Impacts of Climate Change on Navigational Choke Points for Ships Operating in the Canadian Arctic

Prepared for Innovation and Policy Branch of Transport Canada

by

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NOTICES

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Un sommaire français se trouve avant la table des matières.

EXECUTIVE SUMMARY

Climate change is causing a reduction in sea ice extent and thickness in the Canadian Arctic, while simultaneously increasing the mobility of hazardous sea ice. This situation creates navigational challenges for Arctic ship operations. The operational risks vary depending on the Ice Class (i.e. level of ice strengthening) of the vessel and on the extent to which sea ice is prevalent and changing in the regions where ships operate.

Locations where sea ice is frequently present throughout a shipping season, impeding travel along routes that are otherwise largely ice free, have been called choke points in previous studies (e.g., Stewart et al., 2007; Xu et al., 2011). These are regions that could pose higher than average risks, particularly if sea ice is becoming more mobile and drifting into shipping corridors. This study analyzes how climate change is influencing navigational risks to ships in these regions based on changing sea ice conditions and on the changing composition of ships by:

1) Creating a temporal and spatial inventory of historic shipping traffic by the vessel Ice Class (1990-2017)
2) Examining the geographic areas that have been identified as sea ice choke points
3) Analyzing the changing level of risk to ships during early-season (~June 25), mid-season (~Sept. 3) and late-season (~Oct. 15) conditions by comparing historic ship traffic by Ice Class at the identified choke points

Results reveal that over the 27 year period since 1990 there has been a marked reduction in the voyages of highly strengthened PC3 ships, but large increases in the number of voyages of ships with medium ice strengthening (PC7) and little ice strengthening (Ice Class 1B[1]). In addition, there are many more voyages by non-ice strengthened ship types occurring throughout the Northwest Passages in the 2010s than in the 1990s.

Despite recent easing of navigational conditions in the Canadian Arctic due to reductions in sea ice, there is no clear evidence of a coincident reduction in risks to ships due to:

1. An overall increase in the number of ships in the region, in a location where there is a lack of infrastructure and support services (e.g., Search and Rescue) for vessels.
2. The increased mobility of sea ice, particularly for areas of hazardous multi-year ice that are now able to enter the interior channels of the Canadian Arctic from the Arctic Ocean.
3. A rapid increase in the occurrence of non-ice strengthened vessels: for example, when looking at Somerset Island, only one vessel reported in this class in the 1990s, but 87 out of 253 reported in this class in 2012-17.
4. No clear evidence that the reduction in average ship strength is occurring at the same rate as the easing in sea ice navigability.

[1] Ice Class 1B may also include some non-ice strengthened vessels due to NORDREG reporting inconsistencies and disparities in ice classification conversion.

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Definitions and Glossary

AMSA: Arctic Marine Shipping Assessment

CAA: Canadian Arctic Archipelago

Choke points: Locations where sea ice is frequently present throughout a shipping season, impeding travel along routes that are otherwise largely ice free. These are regions that could pose higher than average risks to ships, particularly if sea ice is becoming more mobile and drifting into common shipping corridors.

Closing date: last week of the year when navigation is possible

MCTS: Marine Communications and Traffic Services: centres operated by the Canadian Coast Guard to monitor and assist marine traffic

MMSI: Maritime Mobile Service Identity: a series of 9 digits that uniquely identifies ships

Non-spatial database: a list of all ships which reported in the NORDREG zone between 1990 and 2018 (n=1227), including their characteristics

NORDREG zone: Northern Canada Vessel Traffic Services zone. This region encompasses all Canadian Arctic waters, including the Arctic Bridge through Hudson Strait and Hudson Bay, and the Northwest Passages through the Canadian Arctic Archipelago

Ice Class: classification system for determining ship hull strength based on the type of ice that can be safely navigated

Spatial database: voyage tracks produced from >100,000 reports made by all vessels in the NORDREG zone between 1990 and 2017.

Northwest Passages: a series of sea passages through the Canadian Arctic Archipelago that connects the North Atlantic Ocean to the Beaufort Sea and North Pacific Ocean

Opening date: first week of the year when a vessel can safely navigate into an area

Polar Code: the International Maritime Organizations International Code for Ships Operating in Polar Waters, covering the design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to ships operating in the polar regions.

1.0 Introduction

There has been a marked reduction in sea ice age and extent in the Canadian Arctic over the past several decades (Serreze and Stroeve, 2015; Kwok, 2018), and at the same time there has been a period of rapid increase in ship traffic (Pizzolato et al., 2014; Dawson et al., 2018). For example, the distance traveled by ships in Arctic Canada increased by >250% from 364,179 km in 1990 to 918,266 km in 2015 (Dawson et al., 2018). The fastest growing vessel type by far has been Pleasure Craft, such as private yachts, which travelled a total average distance of 2590 km/yr in the 1990s, 13,580 km/yr between 2006-2010 and 52,799 km/yr between 2011-2015. The number of Passenger Ships for the purpose of cruise tourism have remained relatively constant over this period, while total distance traveled by General Cargo ships has increased dramatically and has become the vessel type that travels the greatest distance by km annually (Johnston et al., 2017; Dawson et al., 2018). Some studies have demonstrated significant correlations between these increases in ship traffic and reductions in sea ice concentration in regions such as the Beaufort Sea, Northwest Passage and Western Baffin Bay (Pizzolato et al., 2016).

In addition to regional decreases in sea ice age, thickness and extent (Mudryk et al., 2018), there is also a corresponding increase in the general variability of sea ice in the Canadian Arctic, particularly in the central part of the Northwest Passages (Haas and Howell, 2015). That is, areas which previously experienced little change in sea ice age or type from one year to the next are now experiencing rapid swings in ice characteristics between years that are less predictable than in the past. In some years there are large regions of open water, but in other years extensive thick multi-year sea ice floes reach the interior channels of the Canadian Arctic Archipelago from the Arctic Ocean. This is because increased temperatures appear to be increasing sea ice mobility, with the removal of first-year ice in the Northwest Passages now allowing greater import of old, thick ice from regions to the north. For example, Howell et al. (2013) reported that the inflow of multi-year ice into the channels of the Northwest Passages increased between 2005-2012 due to the import of additional ice from the Arctic Ocean which has become more mobile.

Given this background, the reality is that sea ice in the Canadian Arctic still presents a significant navigational challenge for most shipping, particularly in more northerly regions and throughout the Northwest Passages (Howell and Yackel, 2014; Tseng and Cullinane, 2018). In fact, it is possible that risks to shipping are increasing and are higher than in the past due to increased sea ice mobility, which is causing ‘choke points’ along typical shipping corridors in the Canadian Arctic. To date there has been no systematic study undertaken of these risks based on the use of actual shipping records with a statistically significant duration (>25 years). In response to this knowledge gap, in this report we present:

(i) The details of all ships that transited the NORDREG zone between 1990 and 2018;

(ii) Details of changes in shipping traffic at 3 ‘choke points’ between 1990 and 2017, including distance travelled, type and number of vessels, and Ice Class of vessel;

(iii) Changes in sea ice characteristics at the 3 ‘choke points’ over the study period;

(iv) An examination of the changing seasonality of shipping traffic by Ice Class, including opening and closing dates of the shipping season permitted by Canadian regulations; and

(v) Discussion of the changing level of risk for ships operating in choke points in the Canadian Arctic.

2.0 Study Area

This report provides an assessment of shipping movements and sea ice conditions within the NORDREG (Northern Canada Vessel Traffic Services) zone. This region encompasses all Canadian Arctic waters, including the Arctic Bridge through Hudson Strait and Hudson Bay, and the Northwest Passages through the Canadian Arctic Archipelago (CAA) (Fig. 1). The Northwest Passages can be split into two primary routes: the more commonly used southern shallow water route which passes to the south of Victoria Island (past Cambridge Bay), and a less commonly used northern deep water route which extends thorough Parry Channel to the west of Resolute. Both routes share the same eastern entrance to the Canadian Arctic Archipelago through Lancaster Sound, near to Pond Inlet, with most ships (estimated at >95%) using the southern route past Cambridge Bay due to easier sea ice travel conditions. The more hazardous ice conditions of the northern route are influenced by the import of increasingly mobile sea ice that drifts south in the CAA from the Arctic Ocean. This dynamic import of ice is expected to continue into the medium term future as a result of ongoing climate change.

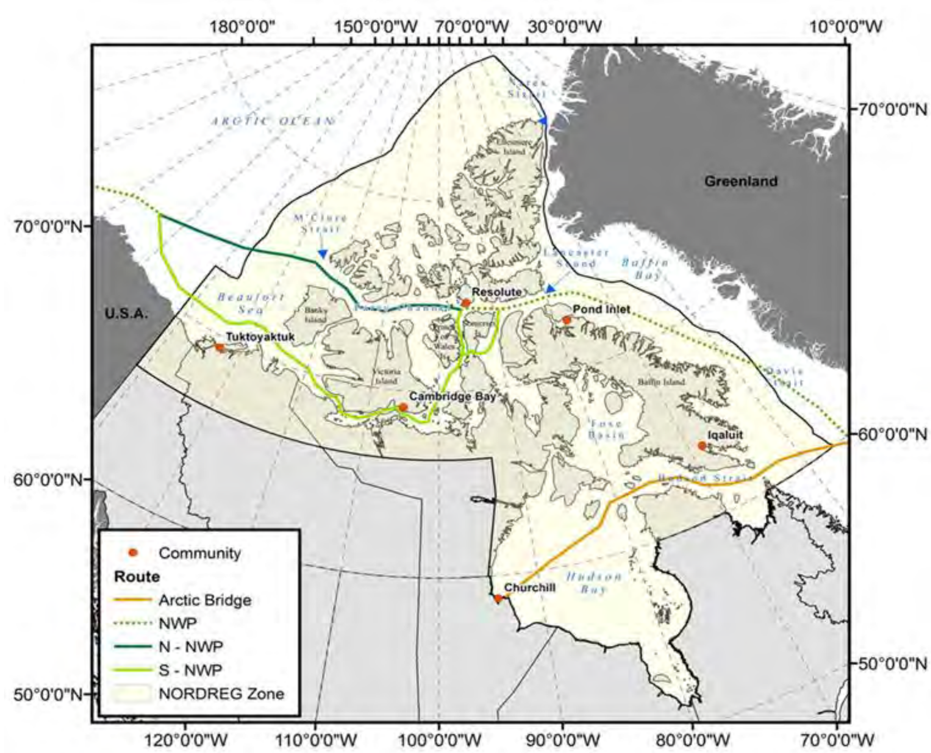


Figure 1. Map of the NORDREG zone in the Canadian Arctic (yellow region), together with the locations of primary shipping routes. Source: Justice Laws (2010), Dawson et al. (2016).

3.0 Shipping Trends

3.1 Shipping Databases

3.1.1 NORDREG reporting

The NORDREG zone describes the region in the Canadian Arctic (Fig. 1) in which vessels provide reporting of their position and vessel information (e.g., name, flag state, call sign, MMSI[2] number) to the Canadian Coast Guard. According to the Canada Shipping Act (Justice Laws, 2010), the following ships must report their position immediately after first entering the zone, before exiting the zone, when encountering a hazardous situation (e.g., vessel in difficulty, hazardous weather or ice conditions, pollutant in water) and at 16:00 UTC daily:

a) vessels of 300 gross tonnage or more;
b) vessels that are engaged in towing or pushing another vessel, if the combined gross tonnage of the vessel and the vessel being towed or pushed is 500 gross tonnage or more;
c) vessels that are carrying as cargo a pollutant or dangerous goods, or that are engaged in towing or pushing a vessel that is carrying as cargo a pollutant or dangerous goods

Other vessels (e.g., small pleasure craft) may also provide voluntary reports if they fall outside of these categories. Overall, it has been reported that 98% of all ships operating in the NORDREG zone notify the Canadian Coast Guard of their presence (Rompkey and Cochrane, 2008), in part due to the advantages accompanied with reporting such as enhanced search and rescue response (also see Johnston et al., 2017).

The data used in this report were collated from ship reports made to the Canadian Coast Guard Marine Communications and Traffic Services (MCTS) office, located in Iqaluit. The primary vessel types recorded in the NORDREG database and identified by the Arctic Council are listed in Table 1. Below, we first describe the 'non-spatial' database, which provides the names and characteristics of all vessels which registered in the NORDREG zone between 1990 and 2018. After that we describe the 'spatial' database, which provides the locations of all known ships within the NORDREG zone between 1990 and 2017.

[2] Maritime Mobile Service Identity: a series of 9-digits that uniquely identifies ships

Table 1: Main vessel types (AMSA class) found in the NORDREG zone. After Arctic Council (2009), Dawson et al. (2016).

Classification	Description	Examples
Government Vessels and Icebreakers	- Designed to move and navigate in ice-covered waters - Must have a strengthened hull, an ice-clearing shape, and the power to push through ice	- Icebreakers (private, research, government) - Research vessels
Container Ships	- Cargo ships that carry their load in truck-size containers	- Cargo transport
General Cargo	- Carries various types and forms of cargo	- Community resupply - Roll on/roll off cargo
Bulk Carriers	- Bulk carriage of materials	- Timber, oil, ore - Automobile carriers
Tanker Ships	- Bulk carriage of liquids or compressed gas	- Oil, natural gas, chemical tankers
Passenger Ships	- Ships that carry paying passengers	- Cruise ships - Ferries
Pleasure Craft	- Recreational vessels that do not carry passengers for remuneration	- Motor yachts - Sail boats - Row boats
Tug / Barge	- Tug: designed for towing or pushing - Barge: non-propelled vessel for carriage of bulk or mixed cargo	- Used for resupply - Bulk cargo transport
Fishing Vessels	- Used in commercial fishing activity	- Small fishing boats - Trawlers - Fish processing boats
Oil and Gas Exploration Vessels	- Designed for the exploration and extraction of natural gas and oil	- Seismic, hydrographic, oceanic survey vessels - Offshore resupply - Portable oil platform

3.1.2 Non-spatial NORDREG Database (1990-2018)

All non-spatial datasets were provided by MCTS in spreadsheets in 5-year intervals since 1990. These were combined into one table, with duplicates removed and the names of ships standardized (occasionally minor typos and differences in ship name were recorded). This left one line per ship, with its most recent time interval displayed (i.e. the last time it was in the NORDREG zone). Attributes were separated into appropriate fields (e.g. "dimensions" into length, width and draught columns), and initial quality checking of these values undertaken using public databases and websites (e.g., https://www.marinetraffic.com). Future refinement of these values may be required due to errors in some MCTS reports and inconsistencies between reported values for the same ship and between various databases.

The final database contains up to 18 attributes per vessel, as detailed in Table 2. The full list of vessels and their attributes is available in a database housed in the Laboratory for Environment, Society, and Policy at the University of Ottawa, and is available upon request (email Jackie.dawson@uottawa.ca).

An important focus for this report is the ice classification of hull strength for ships reporting within the NORDREG zone. MCTS records this information as provided by individual vessels, which encompasses a variety of different classification systems (e.g., ASPPR: Arctic Shipping Pollution Prevention Regulations; Lloyd's, Finnish-Swedish). To standardize these classifications into a single system, Table 3 was used to provide an Ice Class comprising the Polar Class and ice strengthening of each vessel as defined by the International Association of Classification Societies and International Maritime Organization (American Bureau of Shipping, 2016). The conversion between class systems is not exact, but the closest corresponding values were chosen, using the sources and weblinks listed in Table 3. Throughout this report, the term Ice Class 1B primarily refers to vessels with little ice strengthening; however, Ice Class 1B may also include some non-ice strengthened vessels, due to NORDREG reporting inconsistencies and disparities in ice classification conversions.

Table 2. Vessel attributes reported in the non-spatial NORDREG database

Number	Attribute	Description
1	Ship name	Vessel name, as recorded in files from Canadian Coast Guard Marine Communications and Traffic Services
2	Latest Period	Last period the ship entered NORDREG
3	Call Sign	Call sign (during last known period)
4	IMO	International Maritime Organization ship identification number
5	MMSI	Maritime Mobile Services Identity number
6	Flag	Flag state of vessel
7	Type of Vessel	Type of vessel (in MCTS files)
8	AMSA Class	Arctic Marine Shipping Assessment Class
9	Length (m)	Length of vessel in metres
10	Breadth (m)	Breadth of vessel in metres
11	Draught (m)	Draught of vessel in metres
12	HP (Engines)	Horsepower of vessel engines
13	KW (Engines)	Kilowatt power of vessel engines
14	GRT (Tonnage)	Gross register tonnage = ship's total internal volume expressed in "register tons", each of which is equal to 100 cubic feet (2.83 m^3)
15	NRT (Tonnage)	Net register tonnage = internal volume available for carrying cargo (i.e., GRT excluding spaces not available for carrying cargo, such as engine rooms, fuel tanks and crew quarters)
16	DWT (Tonnage)	Deadweight tonnage = how much weight ship can carry (sum of cargo, fuel, fresh water, ballast water, provisions, passengers and crew)
17	MCTS Ice Class	Ice Class of ship as provided in files from Canadian Coast Guard Marine Communications and Traffic Services
18	Ice Class	Ice Class: ice classification based on the MCTS Ice Class and Table 3 below

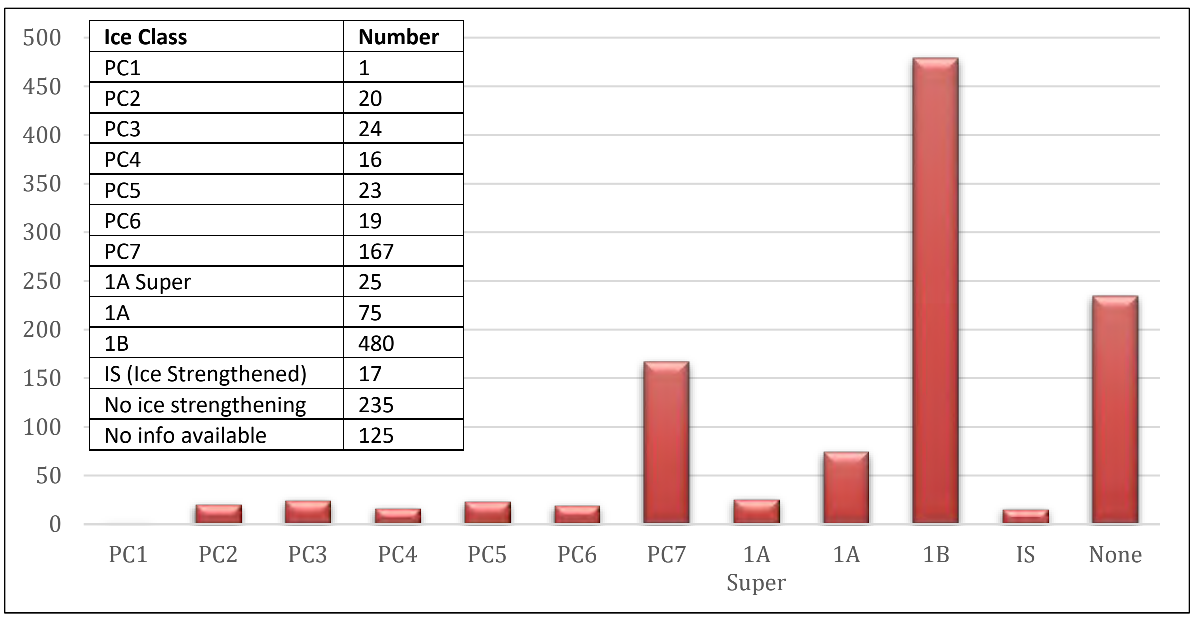
Table 3. Ice Class conversion table between different ice classification systems for hull strength

	American Bureau of Shipping, 2016. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Polar_Code_Advisory_15239.pdf	American Bureau of Shipping, 2016. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Polar_Code_Advisory_15239.pdf	Finnish-Swedish Ice Class Rules.pdf	Vancombe Ice Class Ratings. https://www.vancombe.com/index.php/vesselchartering/ice-class-vessel-ratings	Finnish-Swedish Ice Class Rules.pdf	American Bureau of Shipping, 2016. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Polar_Code_Advisory_15239.pdf	AIRSS pictorial guide (vessel class)	TC ShipSafety Bulletin 2009 and www.tc.gc.ca/eng/marinesafety/tp-tp12259-menu-605.htm	Probably the same as ABS Ice Class for 1-5, and ASPPR for A to E - not clear	CCG: http://www.ccg-gcc.gc.ca/Icebreaking/Ice-Navigation-Canadian-Waters/Regulations-and-Guidelines
Polar categories	**Ice Class**	**ABS Ice Class**	**ABS (alternative)**	**Russian Marine Register (1995)**	**Lloyd's Register of Shipping**	**ABS Baltic Ice Class (Finnish-Swedish)**		**ASPPR**	**Arctic Ice Class**	**Arctic Class**
	PC1 [Year-round operation in all Polar waters]	Ice Class A5			AC3			CAC1	5	
	PC2 [Year-round operation in moderate multi-year ice conditions]	Ice Class A4			AC2			CAC2	4	
A [Operation in Polar waters in at least medium first-year ice, which may include old ice inclusions]	**PC3** [Year-round operation in second-year ice which may include multi-year ice inclusions]	Ice Class A3			AC1.5		"CAC" - Canadian Arctic Class	CAC3	3	
	PC4 [Year-round operation in thick first-year ice which may include old ice inclusions]	Ice Class A2			AC1			CAC4	2	
	PC5 [Year-round operation in medium first-year ice which may include old ice inclusions]	Ice Class A1			1AS			CAC4/Type A	1	Vessels were built to this standard Zone/Date system, ranging from Arctic Class 10 (strong) to Arctic Class 1 (weak), followed by weakest vessels (Type A to Type E). This does not directly correlate with other classes. Since AIRSS was introduced in ~1996, ASPPR took over as standard.
B [Operation in Polar waters in at least thin first-year ice which may include old ice inclusions]	**PC6** [Summer/autumn operation in medium first-year ice which may include old ice inclusions]	Ice Class A1/A0	IAA	UL	1AS	1A Super		Type A	A	
	PC7 [Summer/autumn operation in thin first-year ice which may include old ice inclusions]	Ice Class A0	IA	L1	1A	1A	"Type" vessels - designed for first-year ice	Type B	B	
C [Operation in open water or in ice conditions less severe than those in Categories A or B]	IA Super IA IB Not ice strengthened	ABS First-year ice class: B0, C0, D0, E0	IB, IC, ID	L2, L3, L4	1B, 1C, 1D, 100A1	Baltic Ice Class: IB, IC, Category II		Type C, D, E	C, D, E	
Additional Reference website: https://amarineblog.wordpress.com/2017/06/19/ship-ice-class/										

3.1.3 Non-Spatial Shipping Trend Results

The non-spatial database records a total of **1227 unique vessels** which reported in the NORDREG zone between 1990 and 2018. Of these vessels 1220 of them had a reported flag state, from a total of 63 different countries with almost a third (383 vessels) registered in Canada (Appendix Fig. A1; Appendix Table A1). After this, between 50 and 59 vessels were registered in Russia, Panama, Bahamas and Cyprus. Between 40 and 49 vessels were registered in USA, United Kingdom, Marshall Islands, Denmark and Liberia.

In terms of ice strengthening, this information is available for 1102 out of the 1227 unique vessels recorded in the NORDREG zone between 1990-2018. Out of these vessels, 235 (21%) reported no ice strengthening. Of those that are ice strengthened, most fall into Ice Class 1B (480 vessels), with the next most common category PC7 (167 vessels). Full details are provided in Fig. 2.



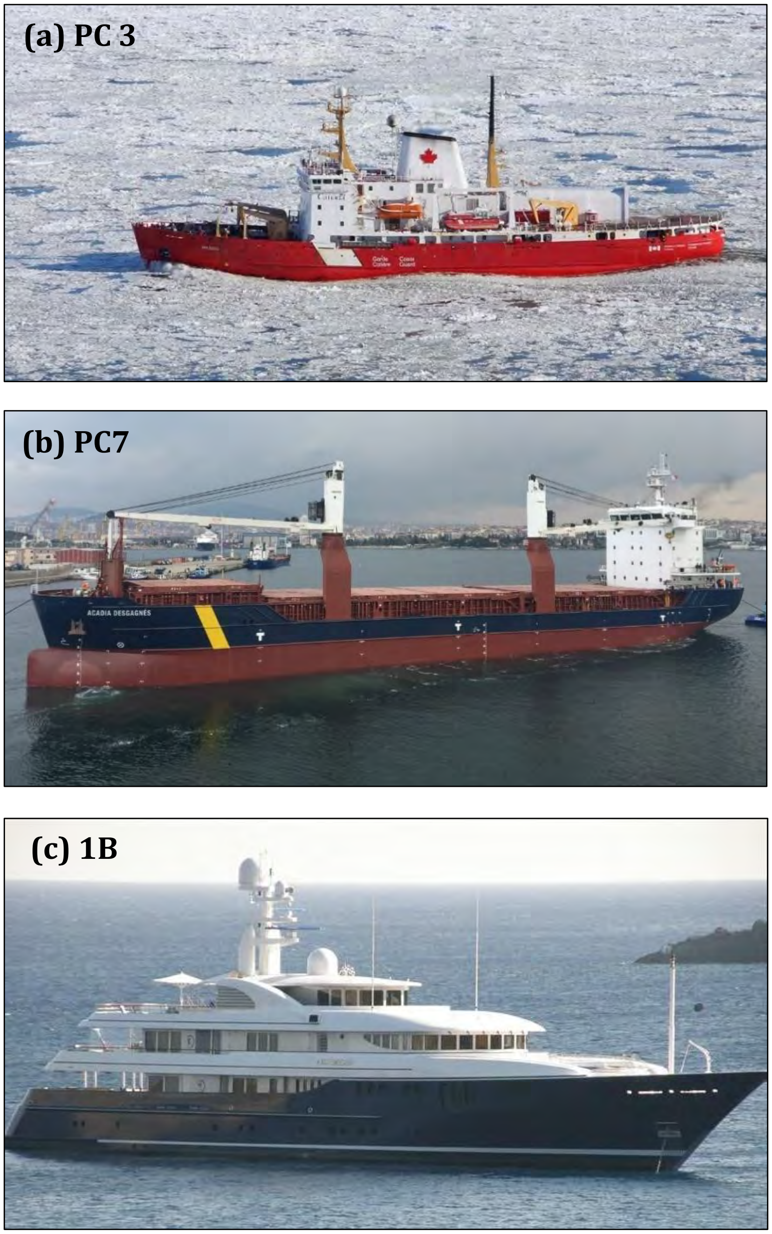
Ice Class	Number
PC1	1
PC2	20
PC3	24
PC4	16
PC5	23
PC6	19
PC7	167
1A Super	25
1A	75
1B	480
IS (Ice Strengthened)	17
No ice strengthening	235
No info available	125

Figure 2. Ice strengthening of unique vessels recorded in the NORDREG zone, 1990-2018, according to Ice Class (note that 'Ice Strengthened' is not an official Ice Class, but is occasionally recorded in the NORDREG database when no information about the specific class is provided).

3.2 Spatial NORDREG Database (1990-2017)

The spatial database was created by collating every position report for every vessel (n=1227) in the NORDREG zone between 1990 and 2017. Over this period there were >100,000 reports made by vessels. The basic unit of analysis for this report is a vessel voyage, which describes the movements of a single vessel along a track for a single trip (e.g., to resupply a community, to undertake a cruise). To convert the individual vessel position reports (which were made daily and often two or three times daily if ice zones were entered) into a continuous track, a least cost path analysis was undertaken. This is based on weighted cost surfaces of total sea ice concentration, bathymetry, and distance from land, as described in detail by Pizzolato et al. (2014, 2016). This enabled identification of ~5000 individual vessel voyages and a model of total kilometers traveled by each vessel.

To provide a measure of changes in navigability conditions over time for a range of representative ship types, changes were analyzed for a highly strengthened ship class (Ice Class PC3), a medium ice strengthened ship class (Ice Class PC7), and for a class with little ice strengthening (Ice Class 1B) for 1992-1996, 2002-2006 and 2012-2017. An example of a PC3 ship is the Amundsen Icebreaker (Figure 3a), which can navigate in Arctic waters throughout most of the year. A PC7 ship can be a general cargo vessel, such as a Desgagnés community resupply ship (Figure 3b), while an Ice Class 1B ship covers vessels that have little ice strengthening, such as a bulk carrier carrying grain from Churchill or a pleasure craft (Figure 3c).



REFERENCE BOX: Ship Definitions

POLAR CLASS

PC1: Year-round operation in all Polar waters
PC2: Year-round operation in moderate multi-year ice conditions
PC3: Year-round operation in second-year ice which may include multi-year ice inclusions
PC4: Year-round operation in thick first-year ice which may include old ice inclusions
PC5: Year-round operation in medium first-year ice which may include old ice inclusions
PC6: Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC7: Summer/autumn operation in thin first-year ice which may include old ice inclusions

POLAR CATEGORY

A: Operation in Polar waters in at least medium first-year ice which may include old ice inclusions (PC1 to PC5)
B: Operation in Polar waters in at least thin first-year ice which may include old ice inclusions (PC6 or PC7)
C: Operation in open water or in ice conditions less severe than those included in Cat A or B (1A Super to 1B No ice class)

Figure 3. Examples of a: (a) Highly ice strengthened ship (CCGS Amundsen; Polar Class 3); (b) Medium ice strengthened ship (Acadia Desgagnés; Polar Class 7); (c) Little ice strengthened ship (Archimedes; Ice Class 1B). See Reference Box and Table 3 for further details.

3.2.1 Spatial Shipping Trend Results

For the Canadian Arctic (NORDREG zone) as a whole, it is clear that there have been significant changes in the distribution of these ships over time (Fig. 4). In particular, there has been a marked reduction in the voyages of highly strengthened PC3 ships, but large increases in the number of voyages of ships with medium (PC7) and little ice strengthening (Ice Class 1B), with many more voyages of these ship types now occurring through the Northwest Passages in the recent past than in the 1990s.

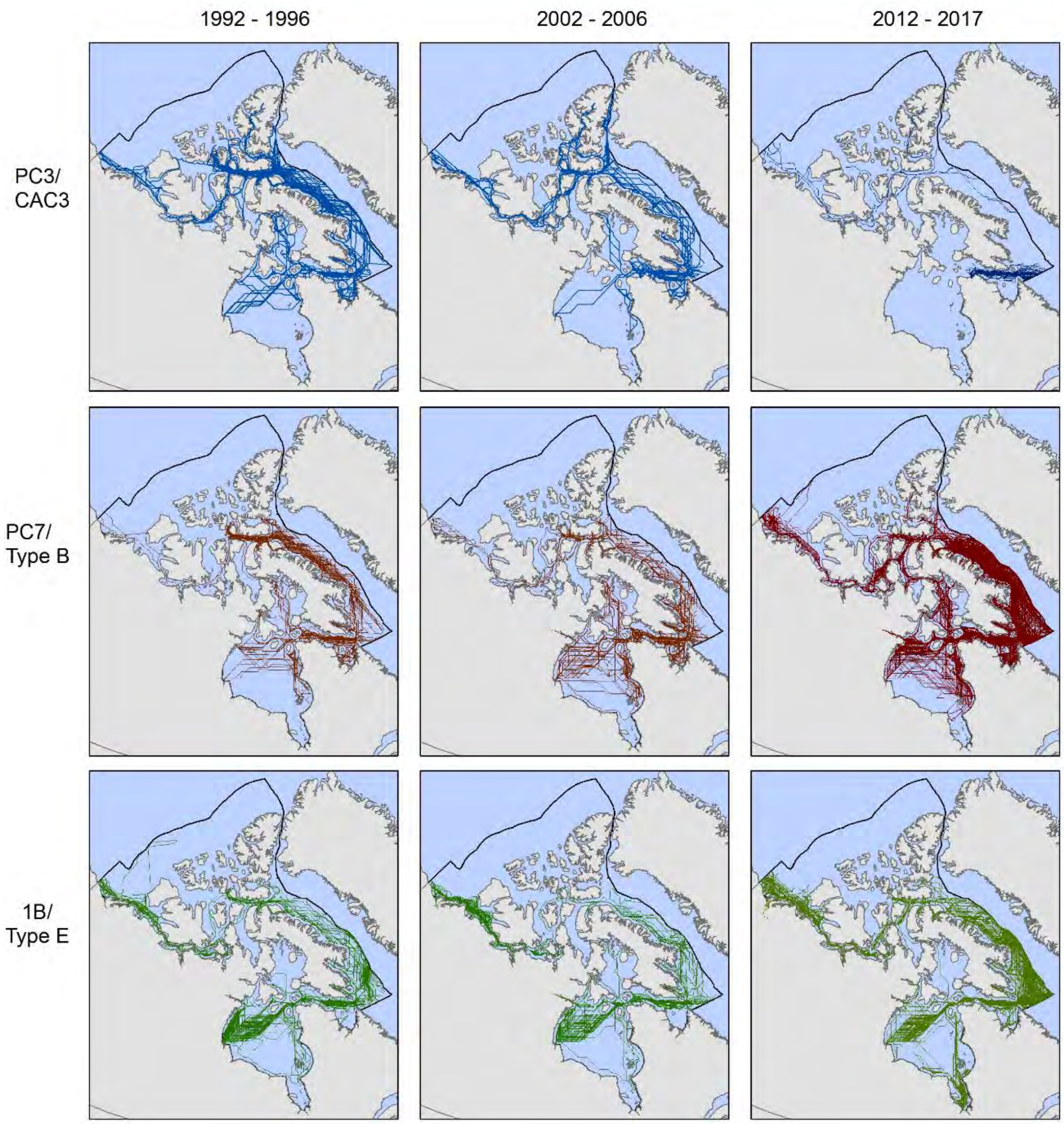


Figure 4. Changes in vessel track distribution over time for: Highly ice strengthened ships (Ice Class PC3/CAC3); Medium ice strengthened ships (Ice Class PC7/Type B); Little ice strengthened ships (Ice Class 1B/Type E). Note the large reduction in PC3 ships towards the present day, in comparison to the large increase in PC7 and 1B vessels over the same period.

3.3 Choke Point Areas

Locations where sea ice is frequently present throughout a shipping season, impeding travel along routes that are otherwise largely ice free, have been called ‘choke points’ in previous studies (e.g., Stewart et al., 2007; Xu et al., 2011). These are regions that could pose higher than average risks to ships, particularly if sea ice is becoming more mobile and drifting into these areas. Naturally, the choke points will cause increased risk to transiting ships as ships in these regions can have few, if any, alternative routes to avoid hazardous sea ice. Thus, in this study choke points were chosen based on analysis of the spatial database of historic shipping traffic, observations from historic sea ice charts, and the patterns shown in Figure 4, which outlines the traffic patterns by ice strengthening among operating ships. Based on these considerations three choke points were identified that are geographically dispersed and located along the Northwest Passages where rapid recent shipping increases have occurred. The three choke point areas chosen for the study are (also see Fig. 5):

(1) The waters around **Somerset Island**, including the narrow pass at Bellot Strait on the south side of the island and Barrow Strait to the north of the island.
(2) The area to the south of **Bylot Island**, including Eclipse Sound and Navy Board Inlet
(3) The shallow waters to the south of **Cambridge Bay**

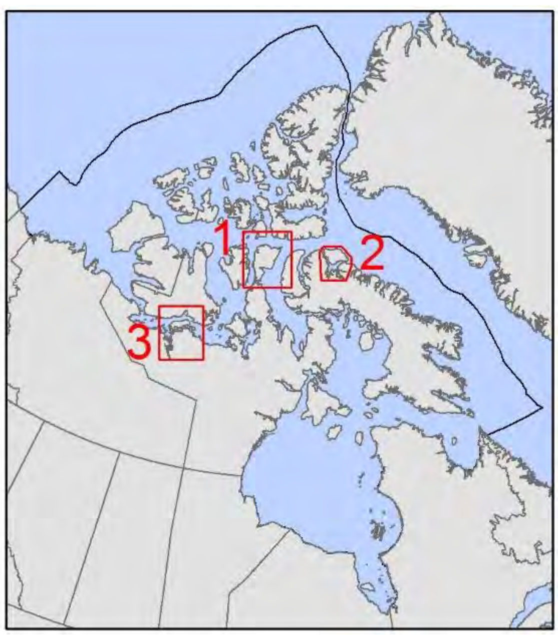


Figure 5. Location of three 'choke points’ identified for this study.

Changes in the distribution of all voyages over time for these regions are shown in Figure 6, and the detailed patterns and trends for each region are discussed in the following sections.

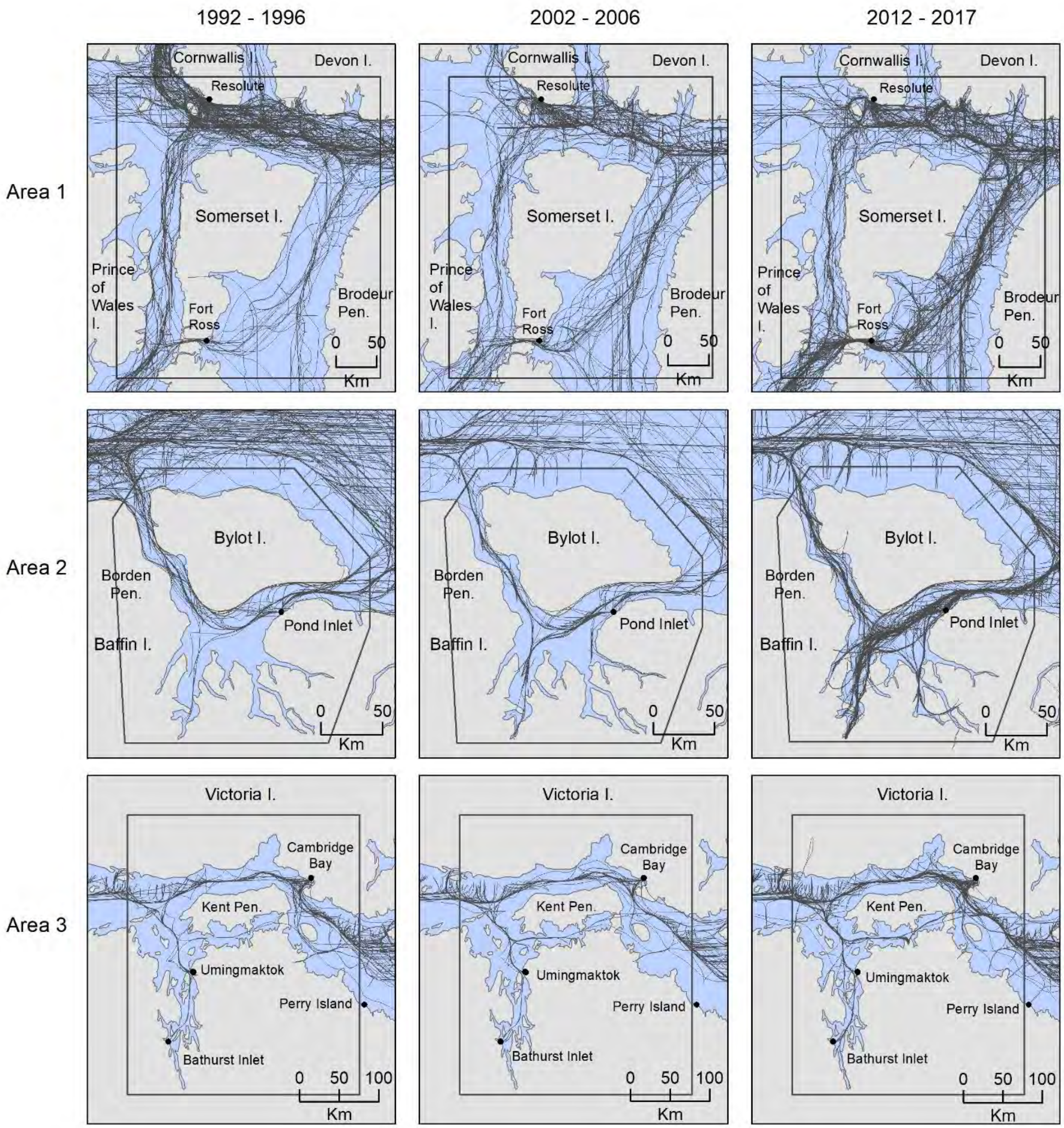


Figure 6. Distribution of vessel tracks over time for all recorded voyages at 3 primary choke points in the Canadian Arctic : (1) Somerset Island; (2) Bylot Island; (3) Cambridge Bay. Locations of regions are shown in Figure 5. Note that the rapid recent increase in ship traffic in all regions, including to the south of Bylot Island related to the opening of the Mary River Mine, and the greater proportion of ship traffic now passing to the south of Somerset Island, rather than to the north.

3.3.1 Somerset Island (Area 1)

The area around Somerset Island is experiencing some of the greatest recent increases in sea ice mobility due to the dynamic import of multi-year ice that is breaking up in the Arctic Ocean and transiting southward and into the Northwest Passages (see Howell et la. 2013). This region has also experienced a greater than doubling of ship traffic over the period 2012-2017 (42 vessels/yr) compared the periods prior to 2006 (18 vessels/yr; Table 4, Figure 7). In terms of ice strengthening, there was a marked trend away from highly strengthened vessels towards less strengthened ones. In the 1990s >36% of all vessels were in classes PC1 to PC3, compared to <15% in those classes over 2012-2017. There was more than a quadrupling of PC7 vessels between the 1992-96 time period (n=15) to the 2012-17 (n=72) time period. Only one vessel reported no ice strengthening in the 1990s, but over a third of vessels (87 out of 253) fell into this category in 2012-2017.

Table 4. Number and Ice Class of vessels in the Somerset Island region.

Somerset Island	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
Total Vessel Count	99	92	79	126	253
Mean Vessel Count Per Year	19	18	16	25	42
	Vessel Counts by Ice Class				
PC1	0	0	0	0	0
PC2	22	25	24	26	32
PC3	14	11	7	3	4
PC4	6	3	5	2	2
PC5	11	2	1	0	0
PC6	6	8	11	18	14
PC7	15	22	16	30	72
1AS	2	0	0	0	1
1A	4	8	2	4	14
1B	8	12	2	4	21
No ice strengthening	1	0	3	34	87

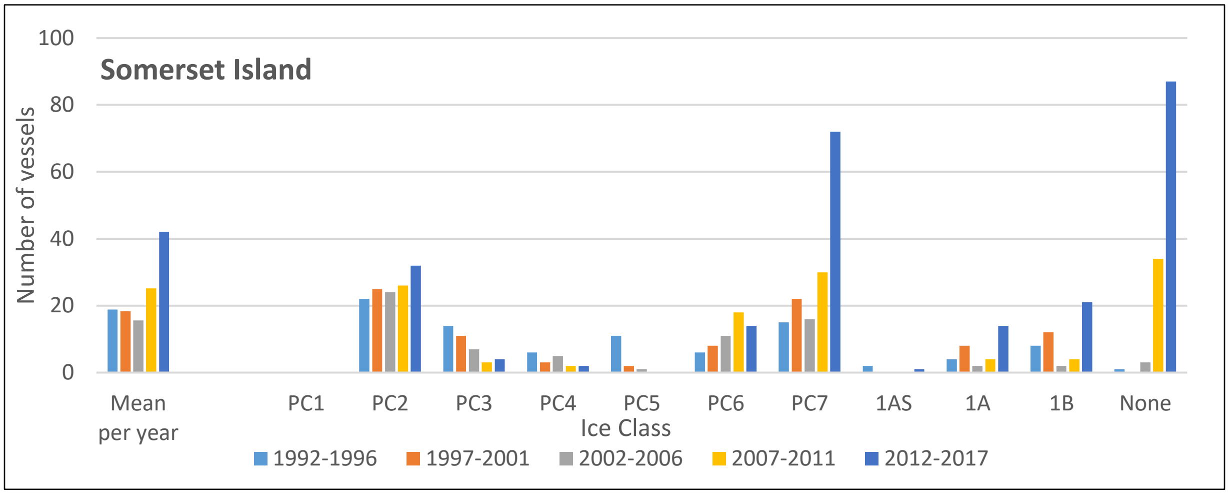


Figure 7. Changes over time in the number and Ice Class of ships undertaking voyages through the Somerset Island region.

In terms of vessel voyages, there has been a clear increase in the routing of weaker vessels (PC7 and 1B) to the south of Somerset Island, through the Bellot Strait by Fort Ross (Figure 8). For example, not a single PC7 vessel passed through Bellot Strait in the 1990s, but dozens of them passed through this area over the period 2012-2017. These recent PC7 vessels primarily consisted of Tanker Ships (n=20), Passenger Ships (n=19), and General Cargo (n=26) (Table 5). Similarly, numerous 1B vessels passed through Bellot Strait in 2012-2017; for example, there were 7 Pleasure Crafts during this period compared to a total of only 2 over the entire period 1992-2011 (Table 5).

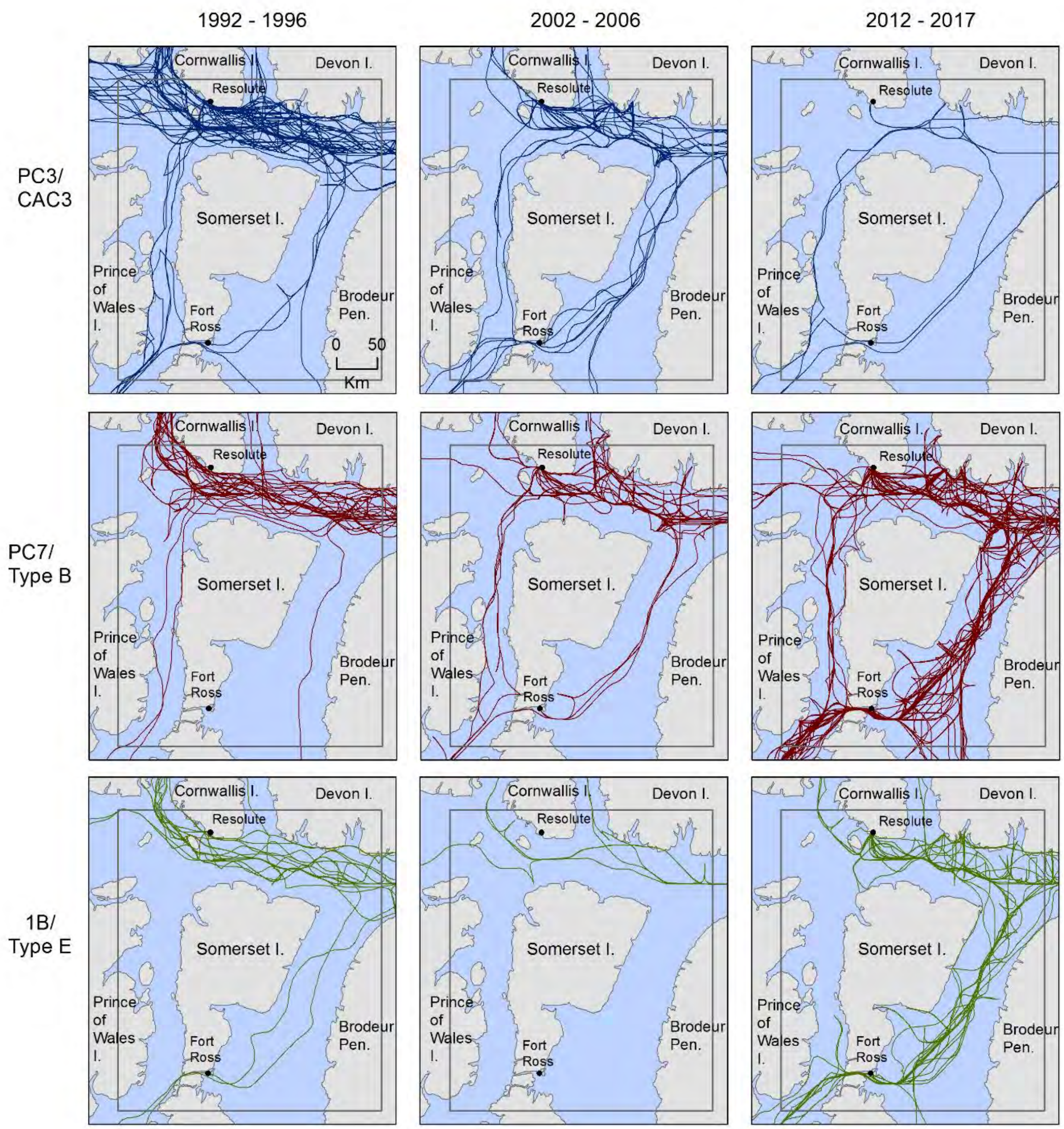


Figure 8. Changes in vessel tracks over time around Somerset Island for representative ship types: Ice Class PC3 (highly ice strengthened), PC7 (medium ice strengthened), and 1B (little ice strengthened).

One of the vessel types that saw the biggest relative change in ice strengthening over time is Passenger Ships. It was common to see these as highly ice strengthened until 2006 (n=5 per period), but in 2012-2017 there was only one Passenger Ship with this class of ice strengthening (Table 5). Rather, Passenger Ships are now more commonly strengthened to a medium level (PC7), with 19 ships of this type in 2012-2017 compared to only 1 in the period 1992-1996. There are likely several reasons for this observed trend. First, highly ice strengthened vessels that were previously chartered by tourism operators have been recalled by international governments based on national needs such as requiring ice strengthened vessels for their own military and industrial purposes. Second, there has been a larger than expected increase in cruise tourism demand in the Polar regions. Ten years ago, experts speculated that there would never be enough demand to warrant the costs associated with purpose-built ice-strengthened cruise ships. As a result the industry relied on chartering and retrofitting existing vessels, which were often originally built for research or military purposes with high ice strengthening, and were typically Russian. However, these highly ice strengthened vessels were expensive to operate and not well designed for tourist use, so many cruise vessels are now being purpose built for Arctic operations directly by cruise operators, with less ice strengthening, cheaper operating costs, and interiors better designed to accommodate cruise passengers.

Table 5. Changes in vessel numbers over time for Somerset Island for the three representative ship types: PC3, PC7 and 1B.

Somerset Island

Ice Class	Vessel Type	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
PC3	Bulk Carriers	8	5	2	0	0
	General Cargo	0	1	0	0	0
	Gov Vessels & Icebreakers	0	0	0	0	3
	Passenger Ships	5	5	5	3	1
	Tug/Barge	1	0	0	0	0
PC7	Bulk Carriers	10	5	0	0	1
	General Cargo	3	8	8	11	26
	Gov Vessels & Icebreakers	0	0	0	0	2
	Passenger Ships	1	6	5	8	19
	Pleasure Crafts	0	0	0	2	2
	Tanker Ships	0	1	0	6	20
	Tug/Barge	1	2	3	3	2
1B	Bulk Carriers	2	5	1	0	0
	Fishing Vessels	0	0	0	0	3
	General Cargo	3	5	0	0	1
	Gov Vessels & Icebreakers	0	0	0	1	6
	Passenger Ships	0	0	0	0	2
	Pleasure Crafts	1	1	0	0	7
	Tug/Barge	2	1	1	2	2
	Other	0	0	0	1	0
	TOTAL	**37**	**45**	**25**	**37**	**97**

Compared to the other choke points, this region has seen a particularly large decrease in the number of bulk carriers. This reduction has primarily occurred due to the closure of the Polaris Mine on Little Cornwallis Island (near to Resolute) in 2002 (Dawson et al., 2018). It is clear that there were a large number of PC3 ships operating to and from Resolute prior to that time, but very few since then (Fig. 8). There has also been a shift in primary ship routing from the north and west of Somerset Island (in the 1990s) to the east and south of it (in the 2010s). In terms of this routing, ice navigability is much easier on the eastern side of Somerset Island (this region is now typically ice-free in summer), compared to the western side of it (where ice still often remains for the summer, and in some years there is increased import of multi-year ice from the Arctic Ocean. As vessel numbers have increased, as vessels have shifted towards much less ice strengthened categories, and as ice conditions have opened up on the east side of Somerset Island, ships have therefore chosen the routing with the lowest risk.

3.3.2 Bylot Island (Area 2)

The area around Bylot Island is representative of the eastern entrance to the Northwest Passages and has also experienced changes in sea ice conditions as a result of climate change. Compared to the other areas, this choke point experiences some of the highest traffic volumes and has attracted more than a doubling in the mean vessel count per year over the period 2012-2017 compared to any previous period (Table 6, Figures 9, 10). The region is attractive to small pleasure craft and private yachts that have little to no ice strengthening and are therefore at higher risk from dynamic sea ice conditions; no vessels without ice strengthening were recorded during 1992-2001, compared to 80 without ice strengthening during 2007-2017.

Table 6. Number and Ice Class of vessels in the Bylot Island region.

Bylot Island	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
Total Vessel Count	78	78	68	98	271
Mean Vessel Count Per Year	16	16	14	20	45
	Vessel Counts by Ice Class				
PC1	0	0	0	0	0
PC2	20	17	22	19	24
PC3	16	9	2	2	0
PC4	2	1	2	0	0
PC5	6	1	4	0	1
PC6	4	8	11	12	9
PC7	11	24	17	33	124
1AS	2	1	0	1	0
1A	7	8	1	7	27
1B	6	9	2	5	20
No ice strengthening	0	0	3	18	62

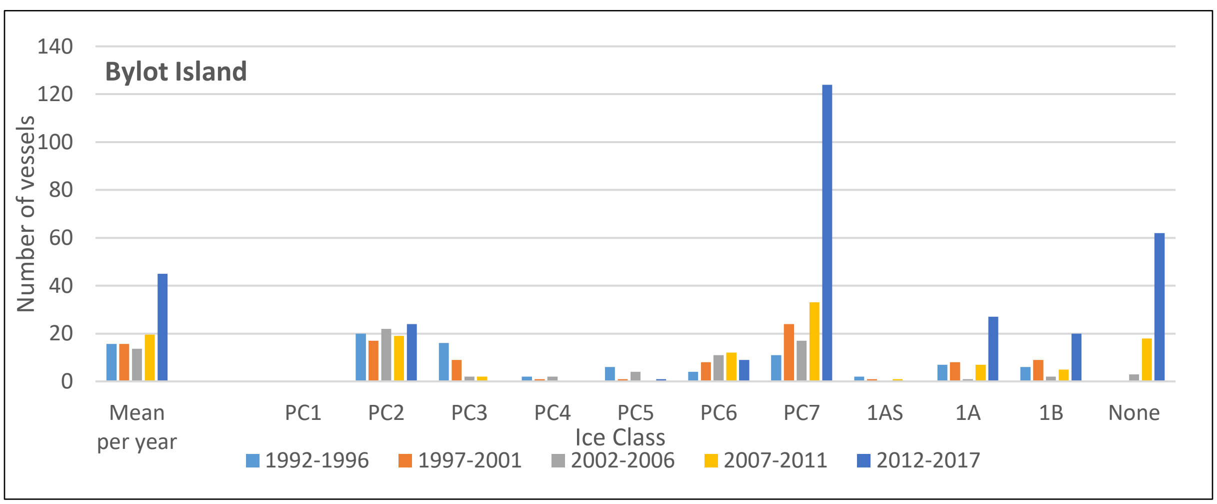


Figure 9. Changes over time in the number and Ice Class of ships undertaking voyages through the Bylot Island region, derived from NORDREG reports.

In terms of ship type, there has been a large reduction in highly strengthened PC3 vessels, with none in 2012-2017, but a large recent increase in ships with PC7 medium ice strengthening (>10x increase between 1992-1996 (n=11) and 2012-2017 (n=124); Figure 10, Table 6). This has arisen due to three converging factors: the opening of the Mary River Mine operated by Baffinland Iron Mines, which ships out its ore in Bulk Carriers (n=0 for 2007-2011, n=44 for 2012-2017) through Milne Inlet, the increase in General Cargo ships (n=4 for 1992-1996, n=33 for 2012-2017), and increases in Passenger Ships (i.e., cruise vessels; n=0 for 1992-1996, n=19 for 2012-2017) (Table 7).

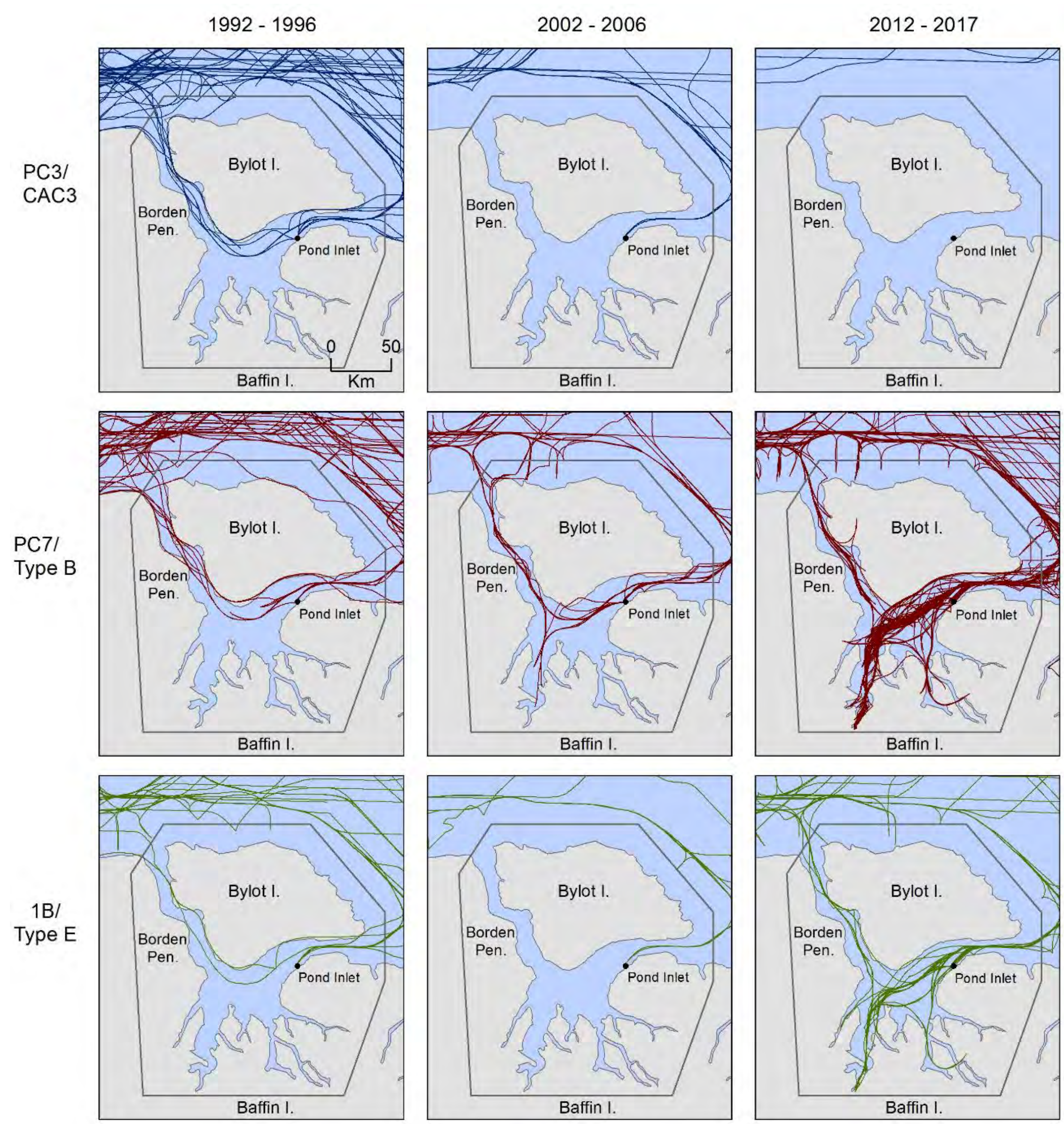


Figure 10. Changes in vessel tracks over time around Bylot Island for representative ship types: Ice Class PC3 (highly ice strengthened), PC7 (medium ice strengthened), and 1B (little ice strengthened).

Table 7. Changes in vessel numbers over time for Bylot Island for the three representative ship types: Ice Class PC3, PC7 and 1B.

Bylot Island

Ice Class	Vessel Type	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
PC3	Bulk Carriers	6	3	0	0	0
	General Cargo	2	2	0	0	0
	Passenger Ships	5	4	2	2	0
	Tanker Ships	3	0	0	0	0
PC7	Bulk Carriers	4	1	0	0	44
	General Cargo	4	9	8	15	33
	Gov Vessels & Icebreakers	0	0	0	0	3
	Passenger Ships	0	6	6	7	19
	Pleasure Crafts	0	0	0	1	2
	Tanker Ships	3	6	0	7	18
	Tug/Barge	0	2	3	3	5
1B	Bulk Carriers	2	2	0	0	2
	Fishing Vessels	0	0	0	0	1
	General Cargo	2	5	1	1	3
	Gov Vessels & Icebreakers	0	0	0	1	5
	Passenger Ships	0	0	0	2	2
	Pleasure Crafts	1	1	0	0	6
	Tug/Barge	1	1	1	0	1
	Tanker Ships	0	0	0	1	0
	TOTAL	**33**	**42**	**21**	**40**	**144**

Lying at the entrance to the Northwest Passages, this region has experienced some of the most dramatic recent increases in shipping in the Canadian Arctic. The location of this region makes it unique compared to the other choke points, as ships are able to reach it much more easily due to the lack of sea ice along eastern Baffin Island in most recent years. Thus, small pleasure craft sailing along eastern Baffin Island are typically able to reach Bylot Island and Pond Inlet even if they don't enter the interior parts of the Canadian Arctic Islands. In addition, almost every ship transiting to or from the Northwest Passages has to pass through this region, while the popularity of Pond Inlet as a stop for cruise ships has dramatically increased recently, with several vessels per week now visiting the community during the peak of the cruise season in August/September. Finally, the opening of the Mary River Mine has created a summer rush of bulk carriers, as environmental regulations specify that all ore must be exported during the open water season; in recent years it has not been unusual for empty bulk carriers to be waiting offshore while others are being filled in Milne Inlet.

3.3.3 Cambridge Bay (Area 3)

The region around Cambridge Bay does not experience as much ice mobility as the other two choke points chosen for this study but the area is experiencing dramatically increased ship traffic, with more than a tripling in mean annual vessel count from 10 per year in the 1990s to 37 per year over the period 2012-2017 (Table 8; Figures 11, 12). In addition, the region is challenging to navigate due to low water levels and dynamic ice that flows into narrow channels. In terms of vessel type the region follows similar trends to elsewhere, with highly ice strengthened PC3 vessels decreasing in comparison to the increasing number of medium (PC7) and little (1B) or non ice strengthened vessels. For example, no non ice strengthened vessels were recorded in the 1990s, whereas 122 have been recorded since 2007.

Table 8. Number and Ice Class of vessels in the Cambridge Bay region.

Cambridge Bay	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
Total Vessel Count	51	48	59	120	222
Mean Vessel Count Per Year	10	10	12	24	37
			Vessel Counts by Ice Class		
PC1	0	0	0	0	0
PC2	10	9	13	10	14
PC3	6	5	5	2	3
PC4	6	6	9	5	6
PC5	3	3	0	0	0
PC6	5	4	3	12	10
PC7	2	2	4	23	54
1AS	1	0	0	0	2
1A	0	0	0	1	7
1B	15	19	21	26	36
No ice strengthening	0	0	3	38	84

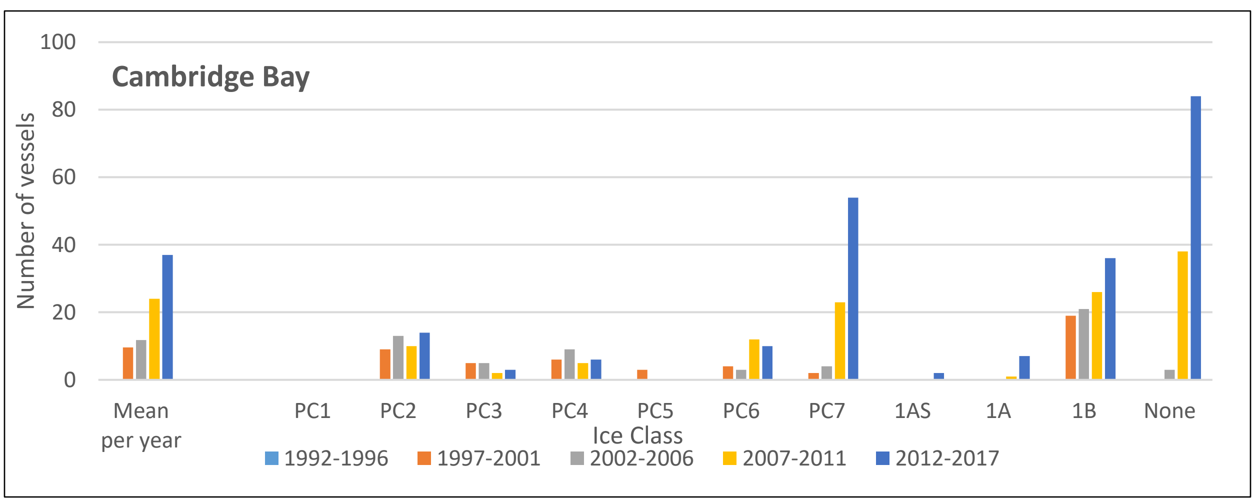


Figure 11. Changes over time in the number and Ice Class of ships undertaking voyages through the Cambridge Bay region, derived from NORDREG reports.

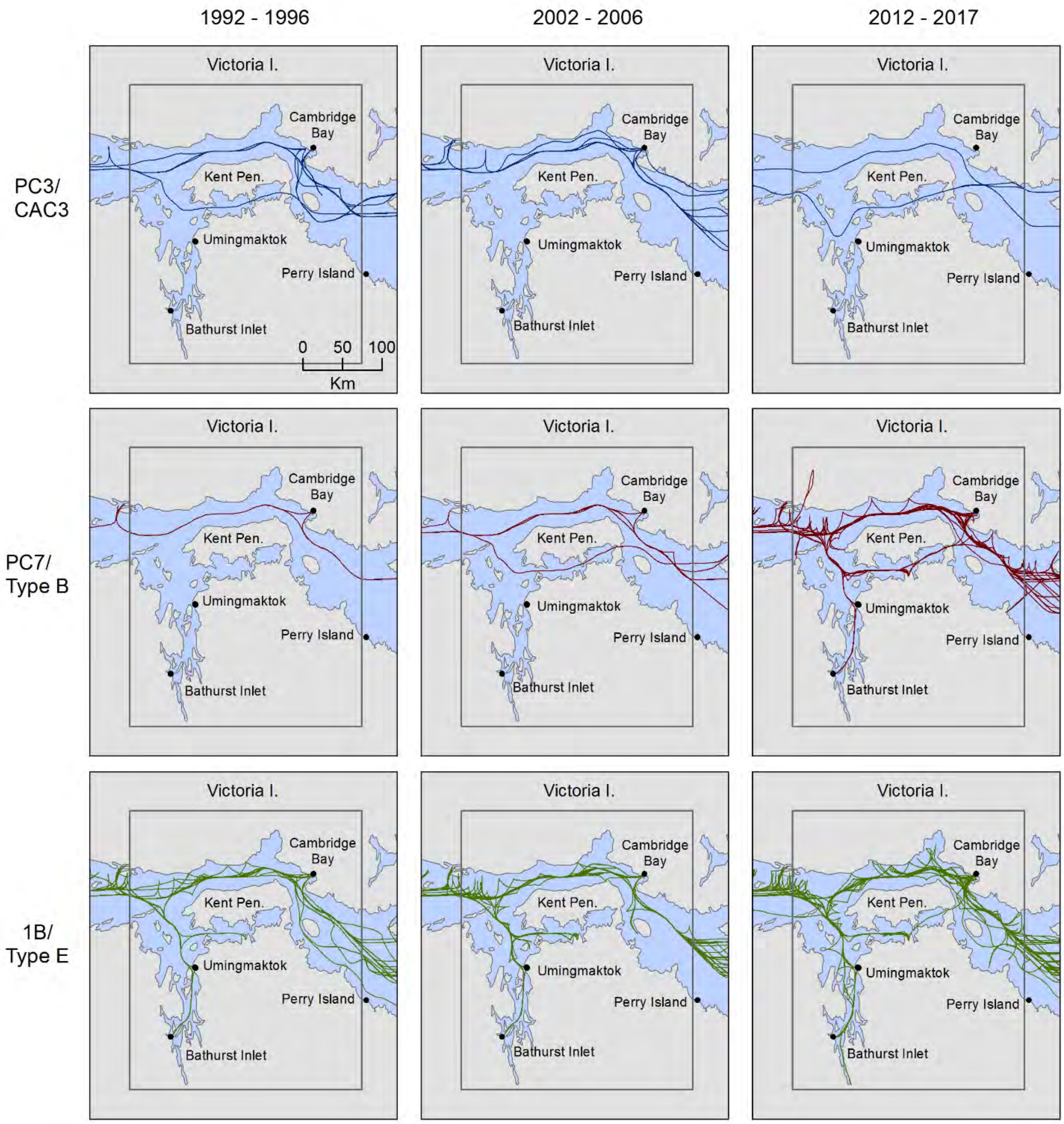


Figure 12. Changes in vessel tracks over time around Cambridge Bay for representative ship types: Ice Class PC3 (highly ice strengthened), PC7 (medium ice strengthened), and 1B (little ice strengthened).

When the ice strengthening of vessels passing through the Cambridge Bay area is examined, it is clear that there has been a significant shift in the class of Passenger Ships (Table 9). Almost all passenger ships were of high ice strength PC3 over the period 1992 to 2006 (n=15), with only 2 of medium type PC7 during this time. In comparison, over the period 2007-2017, only 2 passenger ships were of high ice strength PC3, but 16 were of medium ice strength PC7 (Table 9). Pleasure Crafts are also much more common today than in the past (e.g., 6 vessels of Ice Class 1B during 2012-2017, compared to only a single 1B vessel recorded over the entire period 1992-2011).

Table 9. Changes in vessel numbers over time for Cambridge Bay for the three representative ship types: Ice Class PC3, PC7 and 1B.

Cambridge Bay

Ice Class	Vessel Type	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
PC3	Gov Vessels & Icebreakers	0	0	0	0	3
	Passenger Ships	5	5	5	2	0
	Tug/Barge	1	0	0	0	0
PC7	Bulk Carriers	0	0	0	0	1
	General Cargo	0	0	0	7	19
	Gov Vessels & Icebreakers	0	0	0	0	2
	Passenger Ships	1	0	1	7	14
	Pleasure Crafts	0	0	0	1	2
	Tanker Ships	0	0	0	4	11
	Tug/Barge	1	2	3	4	5
1B	General Cargo	0	1	0	0	4
	Gov Vessels & Icebreakers	0	0	0	1	7
	Passenger Ships	0	0	0	0	2
	Pleasure Crafts	1	0	0	0	6
	Tanker Ships	0	0	0	0	1
	Tug/Barge	14	17	21	24	16
	Other	0	0	0	1	0
	TOTAL	**23**	**26**	**30**	**51**	**93**

4.0 Changes in Sea Ice Navigability

Given the changes in shipping traffic, including the variability in ice strengthened versus non ice strengthened vessels over time discussed above, an important question is whether sea ice navigability is also changing over time? That is, for a ship of a given ice strength, is it becoming easier or more difficult for it to navigate through the Canadian Arctic due to changes in sea ice strength. In addition, it is vital to know if there are particular areas that are becoming more or less risky to navigate based on the combination of sea ice strength change and the type of vessels (ice strengthened or non ice strengthened) that are increasingly operating in the area.

To address this, weekly sea ice charts for the Western Arctic, Eastern Arctic, and Hudson Bay from 1972 to 2016 were downloaded as E00 files from the Canadian Ice Service (CIS) Archive (https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions/archive-overview.html). The charts included sea ice concentration, partial concentration, stage of development, and ice form information, essential for calculating the Ice Numeral (IN) values for shipping navigability. The IN refers to a number within the Arctic Ice Regime Shipping System (AIRSS) which determines whether a ship is permitted to navigate through a region. The system works by calculating the Ice Multiplier (IM) of the ship type and each sea ice type within the ice regime (Table 10), and multiplying this number by the concentration in tenths of the sea ice type, to find the overall Ice Numeral:

$$\mathbf{IN = (C_a \times IM_a) + (C_b \times IM_b) + \ldots}$$

Where:

- IN: Ice Numeral
- C_a : Concentration (in tenths) of ice type "a"
- IM_a : Ice Multiplier for ice type "a" and ship type

When the IN gives a number that is 0 or above the conditions are safe for the mariner to proceed, and if the IN is negative, the conditions are dangerous and the mariner may not proceed. Once the Ice Numerals were calculated, the shapefiles were then transformed into 12.5 km by 12.5 km pixel-sized rasters for each ship type, based on their IN values, by using the Convert To Raster tool in ArcMap 10.2.2.

Table 10. Ice Multipliers for each ship category (modified from Canadian Coast Guard and Fisheries and Oceans Canada, 2012). The conversion between the AIRSS/ASPPR ice classes listed here and the Polar Classes is provided in Table 3.

Ice Codes	***Ice Types/ Stages of Development***	***Ice thickness (cm)***	***Type E***	***Type D***	***Type C***	***Type B***	***Type A***	***CAC 4***	***CAC 3***
7 • or 9 •	Old / Multi-Year Ice		-4	-4	-4	-4	-4	-3	-1
8 •	Second-Year Ice		-4	-4	-4	-4	-3	-2	1
6 • or 4 •	Thick First-Year	> 120	-3	-3	-3	-2	-1	1	2
1 •	Medium First-Year Ice	70 -120	-2	-2	-2	-1	1	2	2
7	Thin First-Year Ice	30-70	-1	-1	-1	1	2	2	2
9	Thin First-Year Ice – 2nd stage	50-70	-1	-1	-1	1	2	2	2
8	Thin First-Year Ice – 1st stage	30-50	-1	-1	1	1	2	2	2
3 or 5	Grey-White Ice	15-30	-1	1	1	1	2	2	2
4	Grey Ice	10-15	1	2	2	2	2	2	2
2	Nilas, Ice Rind	<10	2	2	2	2	2	2	2
1	New Ice	<10	2	2	2	2	2	2	2
	Brash (ice fragments < 2m)		2	2	2	2	2	2	2
= Δ	Bergy Water		2	2	2	2	2	2	2
¦¦¦	Open Water		2	2	2	2	2	2	2

For comparisons with the earlier parts of this report, the AIRSS class CAC3 is assumed to be equivalent to Ice Class PC3 (highly ice strengthened), AIRSS class Type B is assumed to be equivalent to Ice Class PC7 (medium ice strengthened), and AIRSS class Type E is assumed to be equivalent to Ice Class 1B (little ice strengthened) (see Table 3). To assess the change in sea ice navigability over time, a profile of Ice Numerals for each of these 3 representative ship types along the ~4500 km length of the NORDREG zone via the Northwest Passage was calculated for early-season (June 25), mid-season (September 3) and late-season (October 15) (Figure 13). Calculations were performed for the period 1972-1976 (prior to the NORDREG record), 1992-1996 (start of the NORDREG record) and 2012-2016 (end of the NORDREG record) to understand changes in ice navigability over time.

For reference with the previous sections, the choke point at Cambridge Bay is at km1400-1500, Somerset Island at km2000-2400 and Bylot Island at km2700-2900.

Figure 13. Map of the Northwest Passage primary shipping route (A to B) through the NORDREG zone, with 100 km markers, used to produce graphs of AIRSS values with distance in Figs. 14-16. The choke point at Cambridge Bay is at km1400-1500, Somerset Island at km2000-2400 and Bylot Island at km2700-2900.

For highly ice strengthened ships of type PC3, there is no significant change in navigability over time (Figure 14). These types of vessels have been able to access all regions of the Northwest Passage at all times of the year from the 1970s to present day. This is hardly surprising for an icebreaker such as the CCGS Amundsen.

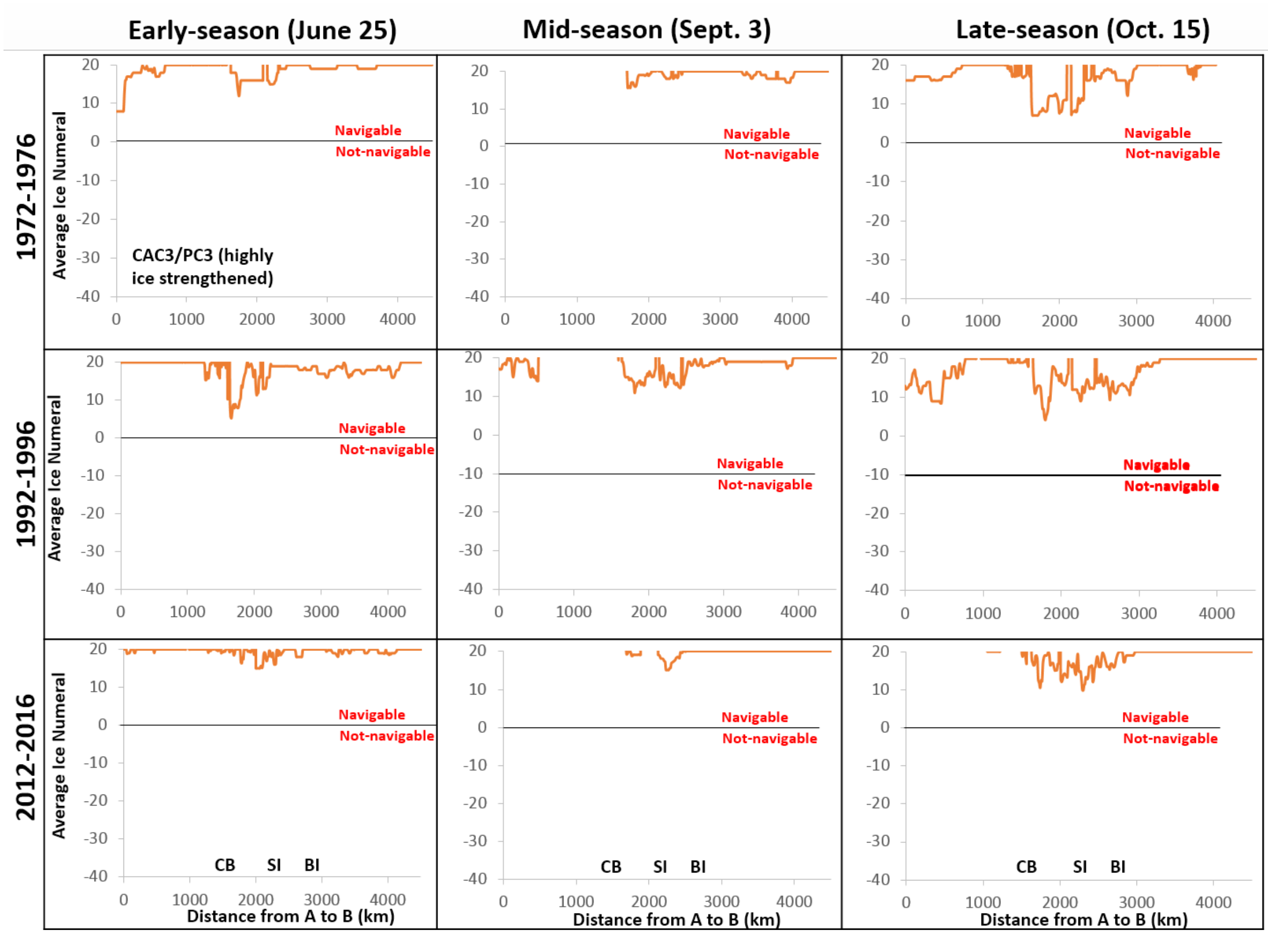


Figure 14. Changes in ice navigability over time along the primary Northwest Passage route for ships of Ice Class CAC3/PC3 (highly ice strengthened). See Fig. 13 for location of distance markers. CB = Cambridge Bay; SI = Somerset Island; BI = Bylot Island. This is the only ship type which has been able to easily navigate all choke points for the entire study period and for every shipping season.

For ships with medium ice strengthening (PC7), there are large regions where these ships are unable to navigate in the early season, from the 1970s to present day. This encompasses much of Baffin Bay and most of the Northwest Passage (Figure 15). However, the accessibility for this ship type has become much easier for mid-season conditions in the most recent period 2012-2016, when ships would be able to pass throughout the Northwest Passage without hindrance. In comparison, this ship type would not have been able to pass the regions around Somerset Island and Cambridge Bay in the 1970s or 1990s (Figure 15). For late season conditions the

Northwest Passage was almost completely passable during 2012-2016, with just a narrow choke point around Somerset Island, compared to large areas of this region being non-navigable in the 1970s and 1990s.

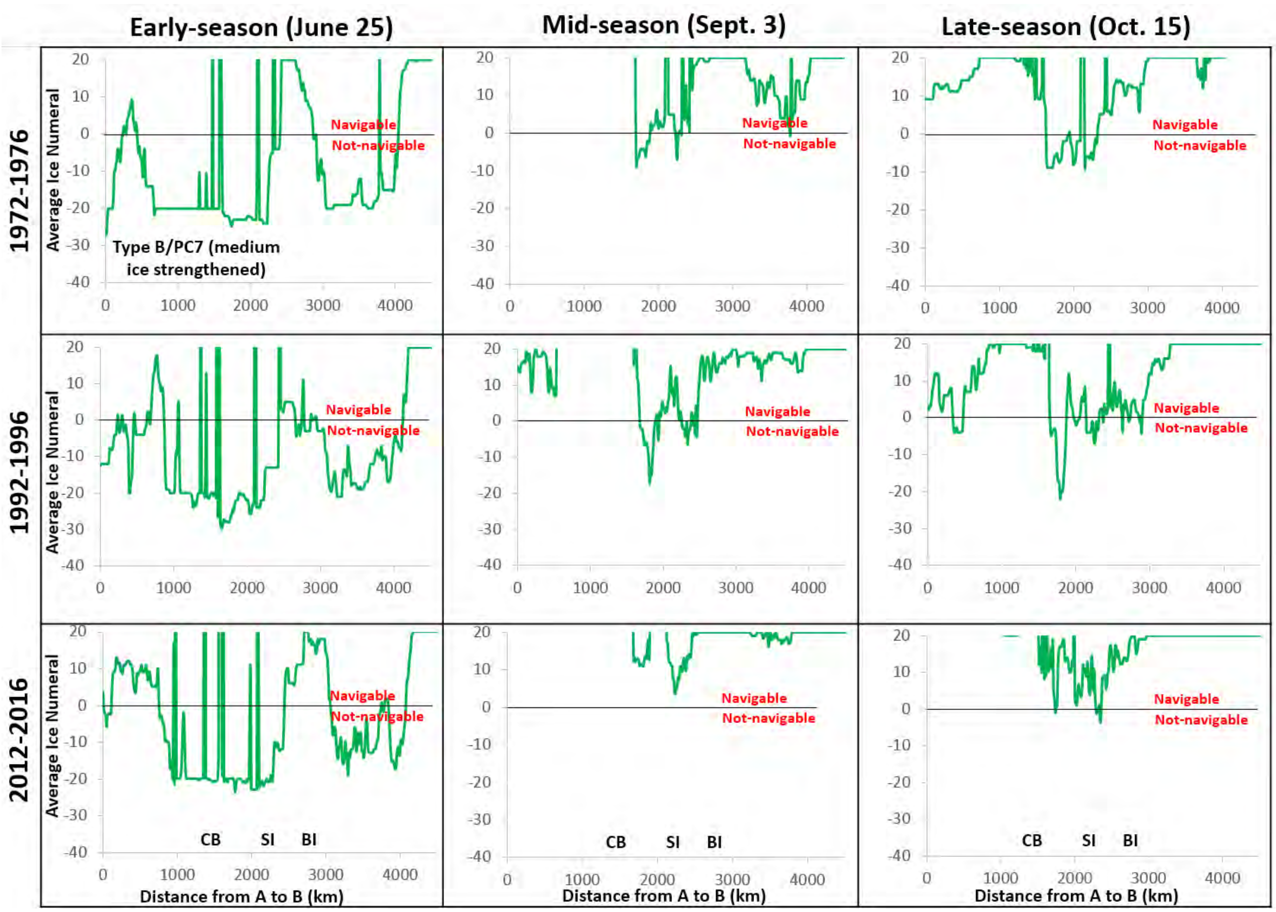


Figure 15. Changes in ice navigability over time along the primary Northwest Passage route for ships of Ice Class B/PC7 (medium ice strengthened). See Fig. 13 for location of distance markers. CB = Cambridge Bay; SI = Somerset Island; BI = Bylot Island.

For vessels with little ice strengthening the only period when they have been able to safely navigate the entire Northwest Passage has been in the mid-season in the most recent period, 2012-2016 (Figure 16). In other periods in the mid-season and late-season the choke points around Cambridge Bay and Somerset Island have been too great for ships to pass. There are still significant hindrances to navigation for this ship type over large areas in the early season for all periods.

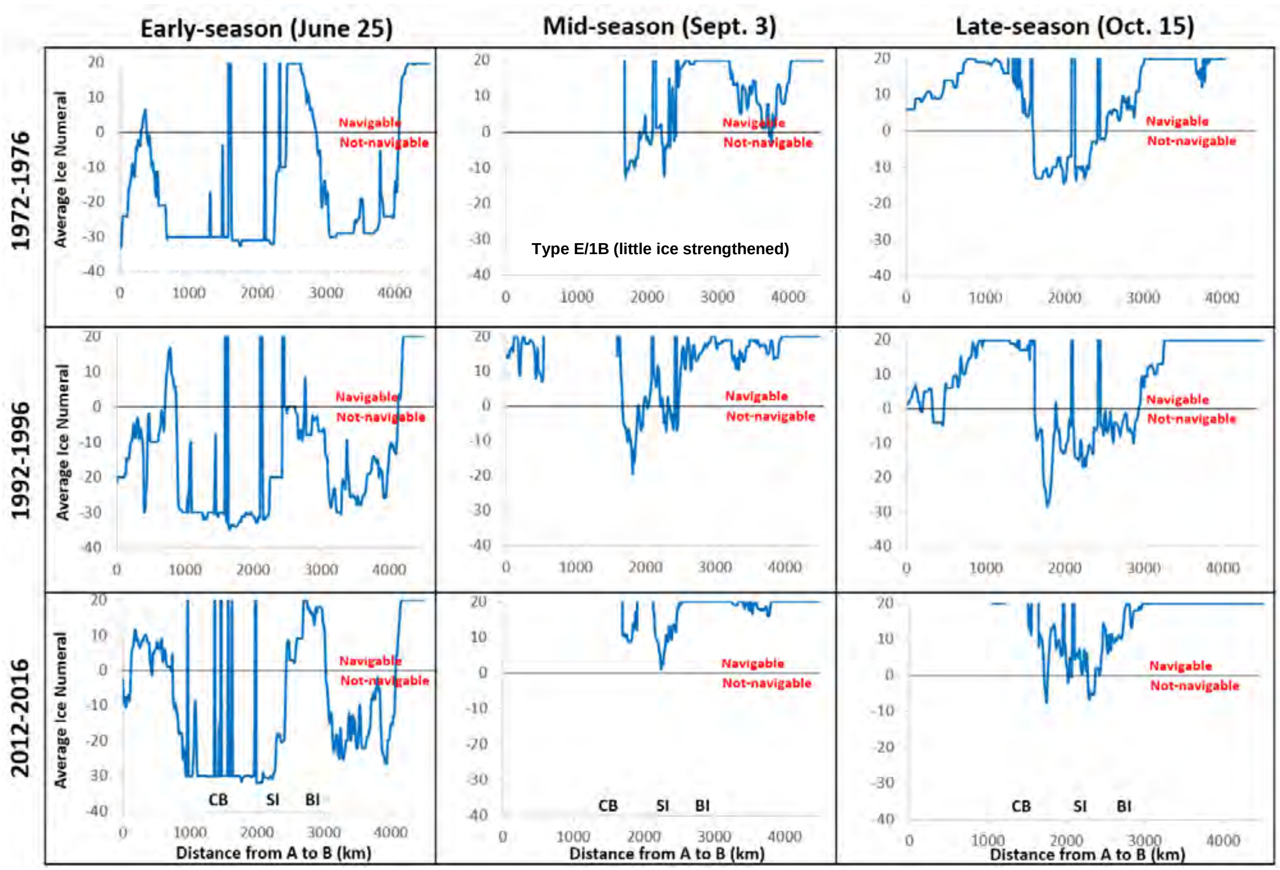


Figure 16. Changes in ice navigability over time along the primary Northwest Passage route for ships of Ice Class E/1B (little ice strengthened). See Fig. 13 for location of distance markers. CB = Cambridge Bay; SI = Somerset Island; BI = Bylot Island. Note that significant barriers to travel have existed for this ship type and Class B/PC7 (Fig. 15) for almost every season and year over the study period; the only time when navigation has been straightforward has been the mid-season over the period 2012-2016.

4.1 Changes in Shipping Season Opening and Closing Dates

To further understand the temporal changes in sea ice navigability for the NORDREG zone and individual choke points, the 'opening' and 'closing' dates for Ice Class PC7 (medium ice strengthening) were calculated. The opening date is defined as the first week of the year when a vessel could safely navigate into an area, while the closing defines the week when navigation is no longer possible. This analysis is somewhat limited as the Canadian Ice Service only starts producing weekly ice charts for most of the Canadian Arctic in mid-to late-June each year (week 26), but it can still provide a useful indication of how navigability is changing over time.

Across the NORDREG zone as a whole there has been a marked increase in the average length of the shipping season, with the season opening earlier and closing later for PC7 vessels (Fig. 17). This has been particularly marked for areas such as Hudson Bay and Baffin Bay. However, navigability across the entire Northwest Passages is still challenging, as the remaining sea ice is becoming increasingly mobile. Choke points also still remain, as outlined further below.

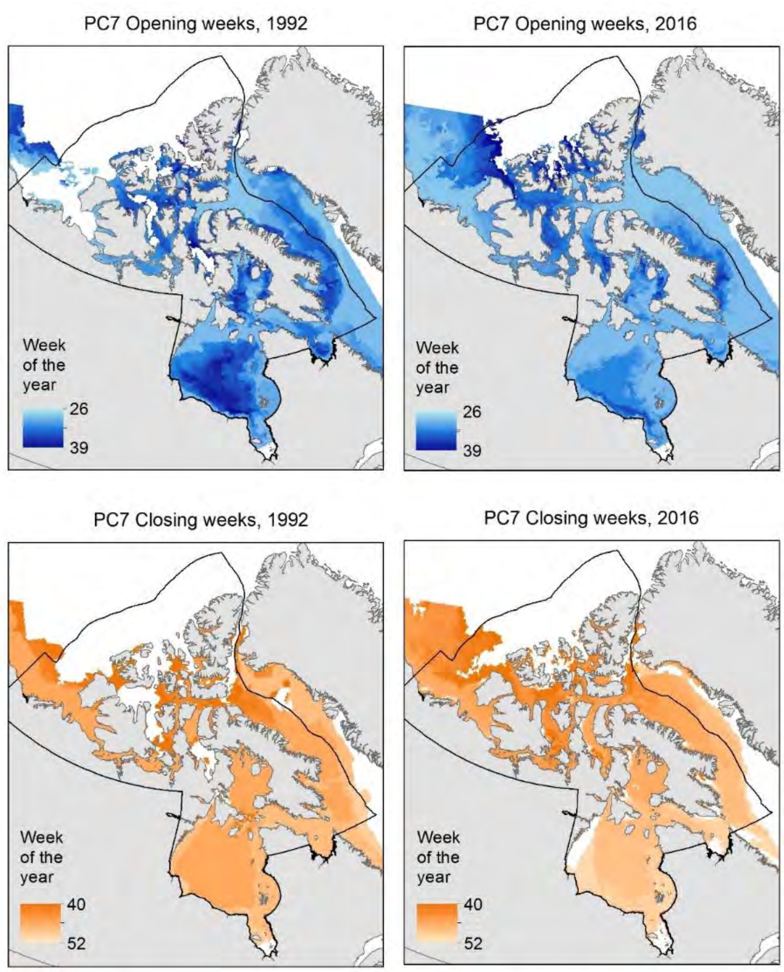


Figure 17. Opening and closing weeks across the NORDREG Zone for PC7 vessels (1992 vs. 2016).

4.1.1 Somerset Island

A large region of difficult ice navigability continues to be present along the west side of Somerset Island (Peel Sound). However, navigability in this area greatly eased between 1992 and 2016 for PC7 vessels as opening is occurring several weeks earlier than before and closing is occurring several weeks later (Fig. 18). The shipping season length along the currently preferred route along the east side of Somerset Island through Prince Regent Inlet and Bellot Strait near Fort Ross is also increasing, with travel conditions in this area much easier than on the west side of Somerset Island. In 1992, there was one voyage that appears to have occurred during 'closed' weeks. The Frontier Spirit Passenger Ship travelled along Peel Sound on August 25, 1992, when the Polar Class shows that the southern end did not open for PC7 ships until week 38, on September 14-20.

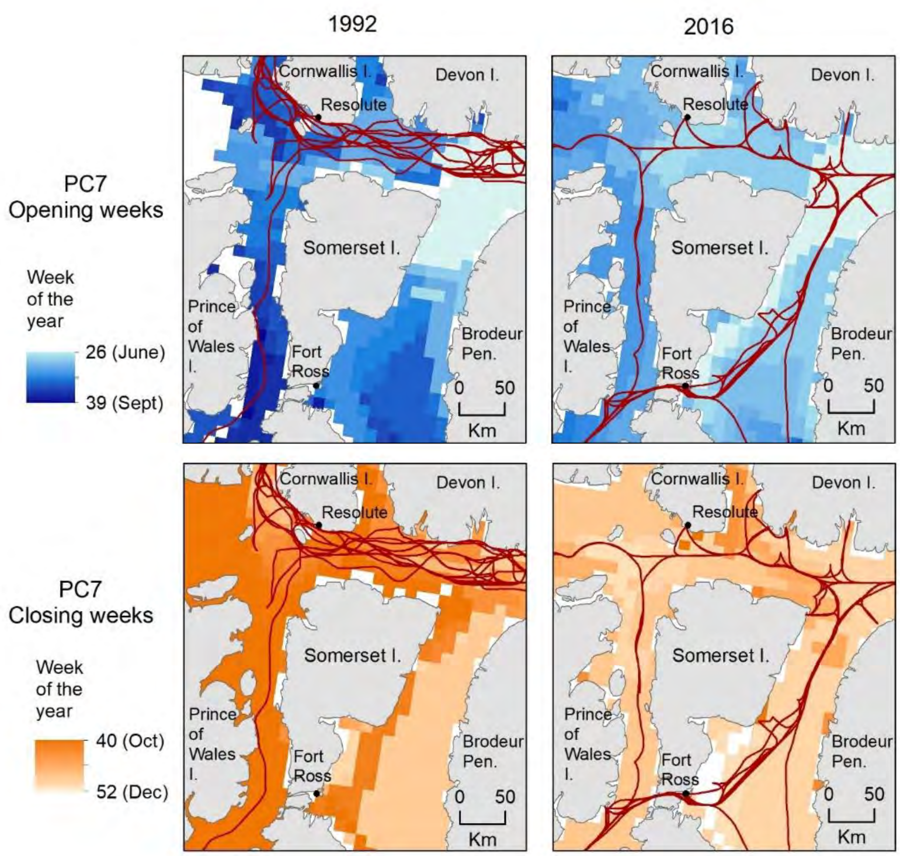


Figure 18. Opening and closing weeks for Somerset Island for PC7 vessels (1992 vs. 2016). Red lines show all PC7 ship tracks that occurred throughout the year. In 1992 one ship travelled along Peel Sound when its Polar Class showed the southern end was closed to PC7 ships.

4.1.2 Bylot Island

The eastern entrance to the Northwest Passages is along the south side of Bylot Island and through the region of Lancaster Sound to the north (Tallurutiup Imanga National Marine Conservation Area). This is a very important shipping corridor and is where the largest congruence of shipping tracks has been observed over the 1990-2017 time period. The shipping season has become substantially longer around Bylot Island between 1992 and 2016, by over a month in locations to the south of the island (Fig. 19a).

When changes are averaged for the region as a whole, it is clear that the closing season is becoming later (Fig. 19b). The opening season is also becoming earlier, but to a lesser extent. However, quantification of the opening season changes is made difficult by the lack of sea ice charts prior to week 26.

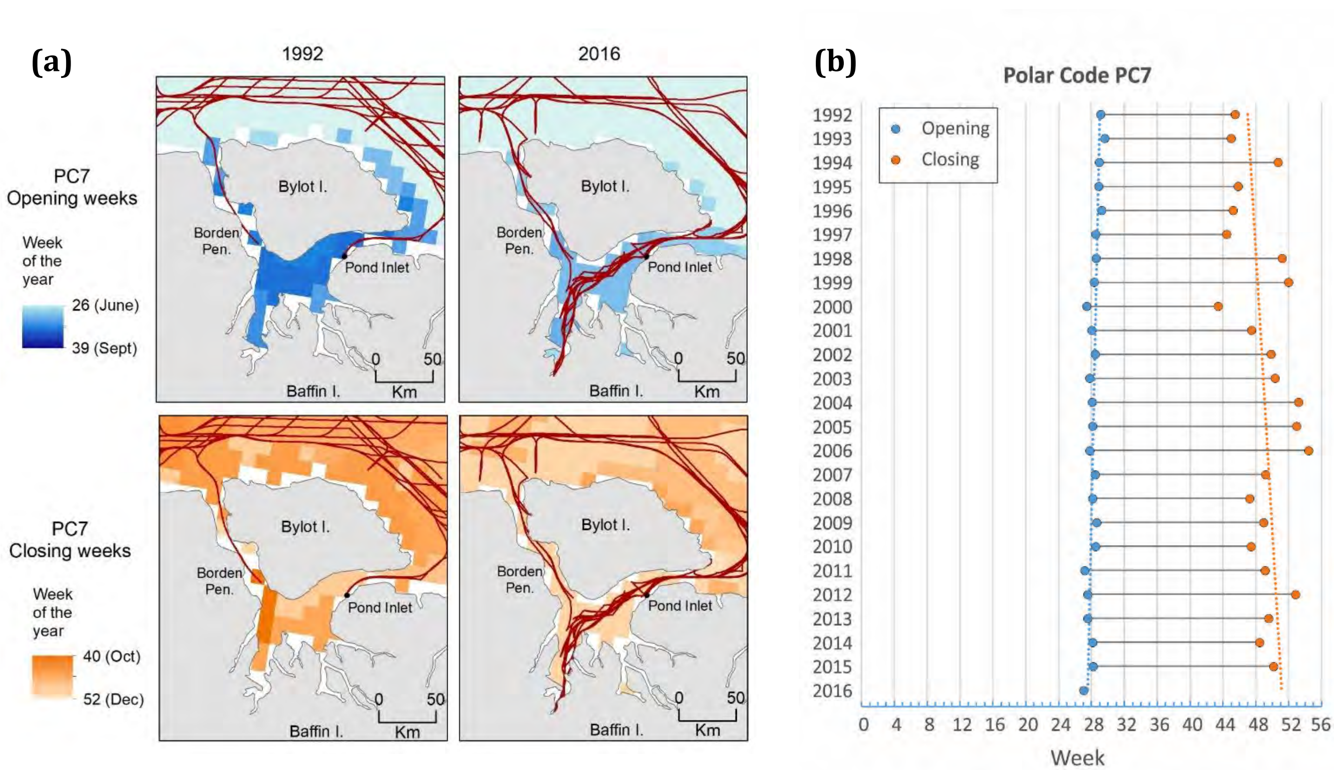


Figure 19. (a) Opening and closing weeks for Bylot Island for PC7 vessels (1992 vs. 2016). Red lines show all PC7 ship tracks that occurred throughout the year. There were no tracks that occurred during the 'closed' weeks in either 1992 or 2016. (b) Change in shipping season length for PC7 vessels from 1992-2016 (average of entire region outlined by polygon in part a). Note: occasionally the shipping season closes in the following January, i.e. after week 52. In addition, ice charts begin in week 26 but opening may occur prior to this time.

4.1.3 Cambridge Bay

The region around Cambridge Bay has experienced some of the greatest increase in shipping season lengths due to changing ice conditions (Fig. 20). This region receives limited import of ice from elsewhere, and is further south than the other choke points. The shipping season around Cambridge Bay that is considered safe and allowable based on Canadian Regulation for PC7 vessels was over a month longer in 2016 than in 1992.

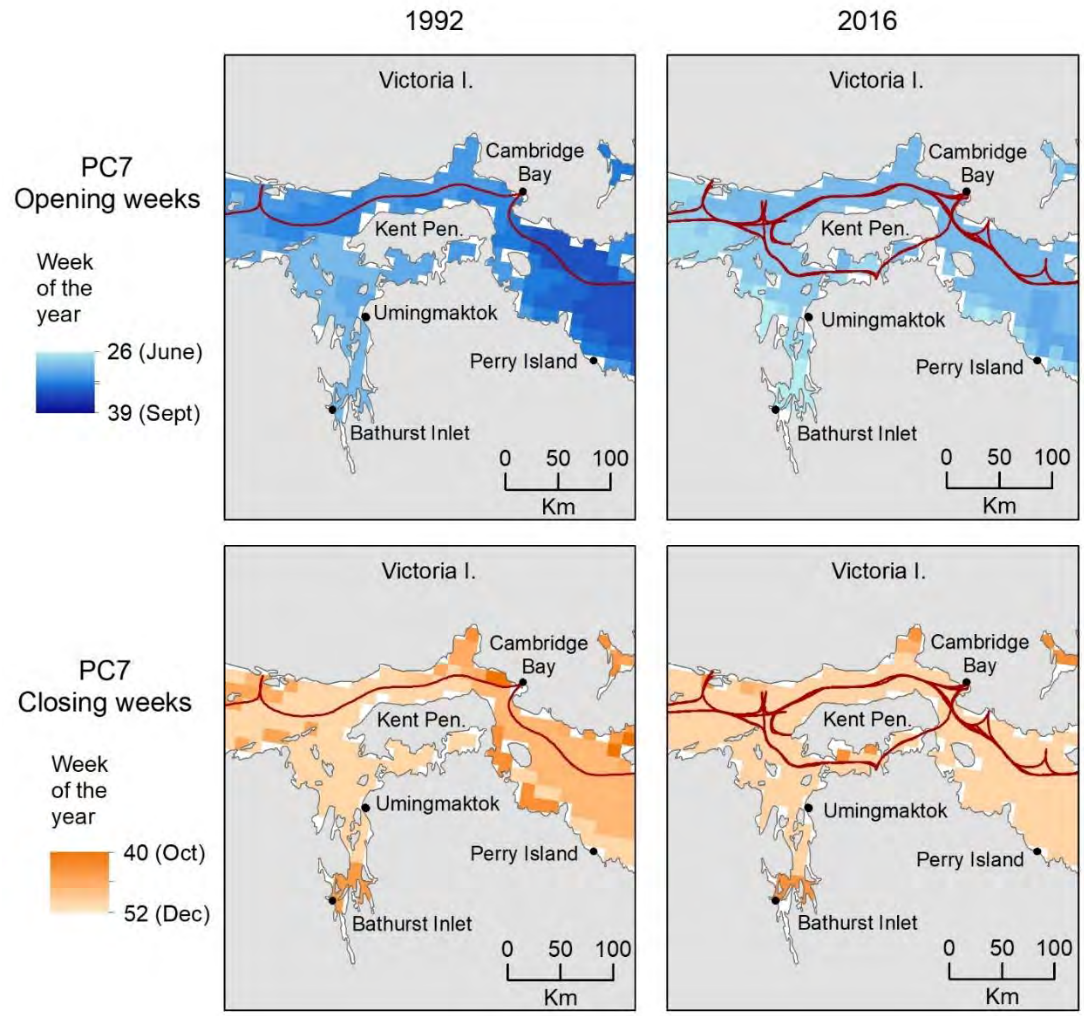


Figure 20. Opening and closing weeks for Cambridge Bay for PC7 vessels (1992 vs. 2016). Red lines show all PC7 ship tracks that occurred throughout the year. There were no tracks that occurred during the 'closed' weeks in either 1992 or 2016.

4.2 Influence of Seasonality on Ship Voyages

From the data presented above (e.g., Figs. 14-16), it is clear that the risks from sea ice for ships in Arctic Canada are highly influenced by seasonality. For example, only highly-strengthened PC3 ships are able to safely navigate in all seasons (Fig. 14), compared to long periods (often >10 months/year) when ships with medium or little or no strengthening are unable to safely navigate due to the presence of sea ice (Figs. 15, 16). For these vessels they are only able to safely travel through the Somerset Island and Cambridge Bay choke points (and therefore the Northwest Passage) in the middle of the summer in the recent past, and in the 1990s weren't able to pass through these regions at all. However, the large variability in sea ice conditions that occur from year to year, even in recent years, means that they can still experience significant risk and get stuck (e.g., Washington Post, '*Even small boats are tackling the fabled Northwest Passage. The ice doesn't always cooperate*', August 9, 2017).

To extend the analysis from section 4.0, an assessment of voyages made by region are provided below by month and by vessel class, for the five time periods between 1992 and 2017. Note that this analysis counts individual ship voyages, rather than raw vessel numbers listed above, to provide an accurate indication of shipping intensity (i.e., some ships make more than one voyage per season, such as cruise ships making multiple trips with different groups of passengers).

4.2.1 Somerset Island

There has been a marked increase in voyages in the month of August around Somerset Island, increasing from 64 in the 1992-96 time period to 180 in recent years (2012-17) (Table 11, Figure 21). Voyages in July have stayed relatively constant, while voyages in September have increased but not as dramatically as August. Similar to the overall trends described in section 3, the number of highly ice strengthened ships (PC3) has decreased while less ice strengthened vessels (PC7 and 1B) have increased, particularly in the months of August and September (Table 12). The spring shoulder season has not experienced any increases in ship traffic, while the fall shoulder season has seen increases, though not significant.

Table 11. Total voyage counts by month for Somerset Island.

	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
May	0	0	0	0	0
June	0	0	0	1	0
July	19	25	18	20	18
August	64	59	56	96	180
September	40	28	24	21	64
October	6	9	0	4	10
November	1	0	0	1	0

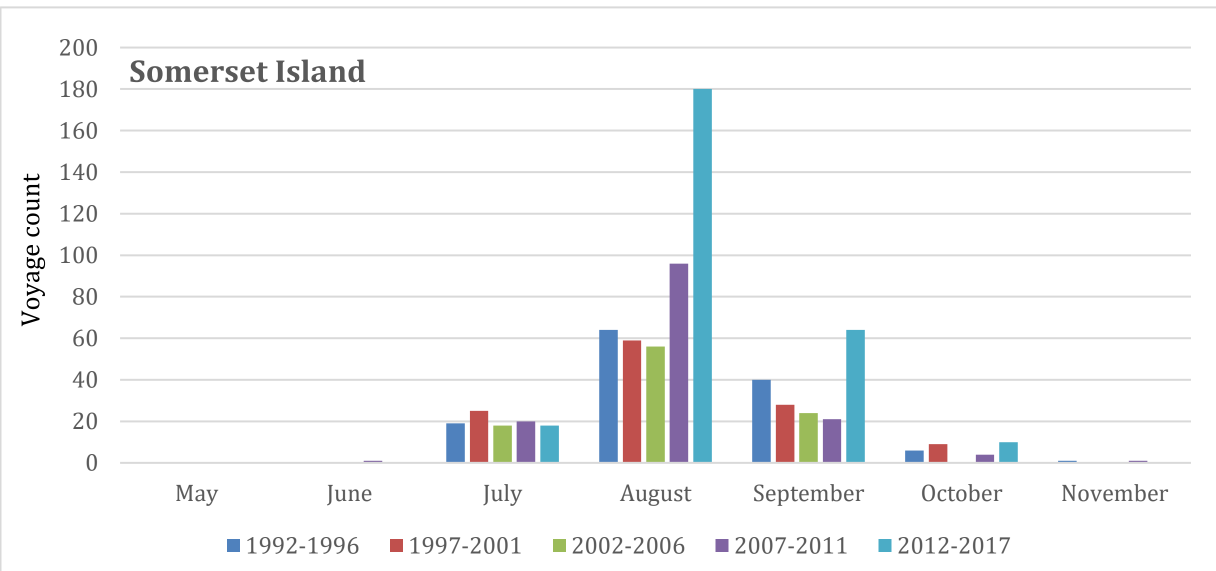


Figure 21. Trends in voyage counts per month for Somerset Island (data from Table 11).

Table 12. Voyage counts by month for the representative Ice Classes for Somerset Island.

		1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
May	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0
June	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0
July	PC3	8	8	1	2	1
	PC7	3	0	5	3	2
	1B	1	5	0	0	1
August	PC3	15	5	11	2	0
	PC7	12	20	15	21	44
	1B	6	6	1	3	11
September	PC3	8	4	4	0	1
	PC7	8	5	3	11	31
	1B	3	7	2	1	7
October	PC3	4	6	0	0	2
	PC7	0	1	0	2	2
	1B	1	0	0	0	2
November	PC3	1	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0

4.2.2 Bylot Island

The number of total voyages for Bylot Island are the highest compared to the other two regions. Total voyage counts in August and September have increased by 7 times and 3 times, respectively, between 1992-96 and 2012-17 (Table 13; Figure 22). Voyages are also increasing in July, but are still highly variable in the shoulder months of June and October. As observed overall and in the other regions, the number of vessel voyages by highly ice strengthened ships have decreased over time while ships that are less ice strengthened have increased rapidly (Table 14).

Table 13. Total voyage counts by month for Bylot Island.

	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
May	0	0	0	0	0
June	0	0	0	1	0
July	5	7	9	13	35
August	33	50	47	65	208
September	27	24	20	29	107
October	19	10	7	3	15
November	1	0	0	0	1

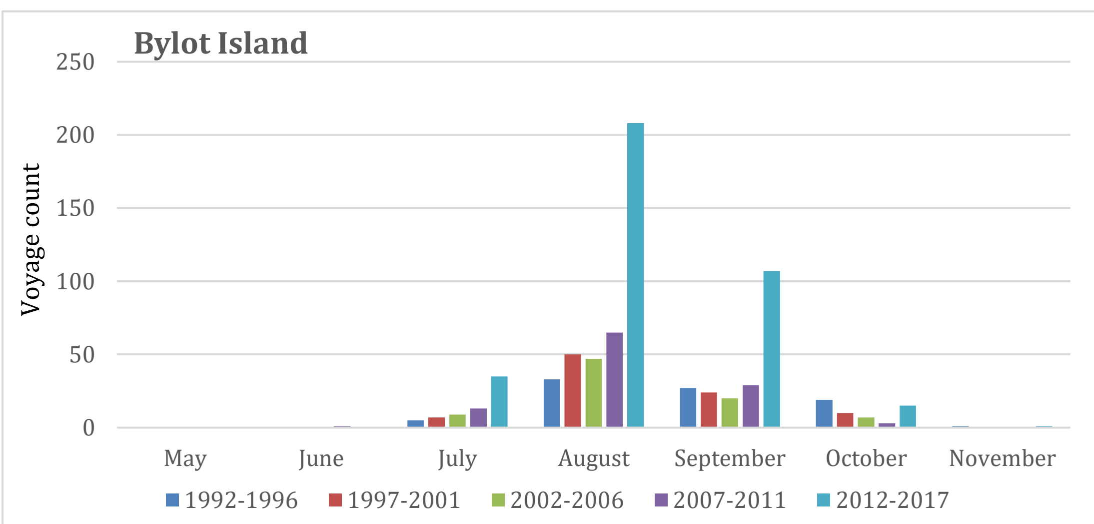


Figure 22. Trends in voyage counts per month for Bylot Island (data from Table 13).

Table 14. Voyage counts by month for the representative Ice Classes for Bylot Island.

		1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
May	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0
June	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0
July	PC3	3	2	0	0	0
	PC7	0	0	3	3	16
	1B	0	1	0	0	1
August	PC3	9	5	2	1	0
	PC7	2	22	17	23	101
	1B	4	3	2	4	13
September	PC3	5	2	0	1	0
	PC7	6	6	4	13	67
	1B	1	8	0	2	11
October	PC3	3	2	0	0	0
	PC7	5	1	2	2	10
	1B	1	1	0	0	1
November	PC3	1	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0

4.2.3 Cambridge Bay

Similar trends can be observed around Cambridge Bay, where there has been a quadrupling of ship voyages in the month of August since 1992 (Table 15; Figure 23). There has been more significant increases in voyages in the month of September in this region from 15 in 1992-96 to 65 in 2012-17. The number of October voyages have increased the most around Cambridge Bay compared to the other two regions. In terms of hull strength, the shoulder seasons of June, July, and October are not experiencing increases in non-ice strengthened vessels (Table 16). However, in both August and September there are strong trends with decreases in highly ice strengthened vessels and rapid increases in voyages by vessels with little ice strengthening.

Table 15. Total voyage counts by month for Cambridge Bay.

	1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
May	0	0	0	0	0
June	0	0	0	0	0
July	7	8	10	11	14
August	30	30	40	74	139
September	15	11	14	30	65
October	0	2	0	8	10
November	0	0	0	0	0

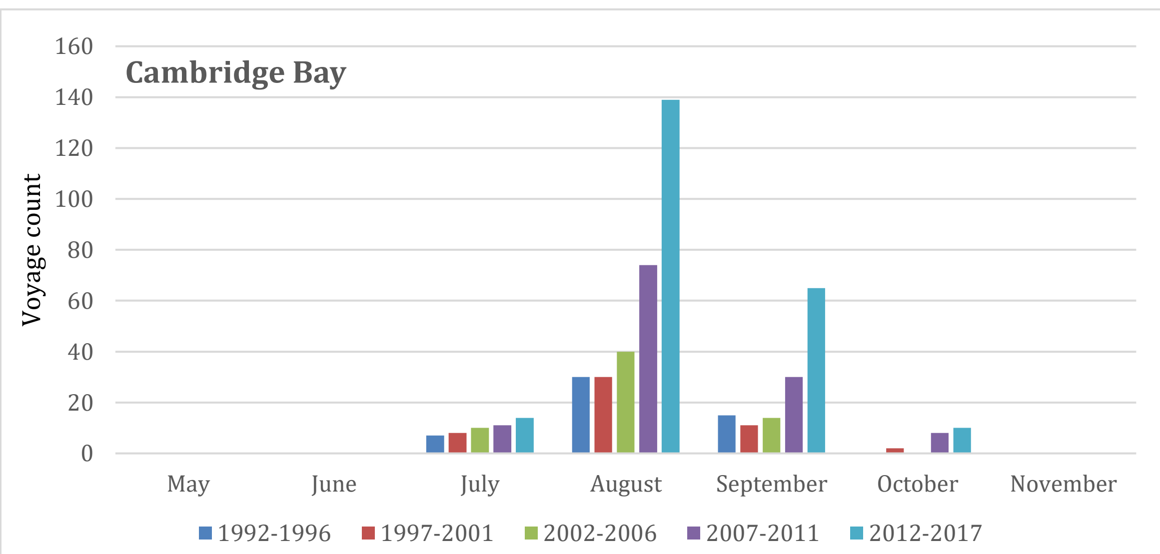


Figure 23. Trends in voyage counts per month for Cambridge Bay (data from Table 15).

Table 16. Voyage counts by month for the representative Ice Classes for Cambridge Bay.

		1992-1996	1997-2001	2002-2006	2007-2011	2012-2017
May	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0
June	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0
July	PC3	4	4	2	2	1
	PC7	0	1	3	0	0
	1B	1	1	0	3	3
August	PC3	2	1	4	0	0
	PC7	1	0	3	10	24
	1B	11	15	12	10	21
September	PC3	1	0	1	0	0
	PC7	1	1	0	10	28
	1B	3	6	9	12	11
October	PC3	0	0	0	0	2
	PC7	0	0	0	3	2
	1B	0	0	0	2	2
November	PC3	0	0	0	0	0
	PC7	0	0	0	0	0
	1B	0	0	0	0	0

5.0 Changing Levels of Risk Related to Ship-Ice Interactions and Choke Points

Despite observations that reduced sea ice extent will increase navigability and shipping season lengths in the Canadian Arctic, it is possible that the risks related to ship-ice interactions will actually increase in the short term under warming conditions. This is related to the fact that while climate change is causing a reduction in sea ice extent and thickness in the Canadian Arctic, it is simultaneously increasing the mobility of hazardous sea ice, thus creating navigational challenges in some geographic regions (e.g., areas to the west of Somerset Island). The operational risks also vary depending on the Ice Class (i.e., level of ice strengthening) of the vessels and on the extent to which sea ice is prevalent and changing in the regions where ships tend to operate. The study is limited in its examination of only three choke points and a general analysis of the Northwest Passage, so there are likely other risk areas that warrant consideration in the future.

Based on the results of this study a number of risk-related conclusions can be made:

(a) Over the past 25 years reductions in sea ice have occurred coincident with an increase in vessel traffic

The marked reduction in sea ice in the Canadian Arctic over the past several decades (Serreze and Stroeve, 2015; Kwok, 2018) has coincided directly with a period of rapid increase in ship traffic (Pizzolato et al., 2014; Dawson et al., 2018). Vessel traffic by distance travelled in Arctic Canada has increased by >250% from 364,179 km in 1990 to 918,266 km in 2015 (Dawson et al., 2018). The total volume of traffic in Arctic Canada is low compared to other Arctic regions such as Svalbard, Russia, and Alaska, but the rate of increase has still been notable relative to the lack of infrastructure and services in the region.

Overall, analysis of ice navigability patterns across the Canadian Arctic indicates that it is becoming generally easier for all ship types to navigate this region. This is due to overall reductions in sea ice, and an increase in shipping season length, albeit at different rates depending on vessel ice class. There are many regions where vessels with little ice-strengthening, such as Ice Class 1B (e.g. Pleasure Craft), were previously unable to go in the 1970s-1990s but are now regularly present. For example, prior to 2000, there were very few periods when pleasure craft were able to transit the Northwest Passage, whereas today >20 pleasure craft per year transit this part of the Arctic. An increasing number of ships in the region will inherently increase overall risk, especially considering the lack of infrastructure and support services (e.g., Search and Rescue bases) for vessels.

(b) There are now fewer highly ice strengthened vessels and more non-ice strengthened vessels operating in the Canadian Arctic compared to the past

Since 1990 there has been a marked reduction in the voyages of highly strengthened PC3 ships, and a large increase in the number of voyages of ships with medium ice strengthening (PC7) and little (Ice Class 1B) or no ice strengthening. This trend is particularly apparent in the Northwest Passages in the 2010s compared to the 1990s. For example, in the waters around Somerset Island in the 1990s >36% of all vessels were in classes PC1 to PC3, compared to <15% in those classes over 2012-2017. There was more than a quadrupling of PC7 vessels between the 1992-96 time period (n=15) to the 2012-17 (n=72) time period. Only one vessel reported no ice strengthening in the 1990s, but over a third of vessels (87 out of 253) fell into this category in the 2012-2017 time period.

Passenger Ships are the vessel type that has had the biggest relative change in ice strengthening over time. For example, it was common for Passenger Ships to be highly ice strengthened until 2006 (n=5 per period), but in 2012-2017 there was only one Passenger Ship with this class of ice strengthening. Passenger Vessels with medium ice strengthening (PC7) are now the most common, together with many Pleasure Craft with little or no ice strengthening. It has only been in the past decade that sea ice conditions have become navigable in some years for vessels for medium or little ice strengthening to pass through the Northwest Passages, but conditions are still highly variable from one year to the next, and navigation has still been difficult in recent years such as 2018.

(c) Climate change has increased sea ice mobility creating choke points and navigation hazards

Despite overall increases in open water areas and shipping season lengths, general variability of sea ice in the Canadian Arctic has greatly increased, particularly in the central part of the Northwest Passages (Haas and Howell, 2015; Tseng and Cullinane, 2018). Previous studies have noted that increased temperatures are enhancing sea ice mobility. For example, melting first-year ice in the Northwest Passages is now allowing for greater import of old, thicker ice from the Arctic Ocean which was previously intact and less mobile (Howell et al. 2013). This situation can create increased risks for ship navigation as multi-year ice is much more hazardous than first-year ice, especially for non-

> "*There's a bit of a misconception that climate changes means warming, less ice, and it's easier to navigate… In fact, it's making navigation a little riskier or more complex. For years, we could be certain that ice would be there or wouldn't be there… What we're seeing more recently is we don't know what kind of weather patterns and what kind of ice we're going to get*."
>
> Neil O'Rourke, assistant commissioner of the Canadian Coastguard in the Arctic (Financial Post, Jan. 2, 2019)

little- and-medium-ice strengthened vessels.

Areas which previously had little change in sea ice age or type from one year to the next are now experiencing rapid swings in sea ice characteristics between years that are less predictable than in the past. In some years there are large regions of open water, but in other years extensive thick multi-year sea ice floes reach the interior channels of the Canadian Arctic Archipelago from the Arctic Ocean. Furthermore, it is becoming increasingly common for there to be large unpredictable changes in navigability in certain areas because of changing wind patterns. For example, loose mobile ice can more easily and more rapidly move during periods of increased wind and intense storms, changing an open water area from navigable to non-navigable in a matter of hours.

(d) The choke point region around Somerset Island is experiencing some of the greatest increases in sea ice mobility concurrent with a relatively rapid increase in non-ice strengthened vessels

The area around Somerset Island, and in particular the area around Bellot Strait by Fort Ross, is highlighted as an important choke point with the potential to create navigational risks for transiting vessels. Indeed, rescues of little or non-ice strengthened private pleasure craft have occurred several times in the Northwest Passage over the past couple of years, such as several in the Bellot Strait last August (CBC, 2018a, 2018b), with the Coast Guard reporting at least 20 Arctic-based Search and Rescues in 2018 (Coast Guard, 2018). This region is experiencing some of the greatest increases in sea ice mobility due to the dynamic import of multi-year ice that is breaking up in the Arctic Ocean and transiting southward and into the Northwest Passages (Howell et al. 2013), and has also witnessed a greater than doubling of ship traffic over the period 2012-2017 (42 vessels/yr) compared the periods prior to 2006 (18 vessels/yr).

Bellot Strait has also had a clear increase in the routing of weaker vessels (PC7 and 1B). For example, not a single PC7 vessel passed through Bellot Strait in the 1990s, but a significant number of them passed through this area over the period 2012-2017, including non-, little- or medium-ice strengthened Tanker Ships (n=20), Passenger Ships (n=19), and General Cargo ships (n=26).

In terms of ice navigability, it has been much easier to navigate on the eastern side of Somerset Island (this region is now typically ice-free in summer), compared to the western side of it (where ice still often remains for the summer, and in some years there is increased import of multi-year ice from the Arctic Ocean). As vessel numbers have increased, as vessels have shifted towards much less ice strengthened categories, and as ice conditions have opened up on the east side of Somerset Island, ships have more often chosen the routing with the lowest risk.

(e) Risks from sea ice for ships in Arctic Canada are highly influenced by seasonality

For vessels with little ice strengthening (Ice Class 1B), the only time when they have been able to regularly navigate from one end of the Northwest Passages to the other has been in the mid-season (early September) over the past decade (Figure 16). In earlier periods the ice conditions in mid-season and late-season choke points around Cambridge Bay and Somerset Island, and sometimes Bylot Island, have been too great for these kinds of ships to pass. Early September (mid-season) accessibility to the Northwest Passages for medium ice strengthened (PC7) ships has increased dramatically over the past decade, compared to the 1970s to early 2000s (Figure 15). In addition, late season conditions have also eased in recent years, but only via a narrow passage to the south and east of Somerset Island.

Given the rapid recent shift towards vessels with medium or less ice strengthening as the dominant ship type now operating in the Northwest Passages, the relatively narrow time window and limited region in which these vessels can safely operate means that significant risks still exist for their operation. The large variability in sea ice conditions that occur from year to year, even in recent years, means that they can still experience navigational hazards and get stuck (e.g., Washington Post, 2017). Further, there are still significant hindrances to navigation for all medium or less ice strengthened vessels over large areas in the early season (late June).

6.0 Conclusion

In conclusion, shipping in the Canadian Arctic is undergoing profound change. Vessel numbers and distance travelled are rapidly increasing, with a shift towards many more ships with little to no ice strengthening than has ever been seen before. Sea ice navigability is also easing over time, but not necessarily as quickly as the reduction in ship strength. In some warm summers over the past decade, vessels with no ice strengthening have been able to easily pass through the Northwest Passages. However, sea ice conditions are still highly variable from one year to the next, meaning that a voyage through this region can quickly turn to disaster for poorly strengthened vessels with inexperienced crew, particularly Pleasure Craft. This was highlighted by the rescue and sinking of several vessels of this type in the summers of 2017 and 2018 (Washington Post, 2017; CBC, 2018a, 2018b; Coast Guard, 2018).

There is limited infrastructure and a lack of shipping support services in Arctic Canada and this will in effect compound any risks that exisit for ship-ice interactions. It is difficult to model or understand the cumulative risks associated with climate change and shipping but it is clear that the combination of increased shipping traffic, with increased numbers of non-ice strengthened vessels, increased mobility of sea ice and the presence of identifiable choke points with limited infrastructure and support services, will create additional risks for the region.

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8.0 Appendix

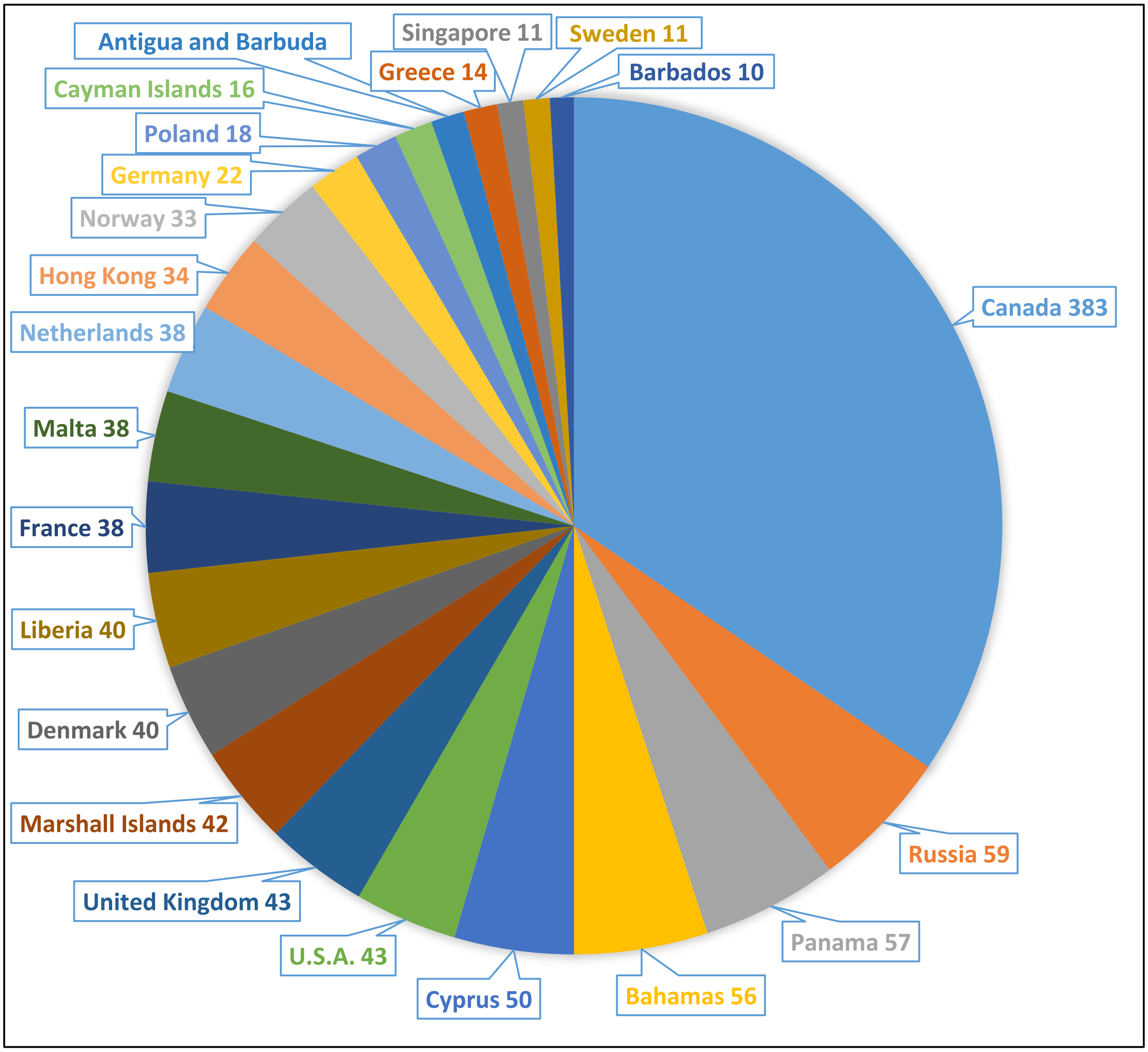

Figure A1. Distribution of vessels by flag state recorded in the NORDREG zone, 1990-2018, for states with 10 or more registrations.

Table A1. Number of vessels by flag state recorded in the NORDREG zone, 1990-2018

Flag State	Number
Canada	**383**
Russia	**59**
Panama	**57**
Bahamas	**56**
Cyprus	**50**
U.S.A.	**43**
United Kingdom	**43**
Marshall Islands	**42**
Denmark	**40**
Liberia	**40**
France	**38**
Malta	**38**
Netherlands	**38**
Hong Kong	**34**
Norway	**33**
Germany	**22**
Poland	**18**
Cayman Islands	**16**
Antigua and Barbuda	**14**
Greece	**14**
Singapore	**11**
Sweden	**11**
Barbados	**10**
Finland	**8**
New Zealand	**8**
Switzerland	**8**
Estonia	**7**
Belgium	**6**
Australia	**5**
Bulgaria	**5**
Saint Vincent	**5**
China	**4**
Japan	**4**
Lithuania	**4**

Flag State	Number
Thailand	**4**
Austria	**3**
Croatia	**3**
Iceland	**3**
Turkey	**3**
Cook Islands	**2**
Egypt	**2**
Gibraltar	**2**
Greenland	**2**
Korea	**2**
Ukraine	**2**
Brazil	**1**
British Virgin Islands	**1**
Curacao	**1**
Falkland Islands	**1**
Hungary	**1**
India	**1**
Indonesia	**1**
Italy	**1**
Jamaica	**1**
Latvia	**1**
Malaysia	**1**
Philippines	**1**
Seychelles	**1**
South Africa	**1**
Spain	**1**
Trinidad and Tobago	**1**
Turks Islands	**1**
Union of Comoros	**1**
Unknown	**7**
TOTAL	**1227**