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POLICY BRIDGE

Climate change and sea ice: Shipping accessibility on the marine transportation corridor through Hudson Bay and Hudson Strait (1980–2014)

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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 $\leq$ 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.

Keywords: sea ice; shipping; breakup; freeze-up; Hudson Bay; Hudson Strait

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Introduction

A growing body of scientific evidence suggests that climate change is having a significant impact on sea ice conditions throughout the Canadian Arctic (Comiso, 2012; Vaughan et al., 2013). In the waters of Hudson Bay and Hudson Strait, climate change appears to be driving a trend towards longer ice-free periods during the summer and fall (Hochheim and Barber, 2014; Kowal et al., 2015). Sea ice is a defining element of the environment and culture of the Bay and Strait (e.g. Laidler at al., 2010; Joly et al., 2011; Durkalec et al., 2015), and climate-driven changes to ice conditions could produce enormous change in the region. One facet of this change is the potential growth in the shipping industry of the area, as lengthening ice-free periods enable longer shipping seasons (Pizzolato et al., 2014). This paper focuses on a scientific examination of sea ice timing along the shipping corridor through Hudson Strait and Hudson Bay to the Port of Churchill between 1980 and 2014.

Sea Ice in Hudson Bay and Hudson Strait

Figure 1 shows Hudson Bay and Hudson Strait and the course of the shipping corridor to the Port of Churchill. Articles in the scientific literature (e.g., Hochheim and Barber, 2014; Kowal et al., 2015) tend to define the border between the Bay and Strait as a line running north from the northwestern tip of mainland Quebec to the southwestern tip of Baffin Island. According to that definition the entire shipping corridor to the Port of Churchill is contained within the Bay and Strait. In this analysis, the portion of the corridor falling within the traditional area of Hudson Bay was further subdivided into two sections, "Hudson Bay" and the "Hudson Islands" (**Figure 1**), so as to examine differences in ice timing between the two sections.

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Hudson Bay and Hudson Strait, along with Foxe Basin to the north, are often treated as a relatively distinct component of the Canadian Arctic in the scientific literature (e.g., Joly et al., 2011; Hochheim and Barber, 2014). This treatment is partly because the Bay and Strait both undergo a complete freeze/melt cycle each year: the marine waters are entirely frozen in the winter and entirely ice-free in the summer and there is very little multi-year ice (Gagnon and Gough, 2005; Hochheim and Barber, 2014). The "typical" timing of sea ice in Hudson Bay is as follows: the Bay is entirely covered with first-year ice during the winter, breakup begins in the northeast and northwest in late May, the Bay is ice-free from late-July or mid-August until late-October or early November, and freeze-up is usually complete by early December (Tivy et al., 2011; Hochheim and Barber, 2014). Hudson Strait typically follows a similar pattern, though breakup tends to begin several weeks earlier and freeze-up tends to begin several weeks later (**Table 1**). Environment Canada's *Sea Ice Climatic Atlas for the Northern Canadian Waters 1981 – 2014,* which is based on charts from the Canadian Ice Service (CIS), presents 1981–2014 average breakup and freeze-up dates of July 16 and November 19 along the corridor to the Port of Churchill (Environment Canada, 2013; Andrews et al., 2016).

Describing the "typical" timing of sea ice in Hudson Bay and Hudson Strait is a challenge because of the considerable spatial and temporal variability in the timing of sea ice in the region. Moreover, research indicates that the lengths of the ice-free (or open water) seasons in the Bay and Strait have been growing quite rapidly since 1980.

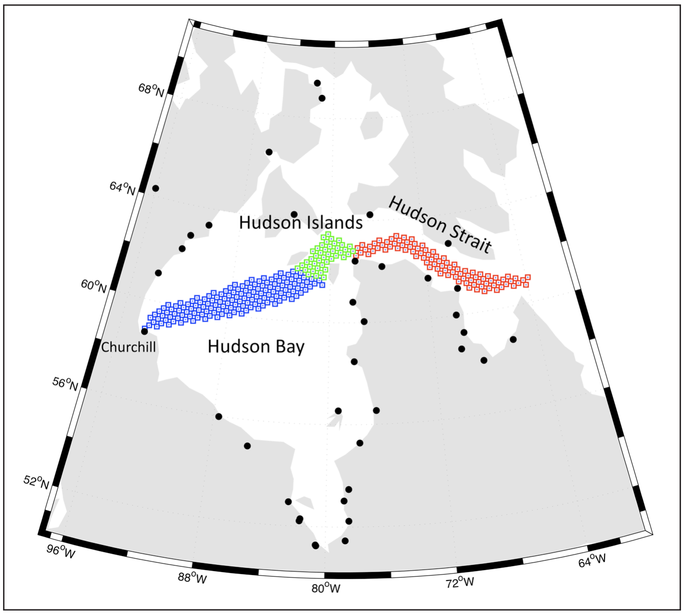

Figure 1: Hudson Bay, Hudson Strait, and the shipping corridor to the Port of Churchill. Hudson Bay, Hudson Strait, and Foxe Basin in the eastern Canadian Arctic are shown. The shipping corridor to the Port of Churchill is indicated with colored squares, subdivided into three sections for analysis: "Hudson 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. DOI: https://doi.org/10.1525/elementa.130.f1

Table 1: Ice timing in Hudson Bay and Hudson Strait[a,b]. DOI: https://doi.org/10.1525/elementa.130.t1

Timing and region	**Breakup**	**Freeze-up**	**Open Water**
Hudson Bay "typical" ice timing[a]	Late May to early August	Late October to early December	Late July or early August to late October
Hudson Strait "typical" ice timing[a]	Late May to early July	Mid-November to early December	Early July to mid-November
Hudson Bay average change 1996–2015 vs. 1980–1995[a]	10.5 days earlier	11.2 days later	21.7 days longer
Hudson Strait average change 1996–2015 vs. 1980–1995[a]	17.5 days earlier	16.8 days later	34.3 days longer
Hudson Bay 1970–2011 trend[b]	–0.49 days year^{-1}	+0.46 days year^{-1}	+0.91 days year^{-1}

[a] From Hochheim and Barber (2014).

[b] From Kowal et al. (2015).

Two recent publications in particular provide evidence of this rapid change (**Table 1**).

First, Hochheim and Barber (2014) used a 2011 version of the Comiso (2000) dataset on passive microwave-based sea ice concentration hosted by the National Snow and Ice Data Centre (NSIDC) to examine changes in breakup and freeze-up timing in Hudson Bay, Hudson Strait, and Foxe Basin between 1980 and 2010. The Comiso (2000) dataset presents data in 25 km by 25 km "pixels". Defining the open water threshold as the point where 50% of the pixels in a given sample area have ice concentrations below 60%, Hochheim and Barber (2014) found strong trends in ice timing over the 30-year time period. Comparing the ice seasons of 1996–2010 with those of 1980–1995, the authors found a mean lengthening of 3.1 weeks in the open water season in Hudson Bay with breakup occurring 1.5 weeks earlier and freeze-up occurring 1.6 weeks later, on average. The mean change for Hudson Strait was +4.9 weeks in the length of the open water season for 1996–2010 vs. 1980–1995, with breakup 2.5 weeks earlier and freeze-up 2.4 weeks later, on average (Hochheim and Barber, 2014).

Kowal et al. (2015) used CIS ice charts to examine the timing of sea ice in Hudson Bay between 1970 and 2011. The CIS ice charts for the Canadian Arctic are produced on a weekly basis and are the product of expert interpretation of remote-sensing imagery (principally Synthetic Aperture Radar since 1996, but also passive microwave, visual, and infrared data). Kowal et al. (2015) extracted ice concentration data from the weekly charts for 36 points in Hudson Bay in order to analyze breakup and freeze-up dates between 1970 and 2011 (note: these 36 points were first established by Gagnon and Gough, 2005). The authors defined breakup to have occurred at a point when the ice concentration fell below 50% during the summer months, while freeze-up was recorded as the earliest date where ice concentration at a point rose above 50% during the fall. The authors found that between 1970 and 2011, 23 of the 36 points had a statistically significant trend towards earlier breakup, with significant trends ranging from –0.09 to –1.2 days year^{-1} and an average trend of –0.49 days year^{-1} across all 36 points (Kowal et al., 2015). During the same time frame, 34 of 36 points had a statistically significant trend towards later freeze-up, with significant trends ranging from 0.32 to 0.69 days year^{-1} and an average trend of 0.46 days year^{-1} across all points (Kowal et al., 2015). Finally, 31 of 36 points displayed significant trends towards longer open water seasons, with significant trends ranging from 0.41 to 1.6 days year^{-1} and an average of 0.91 days year^{-1} for all points together (Kowal et al., 2015).

Despite using different datasets and different definitions for breakup and freeze-up, both Hochheim and Barber (2014) and Kowal et al. (2015) clearly demonstrate that the open water season is becoming significantly longer in Hudson Strait and Hudson Bay.

Shipping in Hudson Bay and Hudson Strait

Shipping regulations

The Canadian government regulates shipping in Hudson Bay and Hudson Strait. Shipping regulations vary between the waters of the Bay and Strait 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, 2010a). 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, 2010a). 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, 2010a). 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, and in the waters of Hudson Strait between July 20 and November 5 (Transport Canada, 2010a; Andrews et al., 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, 2010b). Because of this fixed status, 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, 2010a). 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, 2010c; Andrews et al., 2016). Under the AIRSS, non ice-strengthened shipping vessels may travel the waters north of 60°N in Hudson Bay and Hudson Strait outside of the windows of the Zone/Date System when conditions permit; however, 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, 2013). 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, 2013).

Shipping traffic volumes

There are relatively few data in the academic literature describing shipping traffic in the Canadian Arctic. Nearly all estimates of shipping traffic in the Canadian Arctic (e.g., Judson, 2010; Pizzolato et al., 2014; Dawson, 2016; Oceans North Canada, 2016) are based on data collected by the Canadian Coast Guard (CCG) for the NORDREG Zone. Between 1990 and 2010, vessels travelling in the NORDEG Zone were requested to voluntarily submit position reports to the CCG. Since 2010, vessels with gross tonnage in excess of 300 tonnes have been required to submit position reports but reporting has remained voluntary for smaller vessels (Canadian Coast Guard, 2013). This mixture of voluntary and mandatory reports compiled by the CCG since 1990 represents the main source of data on shipping traffic in the Canadian Arctic.

Analyses of traffic data for the NORDREG Zone suggest that shipping is growing in response to a lengthening of the open water season in the Canadian Arctic (Pizzolato et al., 2014; Dawson et al., 2016). The studies reporting on traffic data in the NORDREG Zone typically use two metrics to discuss traffic: the number of vessels and the number of voyages; it is important to differentiate between the two metrics when considering traffic reports. The number of voyages in the Canadian Arctic each year is clearly on the rise. According to the NORDREG Zone data, roughly 140 vessels completed between 300 and 350 voyages into the Zone each year between 2010 and 2013 (Pizzolato et al., 2014; Dawson et al., 2016; Oceans North Canada, 2016). This number of voyages is considerably higher than the values of 100–175 voyages per year recorded between 1990 and 2006 (Dawson et al., 2016). With regard to the number of vessels in the Zone, Pizzolato et al. (2014) concluded that there was no significant trend in the number of vessels visiting the Zone each year between 1990 and 2012; however, the authors did find a significant increase in the number of vessels visiting during the so-called "shoulder season" months of June, July, and November (Pizzolato et al., 2014).

There is comparatively little analysis of traffic volumes and trends for regions within the broad area of the NORDREG Zone. Judson (2010) reports that shipping traffic in Hudson Strait is almost twice as high as in any other region in the Canadian Arctic, with over 3,400 "ship days" (the total number of days spent by all vessels in the region added together) between 2007 and 2014. The majority of the shipping traffic in Hudson Bay appears to be concentrated along the corridor across the Bay to Churchill (Judson, 2010), but it is difficult to estimate typical traffic volumes for the region.

Shipping traffic in Hudson Bay and Hudson Strait is expected to continue growing at current or accelerated rates in the coming decades (Dawson et al., 2016; Oceans North Canada, 2016). A number of industries are expected to drive increased shipping in the region as the open water season in the area continues to lengthen. For example, shipping generated by the mining industry is expected to grow quite rapidly in the near future: there are currently two mining projects shipping through the Bay and Strait during the open water season (the Meadowbank gold mine near Baker Lake and the Raglan nickel mine in Northern Quebec), and five more projects currently in the exploration or development phase could begin to ship through the region before 2020 (Gavrilchuk and Lesage, 2014). In addition to mining, there is also considerable potential for increased shipping in Hudson Bay and Strait related to the tourism industry, the community re-supply industry, and the Port of Churchill (Andrews et al., 2016; Dawson et al., 2016).

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).

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).

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.

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 et al., 1996) 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 et al., 2008; Meier et al., 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 1**). The colored squares in **Figure 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 25 x 25km 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 1**.

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, 2010c). Ice concentrations of ≤ 15% have been used as shipping-enabling thresholds elsewhere in the literature. For example, Bensassi et al. (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.

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.

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 (e.g., **Figure 6**). 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.

Results

Sea ice on the shipping corridor: Current timing and 1980–2014 trends

Figure 2 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 the Cavalieri et al. (1996) dataset into the current timing of sea ice on the corridor. Breakup on the corridor now typically

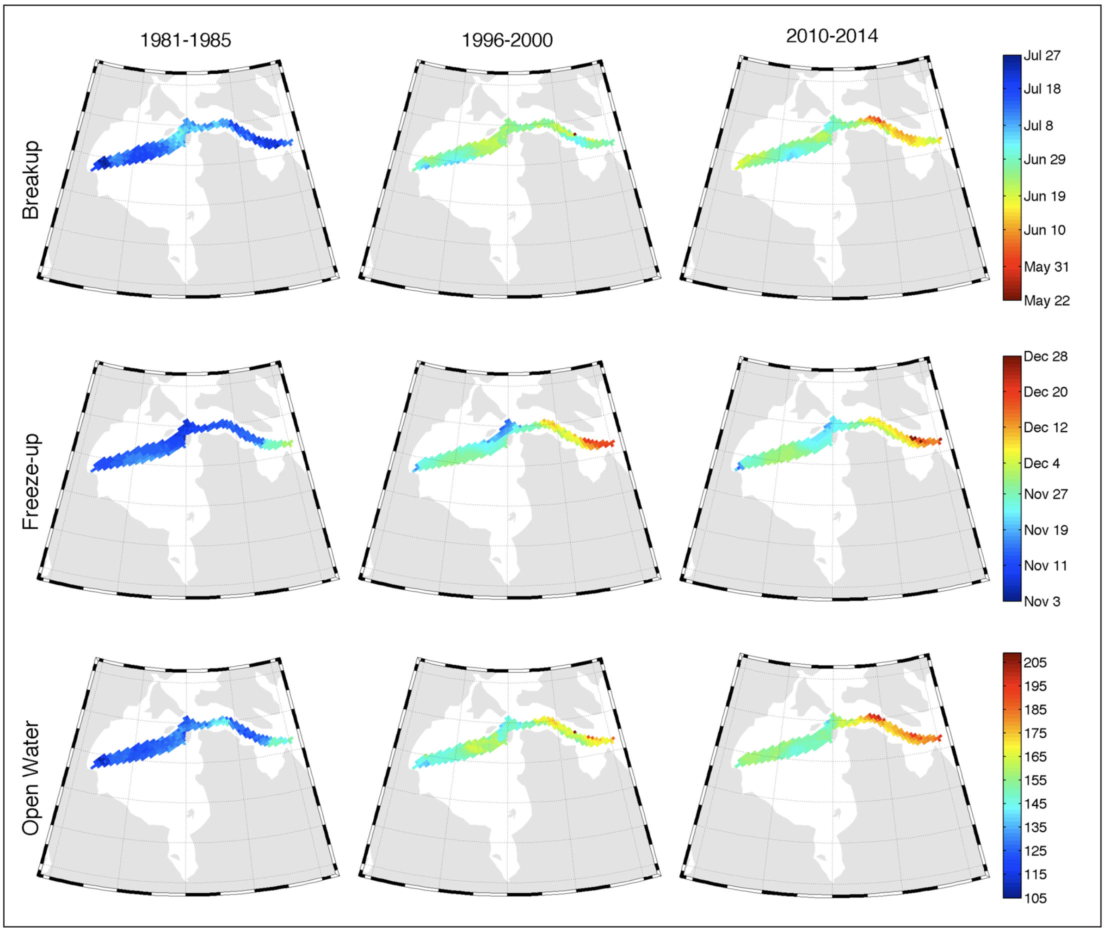

Figure 2: Sea ice timing along the shipping corridor to the Port of Churchill. The timing of breakup, freeze-up, and the open water season are compared for the periods 1981–1985, 1996–2000, and 2010–2014. Maps were generated by calculating the five-year median value for each pixel in the corridor and then assigning a color to that pixel's location on the map. The 5-year window was used to capture inter-annual variation. This figure is provided to help visualize the current (2010 – 2014) timing of sea ice on the corridor and the changes in ice timing over recent decades. DOI: https://doi.org/10.1525/elementa.130.f2

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 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 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. 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 4**): 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 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.

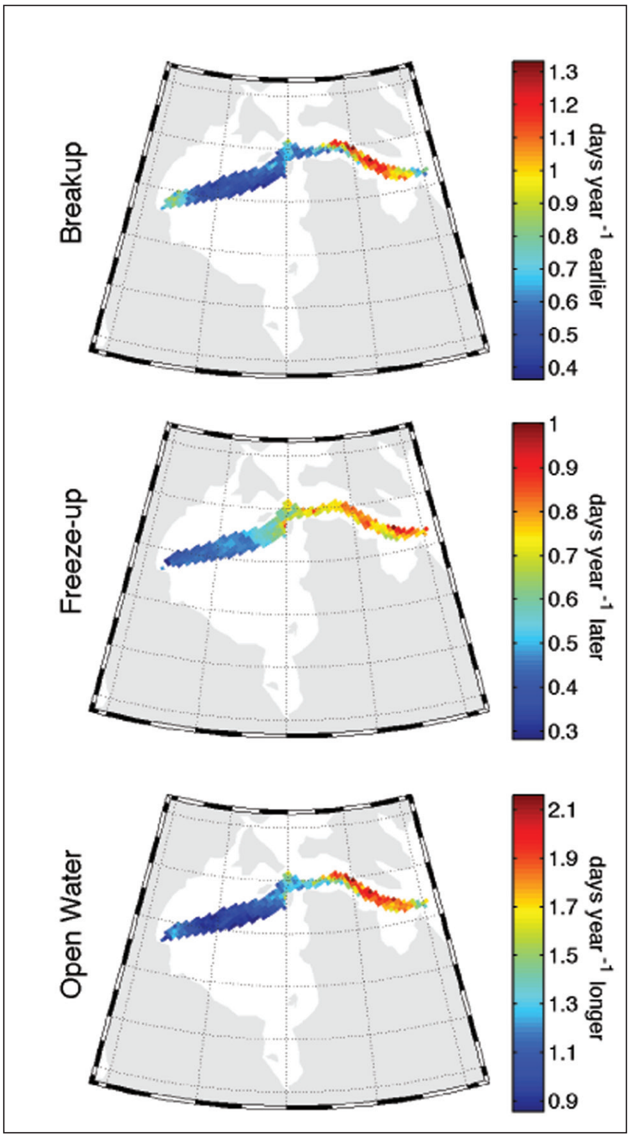

Figure 3: 1980–2014 trends in breakup, freeze-up, and open water for the pixels of the corridor. The 1980–2014 trends in breakup date, freeze-up date, and open water season length are shown for the pixels of the shipping corridor. Trend values are the slope of the linear regression line for each pixel and only significant trends (p-value > 0.05) are shown. DOI: https://doi.org/10.1525/elementa.130.f3

Spatial variability in ice timing within the corridor

As indicated by the 2010–2014 median values displayed in **Figure 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 2**). 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 2**.

The 1980–2014 time series for the three different sections of the shipping corridor (**Figures 5** and **6**) 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 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

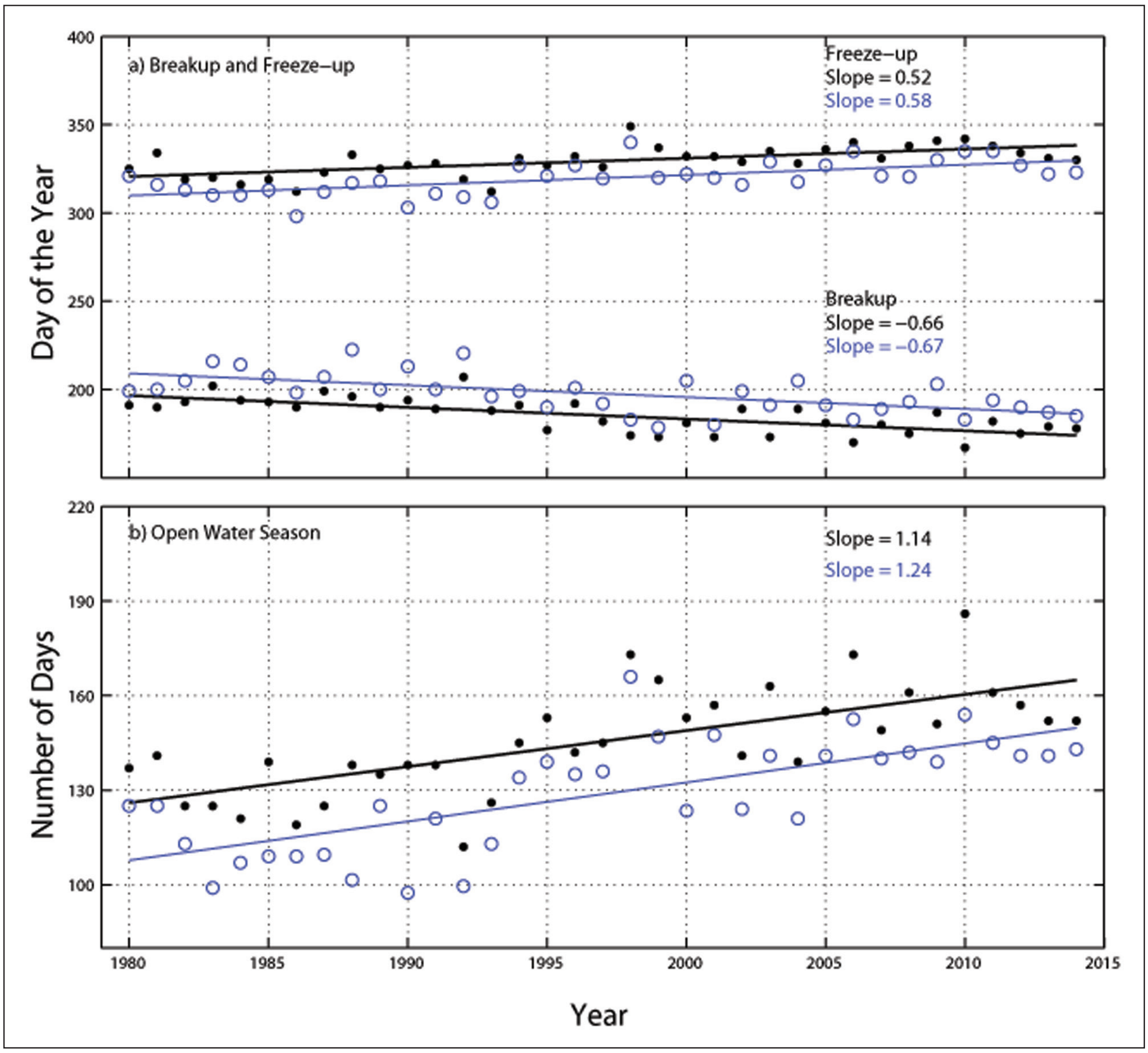

Figure 4: 1980–2014 breakup, freeze-up, and open water season for the shipping corridor. This time series shows breakup, freeze-up, and the length of the open water season on the shipping corridor to the Port of Churchill between 1980 and 2014. The annual median value for the 281 pixels on the shipping corridor is indicated by solid black circles; the annual median value for the 10% of pixels with the most restrictive ice timing in each year is 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}. DOI: https://doi.org/10.1525/elementa.130.f4

Table 2: Median values for the 2010–2014 timing of sea ice on the shipping corridor by section. DOI: https://doi.org/10.1525/elementa.130.t2

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 values**
Hudson Bay	June 29 (June 16–July 6)	June 29	November 29 (November 18–December 3)	December 1	153 (146–159)	156
Hudson Islands	June 30 (June 23–July 6)	June 22	November 24 (November 18–December 3)	November 29	153 (146–173)	161
Hudson Strait	June 17 (June 1–June 22)	June 17	December 8 (November 26–December 27)	December 14	177 (160–200)	184

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

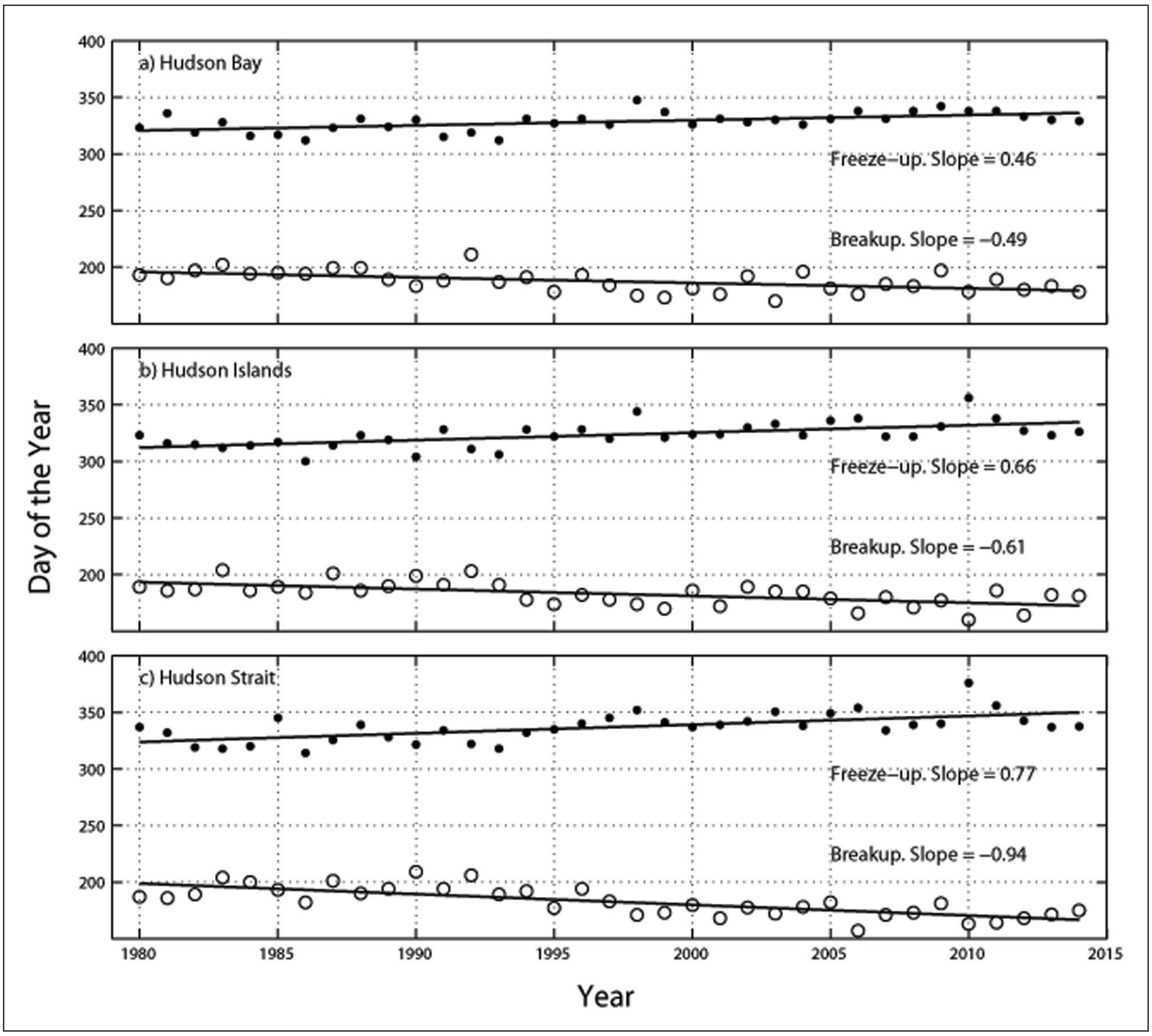

Figure 5: 1980–2014 breakup and freeze-up timing for the three sections of the shipping corridor. This time series shows breakup (open circles) and freeze-up (solid circles) on the Hudson Bay, Hudson Islands, and Hudson Strait sections of the corridor between 1980 and 2014, where data points indicate 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. DOI: https://doi.org/10.1525/elementa.130.f5

linear regression of the 1980 to 2014 time series for the three different sections (**Table 3**): 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 5** and **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.

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**. 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**).

Figure 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

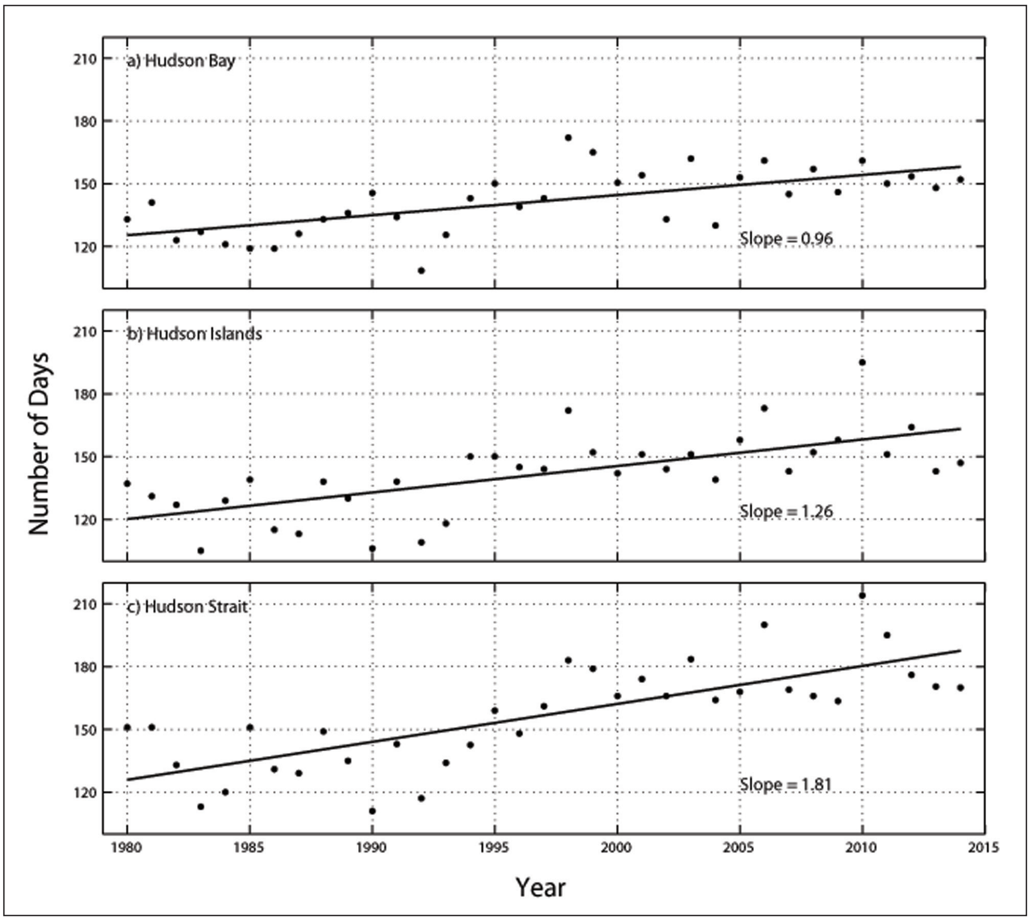

Figure 6: 1980–2014 open water season length for the three sections of the shipping corridor. This time series shows the length of the open water season on the Hudson Bay, Hudson Islands, and Hudson Strait sections of the corridor between 1980 and 2014, where data points indicate the annual median values 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. DOI: https://doi.org/10.1525/elementa.130.f6

Table 3: Characteristics of the 1980–2014 datasets and their regression lines[a] by corridor section. DOI: https://doi.org/10.1525/elementa.130.t3

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 (November 24) ± 8.39, 323 (November 19) ± 11.18, 337 (December 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 ($p < 0.05$).

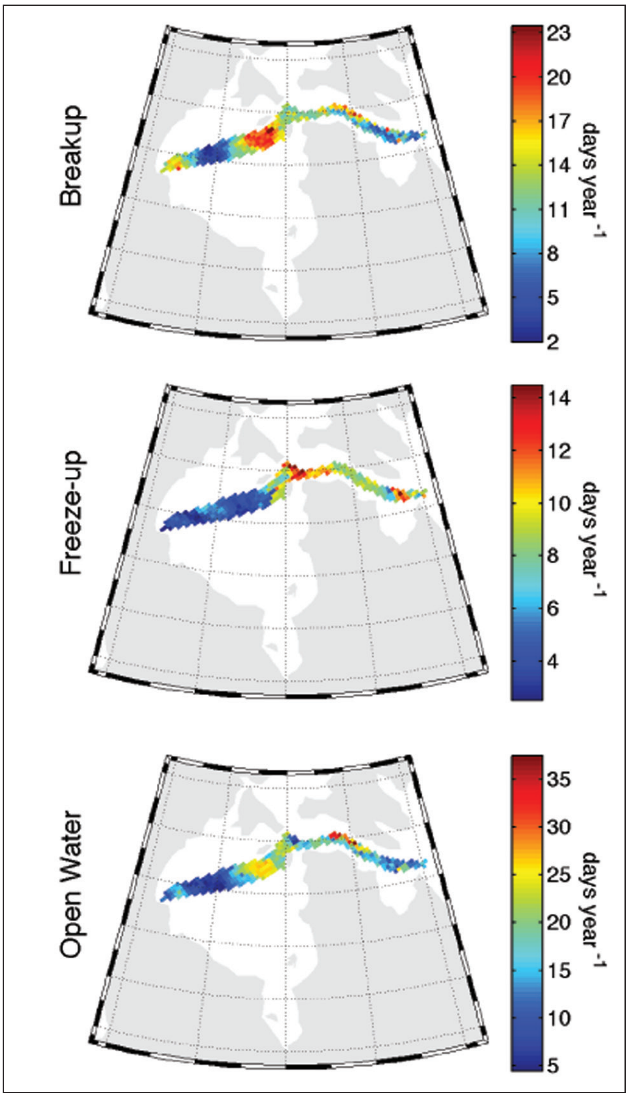

Figure 7: 2005–2014 Following-year Difference along the shipping corridor. Median following-year difference in breakup, freeze-up, and the length of the open water season is shown for 2005–2014. Maps were generated by calculating the ten-year median value for each pixel in the corridor and then assigning a color to that pixel's location on the map. DOI: https://doi.org/10.1525/elementa.130.f7

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.

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.

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

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 4**). 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 8**), that freeze-up one day later corresponds to breakup 0.42–0.74 days earlier the next year (**Figure 9**), and that a one day longer open water season corresponds to breakup 0.23–0.39 days earlier the next year (**Table 4**). 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).

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, 2010b), though vessels can travel outside these dates using the Arctic Ice Regime Shipping System (Transport Canada, 2010c). 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 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 2**). 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

Table 4: Characteristics of relationships among breakup, freeze-up, and open water season length by corridor section. DOI: https://doi.org/10.1525/elementa.130.t4

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 ($p < 0.15$).

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**). 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 (**Table 1**). 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 (November 16 vs. November 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 and Barber, 2014;

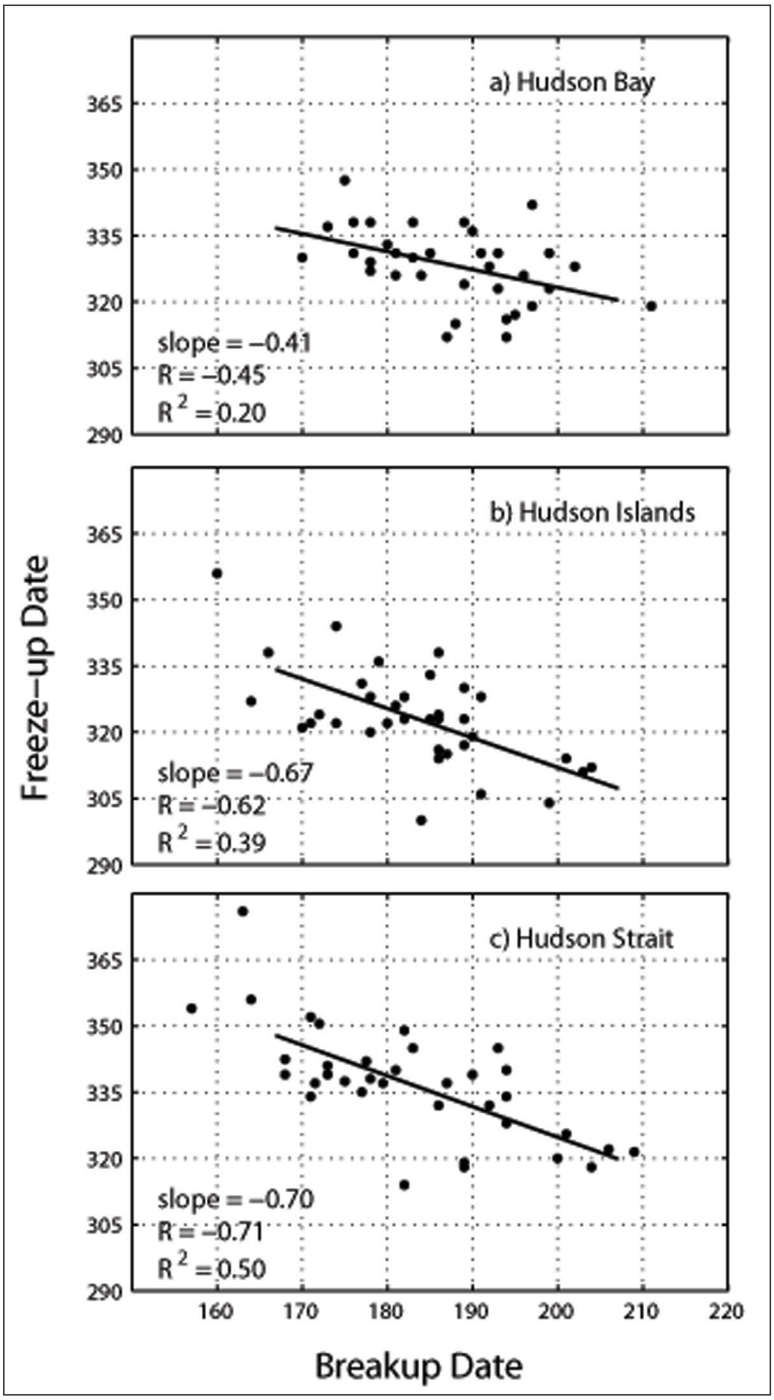

Figure 8: Freeze-up date as a function of breakup date for the three sections of the corridor. Median freeze-up date is shown as a function of median breakup date for 1980–2014. The slope of each regression line is significant at the 99% confidence level ($p < 0.01$). Slope units are days day^{-1}. Characteristics of the datasets and regression lines are displayed in Table 4. DOI: https://doi.org/10.1525/elementa.130.f8

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

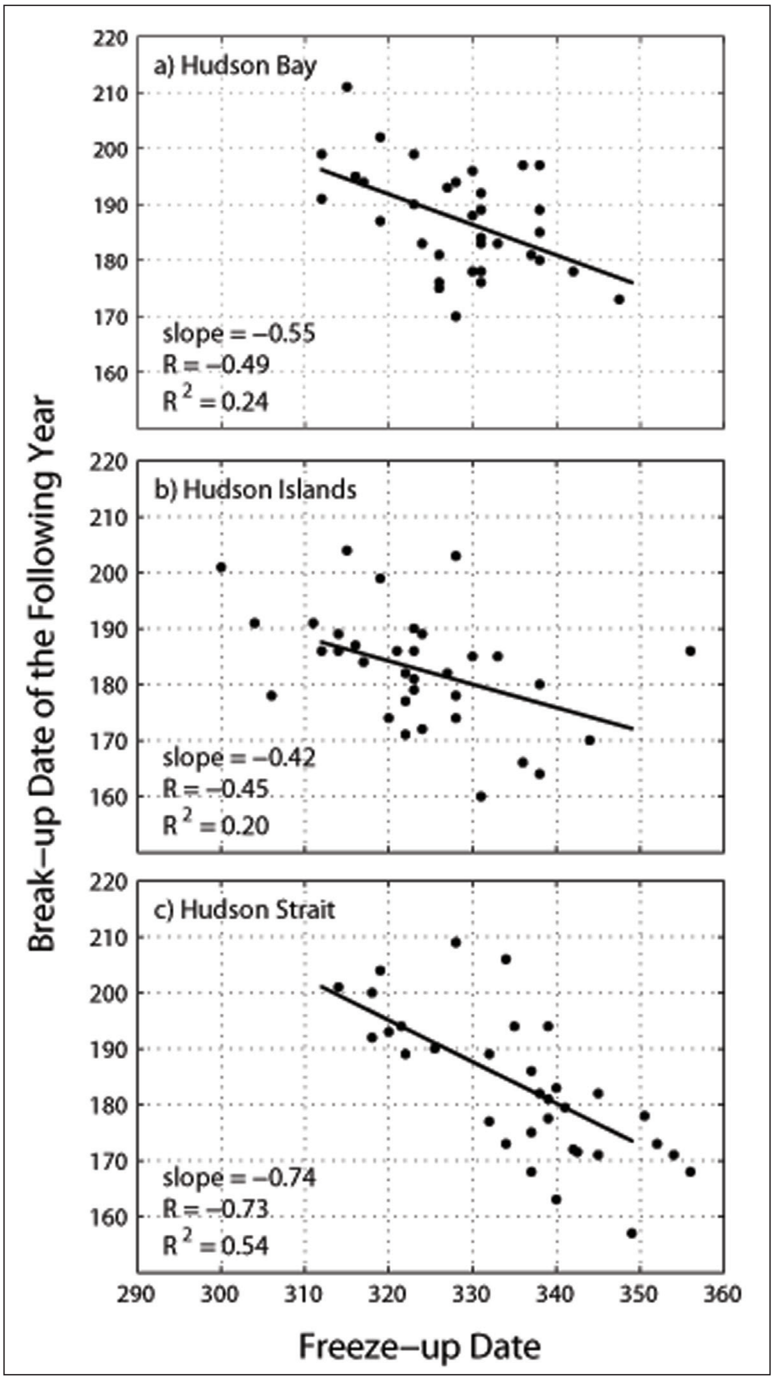

Figure 9: Break-up as a function of freeze-up the year before (1981–2014). The relationship between median freeze-up date (x-axis) and median breakup date of the following year (y-axis) is shown for 1981 to 2014. The slope of each regression line is significant at the 99% confidence level ($p < 0.01$). Slope units are days day^{-1}. Characteristics of the datasets and regression lines are displayed in Table 4. DOI: https://doi.org/10.1525/elementa.130.f9

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 7** and **Table 3** 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 4**) 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 and 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 our 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.

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.

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Competing interests

The authors have no competing interests to declare.

Contributions

- Contributed to conception and design: JA, DBabb, DBarber
- Contributed to acquisition of data: N/A – data downloaded from NSIDC website.
- Contributed to analysis and interpretation of data: JA, DBabb, DBarber
- Drafted and/or revised the article: JA, DBabb, DBarber

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