal et al. (2015) all compare charts from the 1970s or 80s to the present within their trend analyses. However, we deemed this methodology inappropriate for our application: The aforementioned articles have applied the CIS data on a relatively large geographic scale, which may minimize some of the possible error from the sources discussed. Our research, on the other hand, seeks to examine sea ice conditions at a small, local scale. Out of caution, we use only CIS charts for 1996 to 2016 in our analysis; these charts are all within the RADARSAT era, they are largely based on satellite observations (~80%), and they contain relatively little content from now-casting (~20% on average).

Our four study communities - Rankin Inlet, Churchill, Kuuj/Whap, and Salluit - are all encompassed within the area of the CIS ice charts for the Hudson Bay region. These charts were created at a shifting frequency between 1996 and 2016: From 1980 to 2007 the charts were created monthly from January through April, every second week during May, and weekly from June through December. From 2007 to 2011 the charts were created every second week from January through March and weekly from April through December. Since 2008 the charts have been created on a weekly basis throughout the year. However, these general timing patterns were occasionally interrupted by missing charts or longer time gaps.

The 1996-2016 CIS ice charts for the Hudson Bay region were used to examine the local timing of 1) landfast ice and 2) the open water season for each of the four studies communities. “Local” here refers to the marine waters within a 50 km radius of Churchill and Kuuj/Whap, and within a 50 km radius of the entrance to the Rankin and Salluit inlets (“community areas” shown in Figure 4-2). Landfast ice is directly labelled in the CIS data, while “open water” was defined using an ice concentration threshold of <20% (i.e. < 2 tenths). Analysis was conducted by running the ice chart data through a computer program that indicated the presence/absence of landfast ice or open water conditions within each community area. Breakup for landfast and open water conditions were defined as the first week without landfast ice and the first week with no sea ice of concentration ≥20%, respectively. Freeze-up for landfast and open water conditions were defined as the first week with landfast ice and the first week with ice concentrations ≥20%, respectively. The open water season was calculated as the number of weeks between open water breakup and freeze-up (i.e. <20% concentration).

In some years multiple "break-up" events occurred in a community area as ice departed, returned, and departed again over a short time frame (e.g. 3 weeks); in these circumstances the final breakup was used for our record. Similarly, in some years multiple "freeze-up" events occurred and in these circumstances the earliest event was used for our record. As a result of this methodology our measurements reflect the latest possible breakup and earliest possible freeze-up, given the data, and therefore produce a relatively conservative estimate for open water conditions at the 20% ice concentration threshold.

Our data from the CIS ice charts were not examined for trends between 1996 and 2011. We did not feel confident that the results would be scientifically rigorous, because of the short 21-year time period and because the timing of the available CIS charts present some difficulties for analysis. The identification of ice timing (i.e. breakup or freeze-up date) using the CIS charts carries a minimum uncertainty of one week. This was the case with all breakup and freeze-up dates for the 20% concentration threshold. Furthermore, the freeze-up and breakup of landfast ice at the four communities quite regularly occurred during months where CIS charts were created on only a once per two-week or once per month basis; in these cases, the identification of ice timing carried a two-week or one-month uncertainty. Finally, occasional ice charts were missing from the record, resulting in increased uncertainty for several measurements of landfast ice timing.

4.3.3. Local versus offshore comparisons

There is no consensus on whether ice concentration from CIS ice charts and passive-microwave observations may be reliably partnered for scientific analysis. Some studies have observed considerable discrepancies between ice concentrations from CIS charts versus passive-microwave methods (e.g. Agnew & Howell, 2003), though others have indicated reasonable agreement in results from the two different data sources (e.g. Tivy et al., 2011; Kowal et al., 2015; Andrews et al., 2017). In this article we will not quantitatively compare results from the two different analytical methods (local versus offshore). To compensate for this, the CIS charts were used to provide a small element of offshore analysis: we tested each community breakup and freeze-up for the presence of a channel of open water (ice concentration <20%) that extended continuously from the community boundary to the eastern end of our analysis area as shown in Figure 4-1. There was no minimum width for the channel and there was no requirement of a direct route, only continuous open water conditions.

4.4. Results

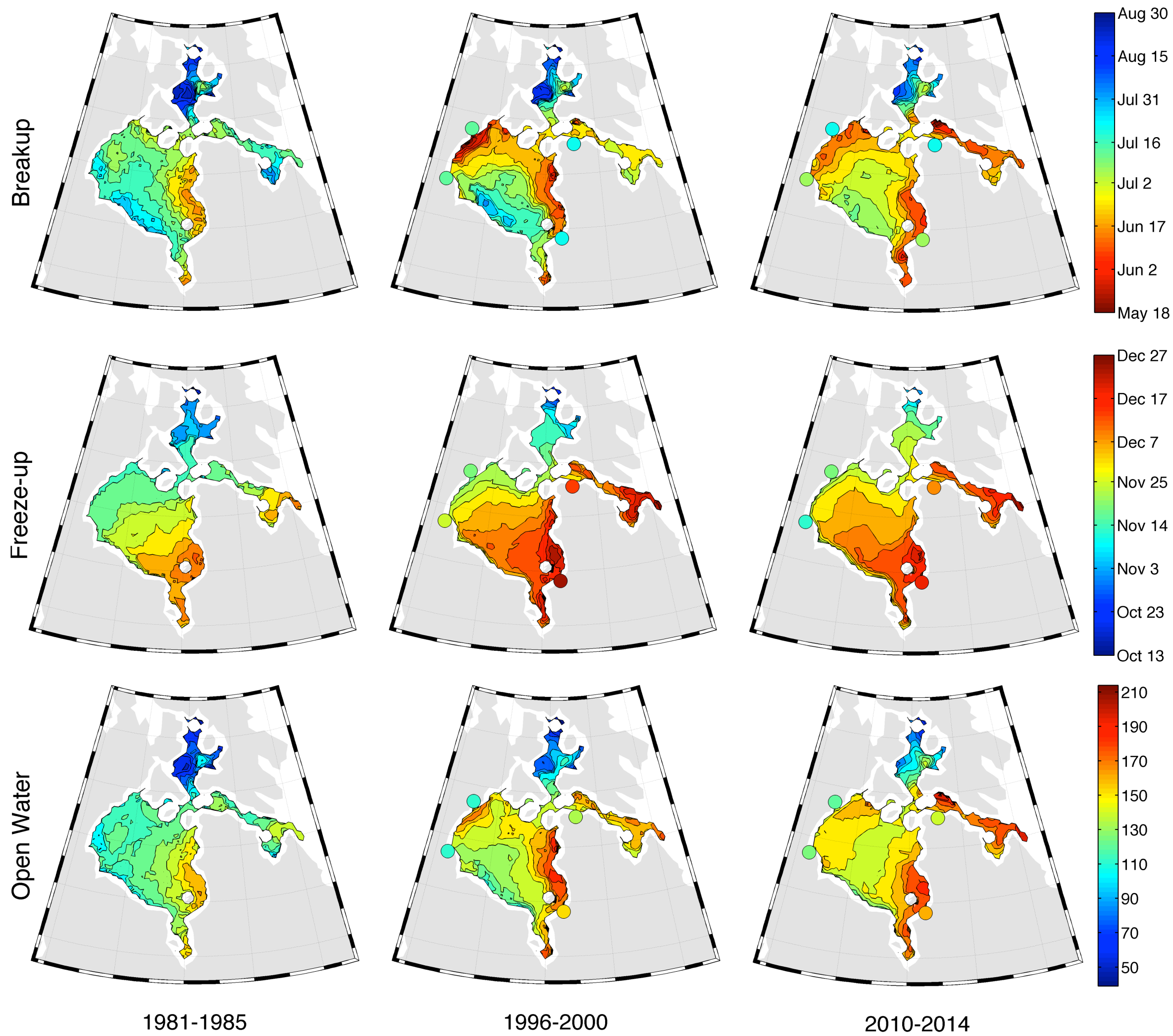

Figure 4-3. Median breakup, freeze-up, and open water for 1981-1985, 1996-2000, and 2010-2014. The timing of breakup and freeze-up, and the length of the open water season in the offshore waters (contoured data) and in the communities areas for Churchill, Rankin Inlet, Kuujjuarapik/Whapmagoostui, and Salluit (coloured circles). Five-year medians are shown for 1981-85 (offshore only), 1996-2000, and 2010-14.

Table 4-1. **Regional medians in offshore data for 1981-1985, 1996-2000, and 2010-2014**

		Entire area	Hudson Bay	Hudson Strait	Foxe Basin
Breakup date	**1981-85**	15-Jul	14-Jul	18-Jul	9-Aug
	1996-00	3-Jul	1-Jul	29-Jun	1-Aug
	2010-14	28-Jun	29-Jun	18-Jun	29-Jul
Freeze-up date	**1981-85**	21-Nov	21-Nov	22-Nov	31-Oct
	1996-00	3-Dec	4-Dec	11-Dec	7-Nov
	2010-14	1-Dec	2-Dec	10-Dec	16-Nov
Open water days	**1981-85**	128	130	132	82
	1996-00	149	149	166	94
	2010-14	155	155	178	108

4.4.1. Offshore sea ice analysis

<u>Current sea ice timing</u>

Figure 4-3 shows the median timing of open water conditions in the study area for 1981-1985, 1996-2000, and 2010-2014. The median values for 2010-2014 provide insight into the current timing of open water conditions in the area (Table 4-1). Breakup for the pixels of the study area varied between May 17th and August 19th, freeze-up varied between October 22nd and December 30th, and the length of the open water season varied between 64 and 224 days (Figure 4-3). These wide ranges indicate the considerable regional variation in offshore ice timing.

Hudson Strait and south-eastern Hudson Bay (and James Bay) exhibited the longest open water season (>160 days) as a result of relatively early breakup and freeze-up. Hudson Bay, with the exception of the south-east, exhibited fairly uniform open water season lengths of 140 - 160 days; however, that result belies considerable variation within breakup and freeze-up. Regional variation within Hudson Bay includes a relatively early breakup (~early June) in the north-western and south-eastern Bay, a steadily later freeze-up from north-western Hudson Bay (mid-

Nov.) towards the southeast (early Dec.), and tight gradients in freeze-up date along the Bay's western and southern shoreline. Finally, the waters of Foxe Basin exhibited the shortest open water season, a product of relatively late breakup and early freeze-up.

Trends for 1980-2014

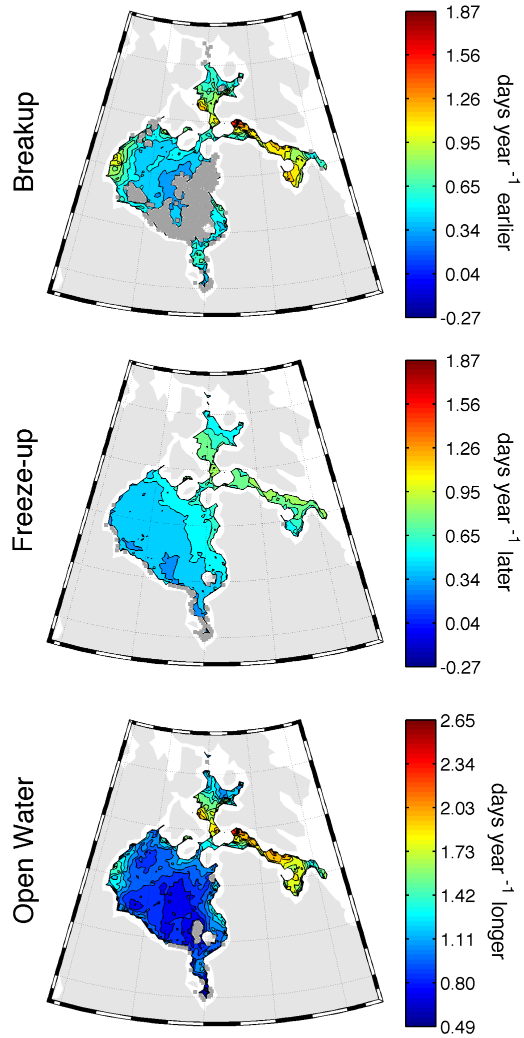

Figure 4-4. Trends in breakup, freeze-up, and open water timing.
1980-2014 trends (days.year^{-1}) in offshore ice timing from linear regression. Pixels with significant trends ($p<0.05$) are shown in colour, all other pixels are shown in dark gray.

Table 4-2. 1980-2014 regional trends in offshore data based on linear regression

		Entire area	Hudson Bay	Hudson Strait	Foxe Basin
Breakup (days.year^{-1} earlier)	**Prop. Sig.**[A]	0.71	0.65	0.97	0.79
	Median[B]	0.58	0.51	1.05	0.70
	Max	1.79	1.11	1.79	1.41
	Min	0.29	0.29	0.55	0.41
Freeze-up (days.year^{-1} later)	**Prop. Sig.**	0.95	0.95	1.00	0.89
	Median	0.47	0.44	0.75	0.62
	Max	1.01	0.88	1.01	0.87
	Min	0.26	0.26	0.36	0.37
Open Water (days.year^{-1} longer)	**Prop. Sig.**	0.95	0.96	1.00	0.88
	Median	0.97	0.91	1.76	1.31
	Max	2.55	1.92	2.55	2.23
	Min	0.45	0.45	1.25	0.64

[A] "Prop. Sig." refers to the proportion of pixels with significant trends (p-value < 0.05), determined via linear regression.
[B] Median, max, and min were calculated using only the significant trends.

The offshore timing of sea ice has clearly been changing in the study area. Significant trends were observed for breakup, freeze-up, and open water season length throughout the area, with a few exceptions (Figure 4-4, Table 4-2). Figure 4-4 reveals considerable and noteworthy spatial variation in the 1980 - 2014 trends:

Trend magnitudes for each variable (breakup, freeze-up, open water) are consistently highest in Hudson Strait and southern Foxe Basin, and are consistently lower in Hudson Bay (particularly the central Bay) than in the other two regions (Table 4-2). Significant freeze-up trends vary between 0.26 and 1.01 days.year^{-1}. Significant breakup trends vary between 0.29 and 1.8 days.year^{-1}, but only north-western Hudson Strait and south-western Foxe Basin exhibited trends greater than 1 days.year^{-1}. Therefore, both breakup and freeze-up trends vary between 0.26 and 1 days.year^{-1} over most of the study area.

Within Hudson Bay, breakup trends increase towards the western region, which exhibits relatively high trends (0.5 - 1 days.year^{-1}). Interestingly, a large portion of south-eastern Hudson

Bay did not exhibit significant trends for breakup. Freeze-up trends increase from the southwest to the northeast, which exhibits trends of ~0.5 days.year^{-1}. Finally, open water trend magnitudes are quite homogenous, with the relatively highest trends (~1.4 days.year^{-1}) occurring in the west.

Trend analyses for all three variables show a number of pixels without a significant trend along the southern coast of Hudson Bay and in coastal James Bay. Also, southern James Bay exhibited relatively few significant trends.

Relationships amongst breakup and freeze-up

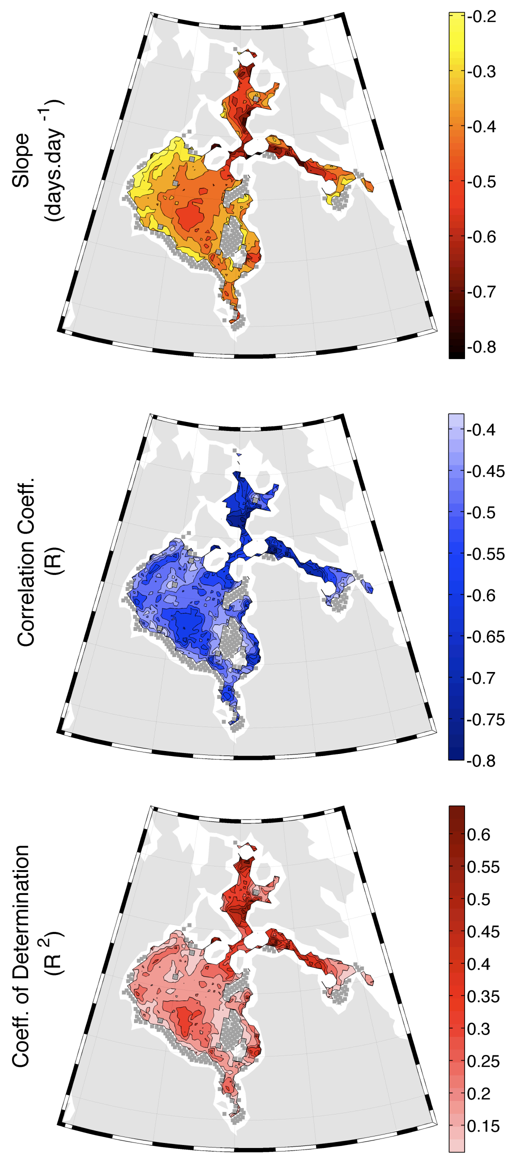

Figure 4-5. Freeze-up date as a function of breakup date for 1980-2014.

Linear regression results for freeze-up date (Y) as a function of breakup date (X) in the offshore data for 1980-2014. From top to bottom: values for slope, the Pearson correlation coefficient (R), and the coefficient of determination (R^2). Values are only shown in colour for pixels exhibiting a significant relationship ($p<0.05$).

Table 4-3. The 1980-2014 relationships amongst breakup and freeze-up dates in the offshore data

Relationship	Characteristic	Entire area	Hudson Bay	Hudson Strait	Foxe Basin
Freeze-up date (Y) as a function of breakup date (X)	Prop. sig. ($p < 0.05$)[A]	0.87	0.86	0.85	0.97
	Median slope	-0.36	-0.34	-0.41	-0.45
	Median R	-0.47	-0.46	-0.53	-0.59
	Median R^2	0.22	0.21	0.28	0.35
Breakup date (Y) as a function of freeze-up date the year before (X)	Prop. sig. ($p < 0.05$)[A]	0.60	0.54	0.90	0.65
	Median slope	-0.57	-0.54	-0.78	-0.60
	Median R	-0.48	-0.47	-0.50	-0.63
	Median R^2	0.19	0.17	0.35	0.19

[A] The proportion of pixels with significant relationships ($p<0.05$) for 1980-2014, determined via linear regression.
[B] Median slope, R, and R^2 were calculated based on the regression lines from the significant relationships only.

Roughly 87% of pixels in the study area exhibited a significant ($p < 0.05$) negative relationship for freeze-up date (Y) as a function of breakup date (X) for 1980-2014, and the percentage was 97% in Foxe Basin (Table 4-3). The significant relationships exhibited a median slope of -0.36 days.day^{-1}, a median Pearson correlation coefficient (R) of -0.47, and a median coefficient of determination (R^2) of 0.22, though with considerable spatial variation (Table 4-3, Figure 4-5). More specifically, Hudson Strait, Foxe Basin, and to a lesser extent the central Hudson Bay area exhibited relatively stronger slopes and larger R and R^2 values, particularly the western Strait and southern Foxe Basin. Meanwhile, the pixels of the western and southern coasts of Hudson Bay typically exhibited weaker values for slope, R, and R^2 and also had a greater proportion of non-significant relationships. Noteworthy pockets of non-significant relationships also occurred in southern James Bay, to the north of the Belcher Islands, and south-eastern Ungava Bay.

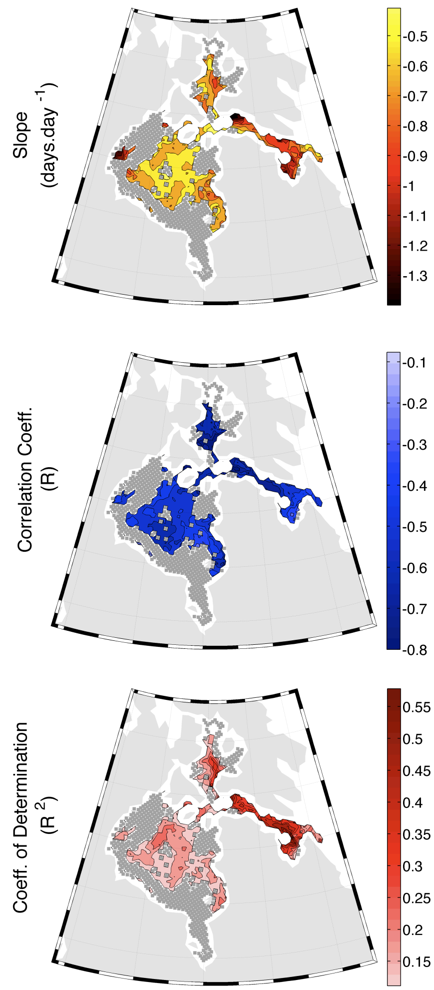

Figure 4-6. Breakup date as a function of freeze-up date the previous year for 1981-2014. Linear regression results for breakup date (Y) as a function of freeze-up date the previous year (X) in the offshore data for 1981-2014. From top to bottom: values for slope, the Pearson correlation coefficient (R), and the coefficient of determination (R^2). Values are only shown in colour for pixels exhibiting a significant relationship ($p<0.05$).

Only 54% of the pixels in Hudson Bay exhibited a significant ($p < 0.05$) relationship for breakup date (Y) as a function of freeze-up date the preceding year (X). As can be seen in Figure 4-6, the Hudson Bay pixels with significant relationships were largely in the central Bay and almost none of the more coastal pixels in the south and west exhibited significant relationships. 65% of pixels in Foxe Basin exhibited a significant relationship and 90% in Hudson Strait (Table 4-3). For the study area as a whole, the significant relationships exhibited a median slope of -

0.57 days.day^{-1}, a median R value of -0.48, and a median R^2 value of 0.19, but with considerable variation between regions. Slopes and R^2 values were relatively high in Hudson Strait, while R values were relatively high in Foxe Basin.

4.4.2. Local sea ice analysis

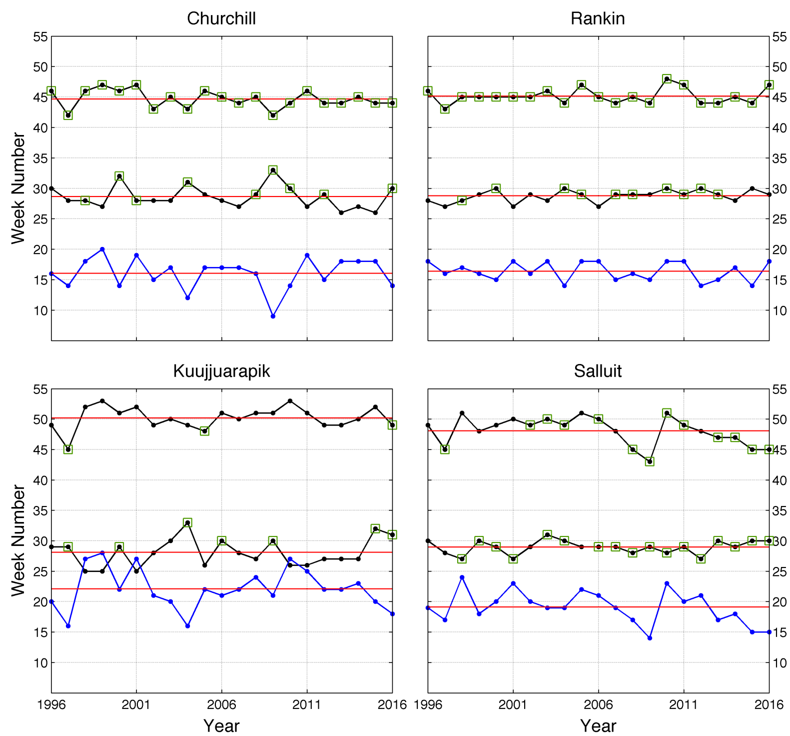

Figure 4-7. Breakup, freeze-up, and open water in the community areas (1996-2016). The timing of open water conditions (ice concentration <20%) from 1996-2016 in the four community areas. Black data depict the week-of-year for breakup and freeze-up, blue data depict the number of weeks in the open water season. Green squares around data points indicate that there was a continuous channel of open water from the community area to the eastern edge of the study area at the time of breakup or freeze-up. Red lines show the average value for each 1996-2016 time series.

Table 4-4. 2010-2014 median ice timing in the four community areas

	Rankin	Churchill	Kuuj/Whap	Salluit
Breakup date (WOY[A])	29	27	27	29
Freeze-up date (WOY[A])	45	44	50	48
Open water days	119	126	161	140

[A]WOY - Week Of Year.

Table 4-5. Statistical characteristics of the 1996 - 2016 sea ice datasets for the community areas

Characteristic	Rankin (B,F,OW[A])	Churchill (B,F,OW[A])	Kuuj/Whap (B,F,OW[A])	Salluit (B,F,OW[A])
Mean (Weeks[B])	28.8, 45.1, 16.4	28.6, 44.7, 16.1	28.1, 50.2, 22.1	29.0, 48.1, 19.1
Standard Dev.	1.00, 1.28, 1.53	1.86, 1.46, 2.62	2.32, 1.86, 3.37	1.12, 2.31, 2.72

[A]B - breakup, F - freeze-up, OW - open water.
[B]Week - week of breakup, week of freeze-up, and number of weeks in open water season.

Table 4-6. The proportion of breakup and freeze-up events between 1996 and 2016 with a continuous channel of open water from the community area to the eastern end of the study area

	Breakup	Freeze-up
Rankin	0.48	1.00
Churchill	0.43	1.00
Kuuj/Whap	0.33	0.14
Salluit	0.81	0.62

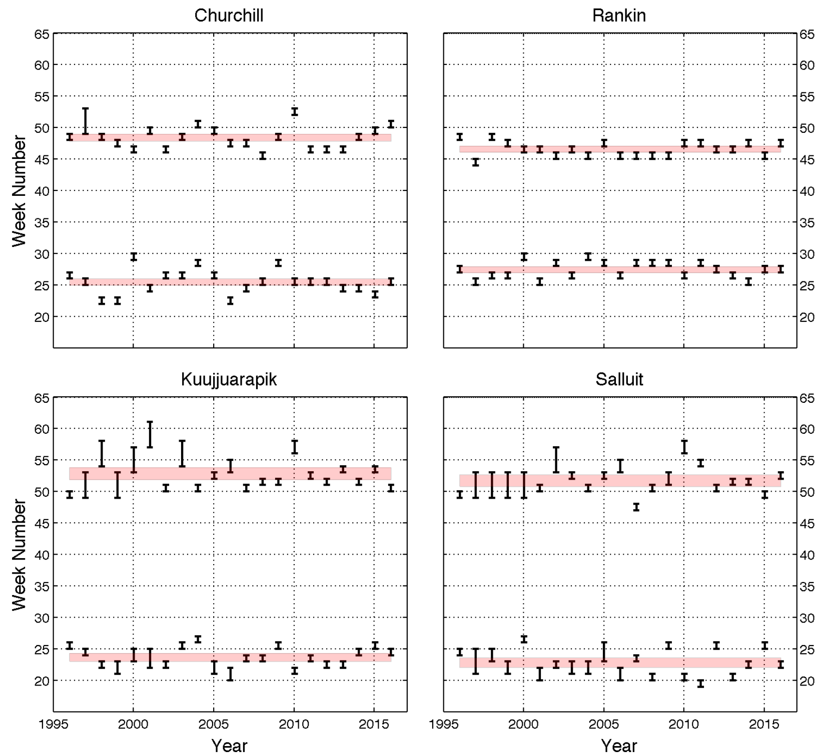

Figure 4-8. Breakup and freeze-up of landfast ice in the community areas (1996-2016).
The week-of-year timing of breakup and freeze-up of landfast ice in the four community areas from 1996 to 2016. Data points carry uncertainty of 1 to 6 weeks, as indicated by the error bars. The red bars depict the average values for 1996-2016 and the width of each bar indicates the uncertainty in these values.

Table 4-7. The 1996 - 2016 average breakup and freeze-up dates (± uncertainty) for landfast ice in the four community areas, in Week of Year (WOY) format

	Breakup	Freeze-up
Rankin	27.9 ± 1.0	47.0 ± 1.0
Churchill	26.0 ± 1.0	49.0 ± 1.1
Kuuj/Whap	24.3 ± 1.3	53.8 ± 2.0
Salluit	23.6 ± 1.5	52.6 ± 1.9

Rankin Inlet

With respect to open water conditions (ice concentrations <20%), the Rankin Inlet community area exhibited a 2010-2014 median breakup of week 29 (~Jul.17-23), freeze-up of week 45 (~Nov.6-12), and open water season of 119 days (the shortest of the four study communities) (Table 4-4). Between 1996 and 2016, breakup timing exhibited a mean of week 28.8 and a standard deviation of 1.00; freeze-up timing exhibited a mean of week 45.1 and a standard deviation of 1.28; the open water season exhibited a mean of 16.4 weeks and a standard deviation of 1.53 (Figure 4-7, Table 4-5). A continuous channel of open water ran from the edge of the community area to the eastern edge of the study area at the time of 48% of breakup events and 100% of freeze-up events (Table 4-6). Finally, the 1996 - 2016 average breakup and freeze-up dates for landfast ice were week 27.9 ± 1 and week 47.0 ± 1, respectively (Figure 4-8, Table 4-7).

Churchill

The Churchill community area exhibited a 2010-2014 median breakup of week 27 (~Jul. 3-9), median freeze-up of week 44 (~Oct. 30-Nov.5, earliest of the four study communities), and median open water season of 126 days (Table 4-4). Between 1996 and 2016, breakup timing exhibited a mean of week 28.6 and a standard deviation of 1.86; freeze-up timing exhibited a mean of week 44.7 and a standard deviation of 1.46; the open water season exhibited a mean of 16.1 weeks and a standard deviation of 2.62 (Figure 4-7, Table 4-5). A continuous channel of open water ran from the edge of the community area to the eastern end of the study area at the time of 43% of breakup events and 100% of freeze-up events (Figure 4-7, Table 4-6). Finally, the 1996 - 2016 average breakup and freeze-up dates for landfast ice were week 26.0 ± 1 and week 49.0 ± 1.1, respectively (Figure 4-8, Table 4-7).

Kuuj/Whap

The Kuujuarapik/Whapmagoostui community area exhibited a 2010-2014 median breakup of week 27 (~Jul. 3-9), freeze-up of week 50 (~Dec.11-17, the latest of the four communities), and open water season of 161 days (the longest of the four study communities by over 20 days) (Table 4-4). Between 1996 and 2016, breakup timing exhibited a mean of week 28.1 and a standard deviation of 2.32; freeze-up timing exhibited a mean of week 50.2 and a standard deviation of 1.86; the open water season exhibited a mean of 22.1 weeks and a standard deviation of 3.37 (Figure 4-7, Table 4-5). A continuous channel of open water ran from the edge of the community area to the eastern end of the study area at the time of 33% of breakup events and 14% of freeze-up events (Table 4-6). Finally, the 1996 - 2016 average breakup and freeze-up dates for landfast ice were week 24.3 ± 1.5 and week 52.6 ± 1.9, respectively (Table 4-7).

Salluit

The Salluit community area exhibited a 2010-2014 median breakup of week 29 (~Jul.17-23), freeze-up of week 48 (~Nov.27-Dec.3), and open water season of 140 days (Table 4-4). Between 1996 and 2016, breakup timing exhibited a mean of week 29.0 and a standard deviation of 1.12; freeze-up timing exhibited a mean of week 48.1 and a standard deviation of 2.31; the open water season exhibited a mean of 19.1 weeks and a standard deviation of 2.72 (Figure 4-7, Table 4-5). A continuous channel of open water ran from the edge of the community area to the eastern end of the study area at the time of 81% of breakup events and 62% of freeze-up events (Table 4-6). Finally, the 1996 - 2016 average breakup and freeze-up dates were week 23.6 ± 1.5 and week 52.6 ± 1.9, respectively (Table 4-7).

4.5. Discussion

4.5.1. Offshore sea ice analysis

If we assume that ice concentrations of ≤15% accurately represent navigable conditions for open-water vessels, our results clearly indicate a growth in the length of the shipping season in the offshore waters of the study area. Over the 35-year time period (1980-2014) the median trends correspond to breakup 20.24 days earlier, freeze-up 16.4 days later, and an open water season 34.0 days longer. There is of course considerable regional variation in these trends (Figure 4-4, Table 4-2).

Our trend results are largely in agreement with similar studies that used passive-microwave based datasets or CIS ice charts. For example, Galbraith and Larouche (2011) reported 1979-2009 trends in breakup date of -3.2 days.decade^{-1} for Hudson Bay, -5.6 days.decade^{-1} for Hudson Strait, and -4.9 days.decade^{-1} for Foxe Basin. These results are similar to our median trends of -3.6 days.decade^{-1} for Hudson Bay, -7.4 days.decade^{-1} for Hudson Strait, and -4.9 days.decade^{-1} for Foxe Basin (Table 4-2). Our stronger trend for Hudson Strait could be a product of trend acceleration in the region, which was reported by Galbraith and Larouche (2011). In another example, our results for Hudson Bay agree very closely with the 1971-2011 trends reported by Kowal et al. (2015). Furthermore, Galbraith and Larouche (2011), Tivy et al. (2011), and Kowal et al. (2015) describe significant changes in breakup date in central and western Hudson Bay and less-significant or non-significant results in the east, and these patterns are also shown in our results (see Figure 4-4). Finally, our results agree fairly well with those of Hochheim and Barber (2014), particularly with respect to the relatively rapid change in ice timing for Hudson Strait and southern Foxe Basin; however, our results do not show the rapid change in breakup and open water season length in eastern Hudson Bay reported by those authors.

Figure 4-3 indicates that the regional variation in ice timing trends between 1980 and 2014 has changed the spatial patterns of breakup and freeze-up in the study area. For example, Hudson Strait is now (2010-2014) exhibiting the earliest breakup and latest freeze-up in the region, whereas in 1981-1985 the Strait's ice timing was similar to that of Hudson Bay at the same latitudes. Also, the relatively strong breakup trends in north-western Hudson Bay have led to a new breakup pattern for the Bay (Figure 4-3, Figure 4-4). Note: Tivy et al. (2011) also reported relatively strong trends in north-western Hudson Bay.

The comparison of medians for 2010-2014 and 1996-2000 in Figure 4-3 display some surprising results: in several regions of Hudson Bay and Hudson Strait freeze-up was later in 1996-2000 than in 2010-2014 (Table 4-1) and in some parts of the Bay breakup was earlier, despite the significant trends in both variables for 1980 to 2014. The time series of Andrews et al. (2017) for the marine transportation corridor through Hudson Bay and Strait also indicate relatively early breakup and late freeze-up in 1996-2000, but the authors tested these time series for inflection points and non-linear behaviour and found no significant result. The late freeze-up and early breakup of 1996-2000 in the Bay and Strait appear to be variation about a linear trend, though we cannot express this with complete certainty. Research into the conditions of ice-forcing factors, such as atmospheric temperatures and wind, in the study area for 1996-2000 might provide some insight into the seemingly anomalous ice timing.

Relationships amongst breakup and freeze-up

Our results suggest a significant relationship between breakup and freeze-up over 87% of the offshore waters of the study area (Figure 4-5, Table 4-3). Based on the median slope values for each region, breakup one day earlier corresponds to a delay of 0.34 to 0.45 days in freeze-up date. Figure 4-5 shows considerable variation in the R and R^2 values of the relationship across the study area. The variation in the Pearson correlation coefficient (R) values indicate that breakup and freeze-up are more closely correlated in Hudson Strait, Foxe Basin, and central Hudson Bay ($R < -0.5$) than in other regions. This suggests that the timing of breakup could more accurately be used to predict the timing of freeze-up in these regions. The variation in the coefficient of determination (R^2) values is scientifically interesting: the higher values for Hudson Strait and Foxe Basin indicate that breakup timing is responsible for a greater proportion of the variance in freeze-up timing in these regions. This suggests that the "climate memory" of breakup (via heat absorbed in the surface layer) has a greater role in freeze-up timing in Hudson Strait and Foxe Basin. That said, no region exhibited median R^2 values greater than 0.35, indicating that the majority of variance in freeze-up date in the study area is driven by factors other than breakup date.

Figure 4-6 shows significant relationships between freeze-up and breakup the following year over 60% of the offshore waters of the study area (Table 4-3). Large portions of the area did not exhibit a significant relationship, including northern Foxe Basin; western, southern, and north-eastern Hudson Bay; and all of James Bay (Figure 4-6). In western and southern Hudson Bay, including the Belcher Islands, the persistent coastal polynyas (areas of open water in sea ice) and counter-clockwise currents (Joly et al., 2011; Hochheim & Barber, 2014; Andrews et al., 2016) could disrupt the relationship between breakup and freeze-up. In James Bay, polynyas and high winter and spring river input (Gough, Robinson, & Hosseinian, 2005; St-Laurent, Straneo, Dumais, & Barber, 2011; Andrews et al., 2016) could have a similar impact.

For the significant relationships between freeze-up and breakup the following year that do exist, the median slope values suggest freeze-up one day later corresponds to breakup 0.54 to 0.78 days earlier the following year. The observed correlation strengths (R values) suggest slightly stronger correlation (and thus predictive ability) in Foxe Basin, followed by Hudson Strait, and then Hudson Bay (Table 4-3). Finally, the R^2 values indicate that the role of "climate memory" from freeze-up timing is a relatively more important factor in breakup timing in Hudson Strait than in other regions, though median values were ≤0.35 in all regions.

4.5.2. Local sea ice analysis

Local ice timing (20% concentration threshold) was similar in Rankin Inlet and Churchill between 1996 and 2016. The two communities exhibited nearly identical averages for breakup (week 28.8 vs. 28.6), freeze-up (week 45.1 vs. 44.7), and open water season length (16.4 vs. 16.1 weeks). Salluit averaged later breakup, later freeze-up, and a longer open water season than Churchill and Rankin Inlet between 1996 and 2016. Kuuj/Whap averaged the earliest breakup, latest freeze-up, and longest open water season.

The variation in ice timing (suggested by the standard deviation values in Table 4-5) was not uniform across the four study communities. Salluit and Rankin Inlet exhibited greater variation in breakup than freeze-up, while Churchill and Kuuj/Whap exhibited the opposite. Rankin Inlet exhibited the lowest variation for all variables, Kuuj/Whap exhibited the greatest variation in breakup, and Salluit exhibited the greatest variation in freeze-up and open water season length (Table 4-5).

The average breakup and freeze-up timing of landfast ice for 1996-2016 followed a uniform pattern across the four communities: average breakup decreased and average freeze-up increased from Rankin Inlet, to Churchill, to Salluit, to Kuuj/Whap. Also, landfast ice arrived after and broke up before the mobile pack ice in every year from 1996-2016 at all four communities (Figure 4-7 vs. 4-8, Table 4-4 versus 4-7).

4.5.3. Offshore and local shipping accessibility

The shipping seasons for the communities of the study area are a product of offshore and local accessibility. Both Figures 4-3 and 4-7 suggest that the Churchill and Rankin Inlet community areas commonly breakup after the nearby offshore waters and freeze-up before. This ice timing can be seen in Figure 4-3, in the CIS ice charts, and in the 1980-2010 “Sea ice Climatic Atlas” from Environment and Climate Change Canada (2013): During spring breakup, open water begins to appear in the offshore waters of north-western Hudson Bay while sea ice remains intact along the coast. Also, relatively high ice concentrations often linger in the south-western and southern Bay; this is likely caused by the counter-clockwise currents of Hudson Bay moving mobile sea ice into the region during spring breakup (Hochheim and Barber, 2014). Churchill is sometimes within the western edge of the region where mobile ice becomes concentrated and persists. During freeze-up, sea ice typically grows southward in a narrow band along the west and south-western coast of Hudson Bay, freezing the coastal waters before the nearby offshore waters. This pattern is just visible in the offshore waters shown in Figure 4-3, where freeze-up is earliest in the westernmost and southernmost areas of Hudson Bay.

Put briefly, our results suggest that shipping accessibility to Churchill and Rankin Inlet is limited by the timing of local sea ice (i.e. within the community areas). We find that the two community areas each have open water seasons (<20% ice concentration) of roughly 16 weeks, and that these ~16 weeks are often encompassed by the open water season in the nearby offshore waters and along a corridor to the eastern end of the study area. We also find that the offshore waters near Churchill and Rankin Inlet exhibited significant trends towards a longer open water season between 1980 and 2014.

The offshore waters of western Hudson Strait, near Salluit, have exhibited remarkable change in ice timing in recent decades. As can be seen in Figure 4-3, in 1981-85 the waters of the western Strait broke up and froze at a similar time to waters at similar latitudes in Hudson Bay. By 2010-2014 western Hudson Strait exhibited the earliest breakup in the study area and a much later freeze-up than similar latitudes in the Bay. A qualitative examination of the CIS ice charts for 1980 - 2016 suggests an interesting change in patterns: The north-western Strait has begun to break up progressively earlier and the open water often expands south and east after appearing, driving earlier breakup in that direction. Freeze-up, meanwhile, initially progressed from Foxe Basin southward into Hudson Bay and western Hudson Strait; but over the years the progression of freeze-up has begun to bypass Hudson Strait, moving from Foxe Basin to the Bay while leaving the Strait unfrozen until a later date. It is not clear what has driven these spatially variable ice timing changes in the central part of the study area.

Between 1996 and 2016, the Salluit community area exhibited an average open water season of 19.1 weeks, the second longest of the four study communities. Figure 4-3 suggests that the community area breaks up considerably later than the nearby offshore waters but freezes up with similar timing. Furthermore, Figure 4-7 suggests that Salluit is typically accessible to shipping throughout the length of the open water season in its community area: local breakup was preceded by a continuous corridor of open water to the east end of our study area in each of the final ten years in the dataset (2007-2016), while local freeze-up occurred with a corridor still remaining in eight of the final ten years. Note: the local community area for Salluit includes Deception Bay (Figure 4-2), thus these findings are also relevant for the port located there.

With respect to the waters near Kuuj/Whap, the CIS charts for recent years show that breakup typically progresses north along the coast from eastern James Bay and south-eastern Hudson Bay, while freeze-up often occurs throughout Foxe Basin and much of Hudson Bay before reaching the coastal waters near the community. These patterns are well reflected in the 2010-2014 medians shown in Figure 4-3. The Kuuj/Whap community area appears to breakup considerably later than the nearby offshore waters but freezes with similar timing, resulting in a slightly shorter open water season for the community area (Figure 4-3). Between 1996 and 2016, the Kuuj/Whap community area exhibited an average open water season of 22.1 weeks, the longest of the study communities. These local results suggest that, with respect to sea ice, Kuuj/Whap is more accessible for sealift and could be a relatively good location for a port. However, the offshore waters may mitigate the local accessibility advantages of Kuuj/Whap: sea ice in the community area often broke up before a corridor of open water had formed through the Bay and Strait (67% of the time) and closed up after the Bay and Strait had closed to open-water shipping (86% of the time) (Table 4-6). Figure 4-3 suggests that shipping accessibility to Kuuj/Whap is limited by ice timing in the waters of north-eastern Hudson Bay.

We did not conduct trend analysis with the 1996-2016 data for the community areas, and thus cannot comment directly on changes to local shipping accessibility. However, regardless of whether ice timing is changing in the community areas, it is conceivable that the trends in the offshore waters could lead to increased accessibility to all four study communities. With earlier breakup and later freeze-up in the offshore waters, vessels travelling to or from communities within the study area may be able to approach and depart the community areas earlier and later than historically possible.

It is important to note that the averages, multi-year medians, and trends used for our discussion of shipping accessibility thus far do not directly present the inter-annual variability or extreme events in sea ice timing; however, these factors have an important impact on shipping accessibility. The standard deviation in the 1996-2016 sea ice timing in the community areas provides some idea of inter-annual variability: the variability in the length of the open water season of the Kuuj/Whap community area was greatest (standard deviation = 3.37 weeks), followed by Salluit (2.72 weeks), Churchill (2.62 weeks), and finally Rankin Inlet (1.53 weeks).

Inter-annual variation and extreme events in sea ice timing may be particularly relevant to Kuuj/Whap's shipping accessibility, as suggested by the relatively high standard deviation values associated with ice timing in the Kuuj/Whap community area. At irregular intervals since 1996, large volumes of sea ice have become concentrated in south and south-eastern Hudson Bay (including the Kuuj/Whap community area) during spring breakup. At times, this sea ice has persisted in high concentrations into late July or August, effectively barring marine access to Kuuj/Whap. This happened most recently in 2015, when abnormally high ice concentrations in the south-eastern Bay delayed shipping accessibility to numerous communities in the area (Government of Canada, n.d.; CBC News, 2015). These extreme events may be caused by an atypically voluminous and mobile ice pack in combination with the westerly winds and counter clock-wise currents of Hudson Bay. These events are difficult to predict and could present a challenge for the long-term planning of shipping operations at Kuuj/Whap.

4.6. Conclusions

The timing of sea ice in the study area has changed since 1980. Offshore shipping accessibility (ice concentrations ≤15%) increased between 1980 and 2014, with significant trends towards earlier breakup, later freeze-up, and longer open water seasons observed for much of the study area. These trends exhibited considerable spatial variability, resulting in a shift in the patterns of breakup and freeze-up in the study area: Breakup in Hudson Bay now progresses from the southeast and the north-west. Hudson Strait now exhibits considerably longer open water seasons than similar latitudes in Hudson Bay.

Between 1996 and 2016, the Churchill and Rankin Inlet community areas both exhibited an average open water season (ice concentration <20%) of roughly 16 weeks. Our research suggests that the nearby offshore waters were typically less ice restricted than these community areas, and therefore we conclude that the shipping accessibility for both communities is typically limited by the timing of ice within the community areas. The Salluit community area exhibited a 1996-2016 average open water season of 19.1 weeks. We observe that the Salluit community area's open water season is typically encompassed by the open water season in the offshore waters, like in Rankin Inlet and Churchill. Thus we conclude that Salluit's shipping accessibility is also typically limited by its local ice timing. Lastly, the Kuujjuuarapik/Whapmagoostui community area exhibited a 1996-2016 average open water season of 22.1 weeks. This is the longest average open water season of our study communities, but we do note that inter-annual variability and irregular ice timing may be particularly problematic for shipping accessibility at Kuuj/Whap. Also, our results suggest that the timing of ice in the Kuuj/Whap community area is fairly similar to ice timing in the nearby offshore waters, and that the community's shipping accessibility may typically be limited by ice timing in north-eastern Hudson Bay.

The shipping accessibility of communities and resource projects in the study area is a product of their local and regional accessibility. Most of the offshore waters of the study area exhibited growing open water seasons between 1980 and 2014, and these trends may enable earlier and later access to the 39 communities of the study area. This would have considerable implications for the people of the study area. For example, growing shipping accessibility could increase sealift, which could reduce the cost of goods in northern communities and facilitate resource projects and economic growth. However, the decline in sea ice represents the decline of a cultural cornerstone for the Inuit people and the loss of travelling and hunting opportunities. With both shipping accessibility and shipping traffic on the rise in the study area, the potential impact on the environment and the people of the area must be kept in mind.

5. Looking ahead: climate model projections for sea ice

How do we predict the future of sea ice? Scientists have developed and refined climate models to predict future climate change and the resultant consequences for Arctic sea ice. Climate models consist of a vast series of inter-connected mathematical equations that attempt to simulate the complex mechanisms of the earth-atmosphere-ocean system. These models are run, or "forced", using estimates for future atmospheric concentrations of greenhouse gases; these estimates are themselves complex entities, based on predictions of climate feedback mechanisms and society's future emissions.

Two series of forcing estimates, or "forcing scenarios", have been created and adopted by the climate modelling community since 2000: the Special Report on Emissions Scenarios (SRES) of 2000, followed by the Representative Concentration Pathways (RCP) scenarios of 2011 (Van Vuuren et al*.,* 2011; Cubasch et al., 2013; IPCC, 2013a). The RCP scenarios include RCP 2.6, 4.5, 6, and 8.5, where the numbers refer to a scenario's radiative forcing in the year 2100 relative to 1750 in watts per meter-squared (W m^2). [As an example, RCP8.5 implies a rise in atmospheric CO_2 concentrations from 370ppm in 2000, to 541ppm in 2050, and to 936ppm in 2100 (IPCC, 2013b).] When the RCP scenarios were established, RCP 2.6 was considered a "low" forcing scenario, RCPs 4.5 and 6 were considered "medium", and RCP 8.5 was considered "high" or "very high" (Van Vuuren et al., 2011; Cubasch et al., 2013). Since that time, global emissions have continued at a rate which suggests that RCP 8.5 presents the most likely emissions pathway of the RCP scenarios and may in fact be somewhat conservative (Barnhart, Miller, Overeem, & Kay, 2016; Aksenov et al., 2017).

Because the task of projecting future sea ice conditions is so complex, it is not surprising that current projections contain considerable uncertainty. The uncertainty in sea ice projections arises from uncertainty in emissions, uncertainty within the climate models themselves, and the inherent variability in natural systems such as Arctic sea ice (Melia, Haines, & Hawkins, 2015; Stroeve & Notz, 2015). Researchers generating sea ice projections apply a number of methods in order to minimize uncertainty. These include, for example, using large numbers of models and model simulations in order to capture the range of possible future scenarios, and the method of "model weighting", which involves pre-selecting only those models that meet certain specific criteria (Stroeve & Notz, 2015). Despite these methods, uncertainty remains high for sea ice projections (Stroeve and Notz, 2015; Swart, Fyfe, Hawkins, Kaye, and Jahn, 2015). For example, Jahn, Kay, Holland, & Hall (2015) estimate that recent projections for the first arrival of a sea-ice free Arctic summer (< 1 million km^2 of sea ice) produced by models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), some of the leading models in the field, carry a prediction uncertainty of over two decades. Awareness of this uncertainty is important when considering the current projections for sea ice and Arctic navigability.

A number of recent articles present sea ice projections that can be used to qualitatively assess the prospects for future Arctic shipping [several examples are outlined below]:

Barnhart et al. (2016) used the Community Earth System Model - Large Ensemble (CESM - LE) forced with RCP 8.5 to project the future prevalence of open water (ice concentrations below 15%) in the Arctic. The CESM-LE produced 30 separate simulations (or ensembles) based on slight differences in the model's initial conditions, with a resolution of 100 km (Barnhart et al., 2016). They used the model to compare projected conditions to a simulated "pre-industrial" state, and found that the Arctic open water season will experience considerable growth: for example, by 2050 the Arctic coastline and much of the Arctic ocean will experience an additional 60 days of open water each year, and many other sites will have more than 100 additional days by that time (Barnhart et al., 2016). Their results also suggest that many regions of the Arctic will have open water for half of the year by mid-century [including the majority of our study area] (Barnhart et al., 2016).

Laliberté, Howell, and Kushner (2016) used 42 models and 91 simulations from CMIP5 forced with RCP 8.5 to examine regional variability in sea ice projections. They present projections for the arrival of ice-free conditions (sea ice concentration below 15% over 94% of a region for 5/6 sequential years) for the months of June to October (Figure 5-1). Their results suggest that [the waters of our study area] and eastern Arctic waters such as the Kara, East-Siberian, Laptev, and Chukchi Seas will experience longer periods of ice-free conditions arriving earlier in the century, while the central Arctic, the Canadian Arctic Archipelago, and to a lesser extent the Beaufort Sea will be slower to become ice-free during June to October (Laliberté et al., 2016).

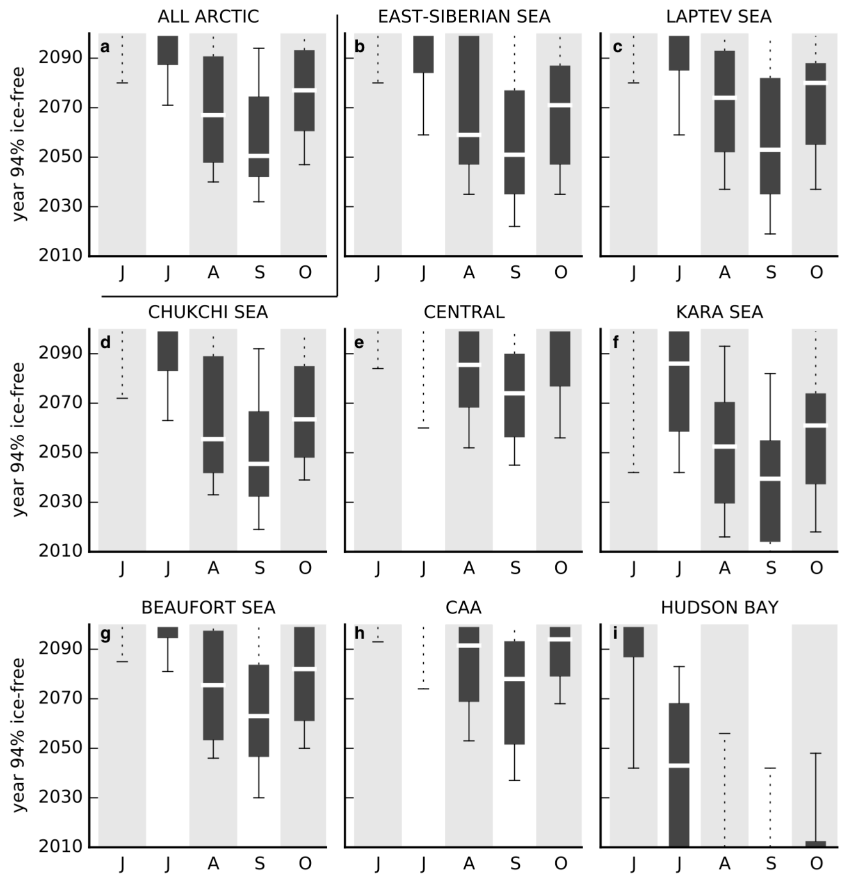

Figure 5-1. Estimates from Laliberté et al. (2016) for the arrival of ice-free conditions during the "summer" (June-Oct) in various Arctic regions. "Ice-free conditions" here refers to ice concentrations below 15% over at least 94% of a region for 5/6 sequential years. The estimates are based on projections from the CMIP5 model ensemble. The white line in the box plot indicates the multi-model median, the box range indicates the two inner-quartiles, and the "whiskers" indicate the 95% model spread. Finally, the "Hudson Bay" region referred to in the figure includes the entirety of our study area (Laliberté et al., 2016).

Joly et al. (2011) used a regional sea-ice-ocean model to project oceanic conditions in our study area in the years 2041-2070. The model was run using temperature simulations produced by the Canadian Regional Climate Model 4.2.3 and the Coupled Global Climate Model 3, forced by the SRES A2 scenario (a "high" forcing scenario with effective carbon dioxide (CO_{2e})

concentrations of 707-950ppm in 2041-2070). The authors compare simulations for 2001-2005 ("present") and 2041-2070 ("warmer") for numerous oceanic variables (Joly et al., 2011). With respect to sea ice, Joly et al. (2011) present projections for a considerable decline in sea ice duration and volume in 2041-2070 versus 2001-2005 in our study area (Figure 5-2). Their simulations also project a decline in "winter" (July-April) sea ice thickness (Joly et al., 2011). Steiner et al. (2015) present similar conclusions in a review article discussing climate projections for the Canadian Arctic.

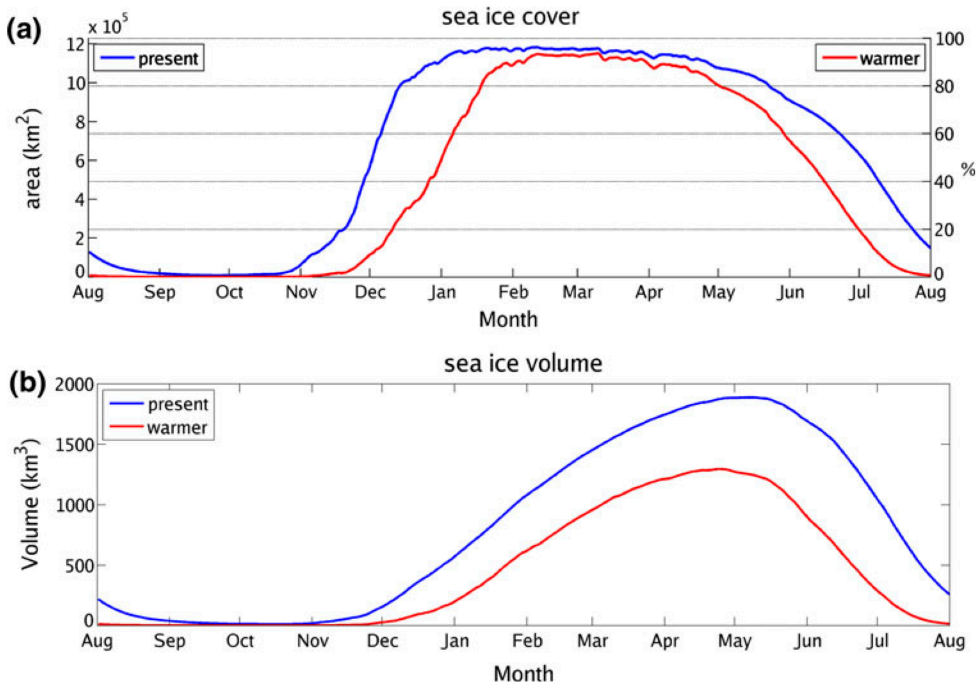

Figure 5-2. Estimates from Joly et al. (2011) for sea ice in our study area for the "present" (2001-2005) and a "warmer" scenario in the future (2041-2070). The displayed estimates for sea ice cover and volume were produced by a regional sea-ice-ocean model run with temperature simulations from climate models forced with SRES A2 (Joly et al., 2011). The upper plot shows sea ice cover as a function of both area (left y-axis) and percentage coverage of our study area (right y-axis).

When considering the shipping implications of the sea ice projections in the articles discussed above, it is important to distinguish between sea ice extent or concentration and sea ice thickness. Because the historical record of ice thickness is less rigorous than the record for ice area, efforts to project future Arctic sea ice often focus on ice area. To wit, the above articles largely present projections in the form of concentration or extent; however, it is sea ice thickness that often directly determines whether an ice-covered region is navigable (e.g. Transport Canada, 2010a). Furthermore, areas with "open water" may still contain small pieces of thick ice that could present a hazard.

6. Conclusion

6.1. Research conclusions

Here we re-visit the two research questions underlying this thesis:

1. **What is the current shipping accessibility in Hudson Bay, James Bay, Hudson Strait, and Foxe Basin, and how has shipping accessibility changed in recent decades?**

Put briefly: Using ice concentrations of less than 15 or 20% as a proxy for shipping accessibility, we conclude that the waters of the study area exhibit considerable variation in accessibility and that accessibility is increasing in much of the area.

First, the current shipping accessibility: Breakup and freeze-up follow spatial patterns that result in considerable regional variation in ice timing and thus shipping accessibility. At present, breakup typically occurs between May 17th and August 19th, freeze-up typically occurs between October 22nd and December 15th, and the open water season ranges from 64 to 224 days across the study area (though regional medians ranged from 108 to 155 days). The open water season tends to be longest in Hudson Strait, south-eastern Hudson Bay, and James Bay, and tends to be shortest in Foxe Basin.

Shipping accessibility for the communities of the study area depends on local and regional ice timing. Some parts of the study area exhibit considerable differences in ice timing between coastal and offshore waters. As a result, accessibility for open-water shipping vessels may be limited by local ice timing in some communities, regional ice timing in others, and more equally in the remainder. For example, the local waters near Churchill and Rankin Inlet, which both have an open water season of roughly 16 weeks, display more restricted ice-timing than the offshore waters from each community to the eastern end of the study area. On the other hand, the

22-week open water season in the Kuujjuarapik community area is longer than the season in some offshore areas between the community and the eastern end of the study area (especially north-eastern Hudson Bay), thus providing a regional constriction on shipping accessibility. These conclusions suggest that the shipping accessibility of coastal locations must be carefully assessed using local- and regional-scale ice observations.

Second, changes in shipping accessibility since 1980: The open water season expanded in 95% of the offshore waters of the study area, driven by trends towards earlier breakup and later freeze-up. The trends in ice timing are marked by spatial variation. The strong and variable trends throughout the offshore waters of the study area appear to have altered the spatial pattern of breakup and freeze-up since 1980. For example, the strong trends in Hudson Strait, southern Foxe Basin, and north-western Hudson Bay considerably altered ice timing in these regions relative to the remainder of the study area. The trends exhibited in some regions could have important consequences for shipping accessibility. For example, linear regression suggests the typical offshore accessibility of Hudson Strait grew by 61.6 days between 1980 and 2014. Also, the marine transportation corridor through the study area to the Port of Churchill now exhibits a significantly longer shipping season for open water vessels.

The research for this thesis did not include trend analysis for ice timing in community areas. Moreover, the observed discrepancy in offshore and coastal ice timing in parts of the study area suggest that trend results for offshore waters may not apply in coastal areas. Nevertheless, even if we assume that a community's local ice timing has not changed in recent decades, that community may still have experienced an increase in shipping accessibility thanks to the widespread growth in the open water season throughout the study area. For example, the growth in the open water season along the marine transportation corridor to the Port of Churchill (+1.14

days.year^{-1} for 1980-2014) should allow open-water shipping vessels to enter the study area earlier and depart the Port later, at least as far as sea ice is concerned.

Finally, it is worth noting that there appear to be significant relationships amongst breakup and freeze-up throughout much of the study area. These relationships are partly a product of causation: energy stored (or not stored) in the surface waters at one stage in the ice cycle has some effect on the timing of subsequent stages. This phenomenon has been described as “climate memory”. Our results suggest that climate memory from breakup or freeze-up could be responsible for as much as 60% of the variation in ice timing in some parts of the study area but is generally responsible for much less. However, causation via climate memory is not necessary for correlation. The relationships amongst breakup and freeze-up exhibit relatively high correlation in many regions of the study area, seemingly because of the direct role of climate memory and because breakup and freeze-up can be similarly influenced by other factors. The analysis of relationships amongst breakup and freeze-up could have a useful application for shipping: the strong correlation in some areas could potentially be used to develop predictions for ice timing several months in advance (e.g. Gough & Houser, 2006; Stroeve et al., 2016).

2. What are the social and environmental implications of shipping in the study area?

Put briefly: The study area is home to 39 communities and roughly 50,000 people. Shipping provides essential services for the communities and industry in the region but could also negatively impact the marine environment.

The social and environmental implications of shipping are interlinked. Most residents of the study area are either Cree or Inuit people, and the environment is a fundamental part of Cree and Inuit culture, sustenance, and well being. Thus an environmental impact is inevitably a social one. Shipping traffic in the study area currently appears to consist of roughly 160 to 180 voyages per year and most of these voyages are completed by bulk carriers, tankers, or general cargo vessels (CCG/University of Ottawa dataset - see section 2.3.2). Shipping activity has the potential to affect the marine environment via contaminant pollution (including an oil spill), the introduction of invasive species, the disturbance of marine mammals, and other mechanisms (e.g. Kelley & Ljubicic, 2012; Siders et al. 2016; Andrews et al., 2016). The risks for the environment and for shippers are exacerbated by the lack of shipping infrastructure and emergency response capacity in the region, and by the paucity of modern bathymetric data and survey charts (e.g. Commissioner of the Environment and Sustainable Development, 2014; Government of Canada, 2015).

Despite the relatively low traffic volumes, shipping does play an important socio-economic role in the study area. 29 communities in the area can only be accessed by sea or air. Sealift provides these communities with essential goods that are too heavy or too costly to be flown in (Brooks & Frost, 2012). Sealift freight is considerably cheaper than air delivery (Mariport Group Ltd., 2005), and the cost of provisioning the road- and rail-less communities of the study area often results in a problematically high cost of living. Sadly this could become even more problematic in the predominantly Inuit communities of the area, where declining sea ice appears to be reducing opportunities for traditional harvesting and inter-community travel (e.g. Laidler et al., 2010; Aporta, 2010). Any price relief enabled by sealift would likely be very welcome. Also, shipping makes possible the mining activity in the study area, which is an important economic contributor. There are currently two mines in production in the study area and several more are in the development or construction stages (Gavrilchuk & Lesage, 2014; Natural Resources Canada, 2016).

6.2. Implications for policy and management

This thesis was motivated by the desire to contribute, in some small way, to the environmentally- and socially-responsible management of shipping in the study area (both now and into the future). To that end, I hope that my research is accessible for policy makers and other stakeholders. The information presented herein on the social and environmental implications of shipping could be easily extracted, but how should the scientific elements of this thesis be applied outside of a scientific context? By extracting the central messages from imperfect yet useful scientific analysis:

The sea ice analysis presented in this thesis is based on data from passive-microwave satellite observations and Canadian Ice Service ice charts. Both of these data sources carry uncertainty, as outlined in sections 3.3 and 4.3 respectively. Also, our analysis relies on the assumption that sea ice concentrations of <15-20% are a valid proxy for shipping accessibility for open water vessels. The results for sea ice timing presented in this thesis should therefore not be regarded as precise measurements of accessibility. But these results, in partnership with other sources from the literature (presented in section 2), do provide a scientifically rigorous indication of the current shipping accessibility in the study area and how it has likely changed since 1980.

Climate modelling is exceedingly challenging: modellers must simulate complex natural systems and global greenhouse gas emissions. Current model projections for sea ice retain considerable uncertainty and these projections should not be treated as definitive measurements for quantitative application. But model projections nonetheless provide a rough guide to the future, which is in itself extremely valuable. Broad conclusions can be trusted and used for social decisions. For example, we can be confident that the decline of sea ice in our study area will continue, resulting in far greater shipping accessibility by mid-century.

We do not know the precise nature of shipping traffic in the study area since 1980. Our best estimates are based on data collected by the Canadian Coast Guard according to a shifting methodology and reliant on voluntary compliance until 2010 (see section 2.3.2). Nevertheless, the data in section 2.3.2 suggest the scale of shipping in the study area and strongly indicate an increase in traffic since 1990.

Ultimately, the key findings from this thesis are as follows:

1. At present, accessibility for open-water shipping vessels typically ranges from roughly 64 to 224 days in the study area, with substantial variation both between regions and between offshore and coastal waters. This accessibility has increased throughout the offshore waters at a rate on the order of +1 days.year^{-1} since 1980, likely providing increased access to many of the area's 39 communities. Specific details are presented in Sections 3.4 and 4.4.
2. Climate models are projecting a continued constriction of the ice season throughout much of the Arctic and sub-Arctic, including the waters of the study area.
3. Shipping in the study area appears to consist of 160 to 180 voyages per year, and has risen considerably over the past two decades. Shipping plays an important role in the area, providing essential re-supply services and supporting the mining industry, amongst other roles. But shipping also represents one of the most environmentally-significant activities in the largely non-industrial study area.
4. The environment, including sea ice, is the foundation upon which the communities of the study area exist. Cultural and social well being are dependent upon the environment.

There is at least one absolute certainty in the future of shipping in the study area: change. I hope that this change can be steered so as to mitigate the environmental risk and seize the social benefit.

6.3. Further questions and suggestions for future research

First, the following questions or issues are highly relevant to my thesis research but I was unable to investigate them as thoroughly as I would have liked:

1. How often does sea ice limit shipping in the study area? Or, is growth in the open water season of the study area accessible to shippers? Sea ice presents the greatest physical barrier to shipping in the study area but there are numerous other constraints, physical and non-physical, that may prevent shipping. These include, for example, weather, regulations, and insurance.
   - Trends and variability in wind in the study area: Reports suggest that the closure of sealift operations into the fall is sometimes brought about by wind rather than sea ice (e.g. Andrews et al., 2016). Wind data is available from weather stations near communities across the study area and from climate models. Wind analyses covering the study area do exist in the gray and peer-reviewed literature (e.g. Laidler et al., 2009; Andrews et al., 2016) but these have not been designed specifically in relation to shipping. An assessment of wind with respect to shipping in the study area would not be overly challenging and could provide valuable information.
   - The Arctic Ice Regime Shipping System: How commonly is this being used by shippers seeking to access the study area? As discussed in section 2.3.1, the AIRSS provides a more flexible regulatory regime which allows access to the study area according to ice conditions and vessel type. But a range of sources suggest the AIRSS is rarely used to ship outside of the restrictive dates of the Zone/Date System. If this is the case, what are the possible explanations?

- Marine insurance: How are insurers responding to the constriction of the ice season throughout the northern hemisphere, and more specifically, in the study area? Do insurance considerations effectively reduce the shipping season in the study area?

It is important to note that numerous other factors, some quite unrelated to shipping, may constrain shipping traffic in the study area. For example, prior to its closure, the Port of Churchill does not appear to have made use of the full shipping season available to open water vessels travelling to and from the Port: Between 2010 and 2014 grain shipping vessels left the Port no earlier than July 28th and no later than November 2nd (Andrews et al. 2016), which would equate to a maximum shipping season of roughly 97 days. The results presented in section 4.4 suggest that shipping accessibility to Churchill is limited by ice in the community area, where between 2010 and 2014 breakup was typically occurring in early July, freeze-up in early November, and the open water season was typically 126 days long.

2. What are the economics of a longer shipping season for marine re-supply (sealift)?
   - For shippers: A longer shipping season should provide an opportunity for a greater number of shipments to the study area. But are other gains possible? For example, might a longer shipping season allow a re-supply service based at one of the communities of the study area (e.g. Churchill)? Or could a longer season make possible new shipping routes or new types of cargo?
   - For communities: A longer season may allow a greater number of sealift deliveries each year. But are other benefits possible? For example, current operations for various community industries, such as construction and retail, may be limited by infrequent sealift; might increased sealift enable new efficiencies or opportunities?

Second, in my opinion the following research avenues could provide important information for the management of shipping in the study area:

1. Sea ice thickness in the study area: A better understanding of both the trends and variability in sea ice thickness would be useful for the modelling community and stakeholders in the shipping industry. At present there is very little information in the peer-reviewed literature and this constitutes a considerable research gap.
2. More current, precise data on shipping traffic: Though valuable, the published data presenting shipping traffic in the study area are highly imperfect. The Canadian government has a growing ability to monitor shipping vessels in the Arctic (section 3.2.2; Coast Guard 2013b). Ideally, higher quality data will be made available to researchers. This data would be valuable for a range of analyses and applications. For example, researchers could quantitatively examine the relationships between sea ice and shipping (similar to, but more precisely than, Pizzolato et al., 2014). The data would also be valuable for environmental risk analyses.
3. Ice prediction: How accurately can the timing of the sea ice in the study area be predicted, and how far in advance? Though quite basic, the analysis of relationships amongst breakup and freeze-up presented in this thesis suggests a possible avenue for ice prediction. Could a more sophisticated analysis of these relationships, partnered with the current capacity for monthly and seasonal temperature forecasting, provide relatively reliable predictions for sea ice several months in advance? If yes, these predictions would likely be of considerable value for shippers.

7. References

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