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Analysis of Changing Levels of Ice Strengthening (Ice Class) among Vessels Operating in the Canadian Arctic over the Past 30 Years

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ABSTRACT. Climate change is impacting sea ice extent and thickness in the Canadian Arctic, creating an increase in maritime accessibility that may accentuate risks related to ship operations due to a related increase in sea ice mobility. The overall risk to ships operating in regions with mobile sea ice will vary significantly depending on the ice class (i.e., level of ice strengthening) of the vessel. Several studies have examined the implications of sea ice change for ship operations, but to date limited analysis has been conducted to understand whether levels of ice strengthening are changing among vessels operating in the Arctic. To address this research gap, more than 100,000 ship position reports covering a 30-year time period were obtained from the Canadian Coast Guard in order to evaluate changes in shipping activities across Arctic Canada by vessel ice class. Between 1990 and 2019, there has been a substantial reduction in the number of highly strengthened PC3 ships (25%) and a large increase in the number of medium-strengthened PC7 (605%) and low-strengthened 1B (180%) vessels. These trends are particularly acute for certain vessel types, including bulk carriers, cargo ships, and passenger vessels, and also within certain geographic areas, including the Northwest Passage. The combination of climate change–induced increases in sea ice–related navigational hazards and the observed decrease in highly strengthened ships operating in the Canadian Arctic could lead to a larger number of accidents and incidents as a proportion of total operational vessels and points to the need for infrastructure and service investment congruent with overall increases in particular types of maritime shipping activities expected in the near- to medium-term future.

Key words: Arctic shipping; climate change; sea ice; shipping risk; hull ice strengthening; ice class; Northwest Passage

RÉSUMÉ. Le changement climatique a des incidences sur l'étendue et l'épaisseur de glace de mer dans l'Arctique canadien, se traduisant ainsi par un plus grand accès maritime susceptible d'accentuer les risques liés à l'exploitation de navires en raison de la plus grande mobilité de la glace de mer. Dans l'ensemble, le risque lié à l'exploitation de navires dans les régions où se trouve de la glace de mer mobile variera considérablement en fonction de la cote glace du navire (soit le degré de renforcement contre les glaces). Plusieurs études ont examiné les répercussions du changement de la glace de mer sur l'exploitation des navires, mais jusqu'à maintenant, peu d'analyses ont été effectuées pour comprendre si les degrés de renforcement contre les glaces changent dans le cas des navires exploités dans l'Arctique. Pour combler cet écart de recherche, plus de 100 000 rapports de positions de navires s'étendant sur une période de 30 ans ont été obtenus de la Garde côtière canadienne afin d'évaluer les changements en matière d'activités de navigation dans l'Arctique canadien d'après la cote glace des navires. De 1990 à 2019, on a enregistré une réduction substantielle du nombre de navires PC3 hautement renforcés (25 %) et une grande augmentation du nombre de navires PC7 moyennement renforcés (605 %) et de navires 1B faiblement renforcés (180 %). Ces tendances sont particulièrement prononcées pour certains types de navires, dont les vraquiers, les navires de charge et les navires à passagers, ainsi que dans certaines régions géographiques, dont le passage du Nord-Ouest. Ensemble, les hausses de dangers de la navigation liés à la glace de mer attribuables au changement climatique et la diminution observée des navires hautement renforcés dans l'Arctique canadien pourraient entraîner un plus grand nombre d'accidents et d'incidents par rapport au nombre total de navires en exploitation. Cela fait ressortir la nécessité d'investir dans les infrastructures et les services en harmonie avec l'augmentation générale de types particuliers d'activités de navigation qui est attendue à court terme et à moyen terme.

Mots clés : navigation dans l'Arctique; changement climatique; glace de mer; risques liés à la navigation; renforcement des coques contre les glaces; cote glace; passage du Nord-Ouest

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INTRODUCTION

Sea ice in the Canadian Arctic presents navigational challenges for ship operators, particularly in more northerly regions and throughout the Northwest Passage (NWP) where there is a higher prevalence of mobile multiyear ice combined with increased overall accessibility and longer open water seasons (Howell and Yackel, 2004; Howell et al., 2013; Tseng and Cullinane, 2018; Copland et al., 2021; Mudryk et al., 2021). The operational risks from changing sea ice conditions will vary significantly depending on a number of factors of which one of the most important is the ice class (i.e., level of hull ice strengthening; hereafter, referred to as ice strengthening) of vessels operating in the region.

Existing regulations including the Arctic Ice Regime Shipping System (AIRSS) and the Polar Operational Limitation Assessment Risk Indexing System (POLARIS) are used to manage which vessel classes can safely operate when and under what ice conditions in Arctic Canada. These regulatory regimes are in place to decrease navigational risks in ice-covered waters and, in doing so, consider both ice conditions and vessel classification by level of ice strengthening. Having a complete understanding of the type of vessels operating in Arctic Canada by ice class may aid in better comprehending the level of navigational risks posed by ice for vessels operating now and in the near future under a changing climate. In this paper, we focus on Arctic Canada as a whole and the NWP specifically in order to analyze changes in the level of ice strengthening among vessels over a period of three decades (1990–2019).

Patterns of Ship Traffic and Navigational Hazards in Arctic Canada

There has been a marked increase in ship traffic in the Canadian Arctic over the past several decades (Pizzolato et al., 2014), including an increase of more than 250% in the total annual distance traveled by ships between 1990 and 2015 (Dawson et al., 2018). These increases are highlighted by a substantial increase in destination traffic from pleasure craft, tankers, bulk carriers, and general cargo vessels servicing growing communities, tourists, and resource extraction projects (Pizzolato et al., 2016; Johnston et al., 2017; Dawson et al., 2018). Some studies have demonstrated correlations between the observed increase in ship traffic and reductions in sea ice throughout the Arctic (e.g., Pizzolato et al., 2016), including an overall decrease in sea ice age, thickness, and extent (Serreze and Stroeve, 2015; Kwok, 2018; Mudryk et al., 2018; Derksen et al., 2019). These changes to sea ice are expected to continue as the climate warms (Jahn, 2018; Sigmond et al., 2018; Mudryk et al., 2021), which will very likely result in additional increases in Arctic ship traffic in the coming decades as the region becomes more accessible overall (Stephenson and Smith, 2015; Melia et al., 2016; Mudryk et al., 2021).

Despite observed and statistically significant decreases in sea ice across the Arctic region, the presence of thick, multiyear ice within the Canadian Arctic Archipelago (CAA) remains a fundamental navigation hazard for ship operators (AC, 2009; Mudryk et al., 2021). Even under future warming scenarios, there will still be ice present in the northern CAA in what is called the Last Ice Area (Derksen et al., 2019; Moore et al., 2019). Further, while total sea ice extent and thickness are decreasing, there is also a corresponding increase in the mobility and interannual variability of ice conditions in the Canadian Arctic (Babb et al., 2013; Kwok et al., 2013; Olason and Notz, 2014; Lukovich et al., 2015; Howell and Brady, 2019), particularly in the central part of the NWP (Haas and Howell, 2015). Areas that 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, making it less predictable than in the past (Haas and Howell, 2015). In some years there are large regions of open water, while in other years, extensive, thick multiyear sea ice floes reach the interior channels of the CAA from the Arctic Ocean (Howell et al., 2013; Haas and Howell, 2015; Moore and McNeil, 2018). These changes in ice conditions are because higher temperatures appear to be increasing sea ice mobility, with the removal of first-year ice in the NWP, as well as the weakening of ice arches and bridges, now allowing greater import of old, thick ice from regions to the north (Howell et al., 2013; Barber et al., 2018; Moore and McNeil, 2018; Vincent, 2019). In short, sea ice is more mobile, variable, and unpredictable than in the past and can still present increased navigational challenges for ship operators (Mudryk et al., 2021).

Risks from Lack of Infrastructure, Services, and other Human Factors

Shipping in the Arctic occurs in remote areas where there is typically a lack of infrastructure and search and rescue (SAR) capabilities, sometimes insufficient charting and other basic information, and generally harsh environmental conditions, including low temperatures and the presence of sea ice (Fu et al., 2016; Kujala et al., 2019). These characteristics complicate Arctic operations and lead to risk to humans, infrastructure, and the environment (Kujala et al., 2019). A large body of literature exists that identifies factors influencing risk in Arctic shipping operations related to environmental conditions (e.g., low visibility, sea ice extent and thickness, high wind), human factors (e.g., improper qualifications of crew, injury, negligence), organizational and management factors (e.g., inadequate emergency planning, insufficient rescue equipment), and characteristics related to the ship itself (e.g., level of ice strengthening, system failure) (Kum and Sahin, 2015; Fu et al., 2016, 2018). One of the major risks for Arctic operations is ships interacting with or becoming beset in sea ice (Kotovirta et al., 2009; Kubat et al., 2013, 2015; Montewka et al., 2015). These ship-ice incidents have a host of consequences, such as uncontrolled ship drift, listing, damage to the hull, and, in the worst case, sinking of the vessel (Fu et al., 2016).

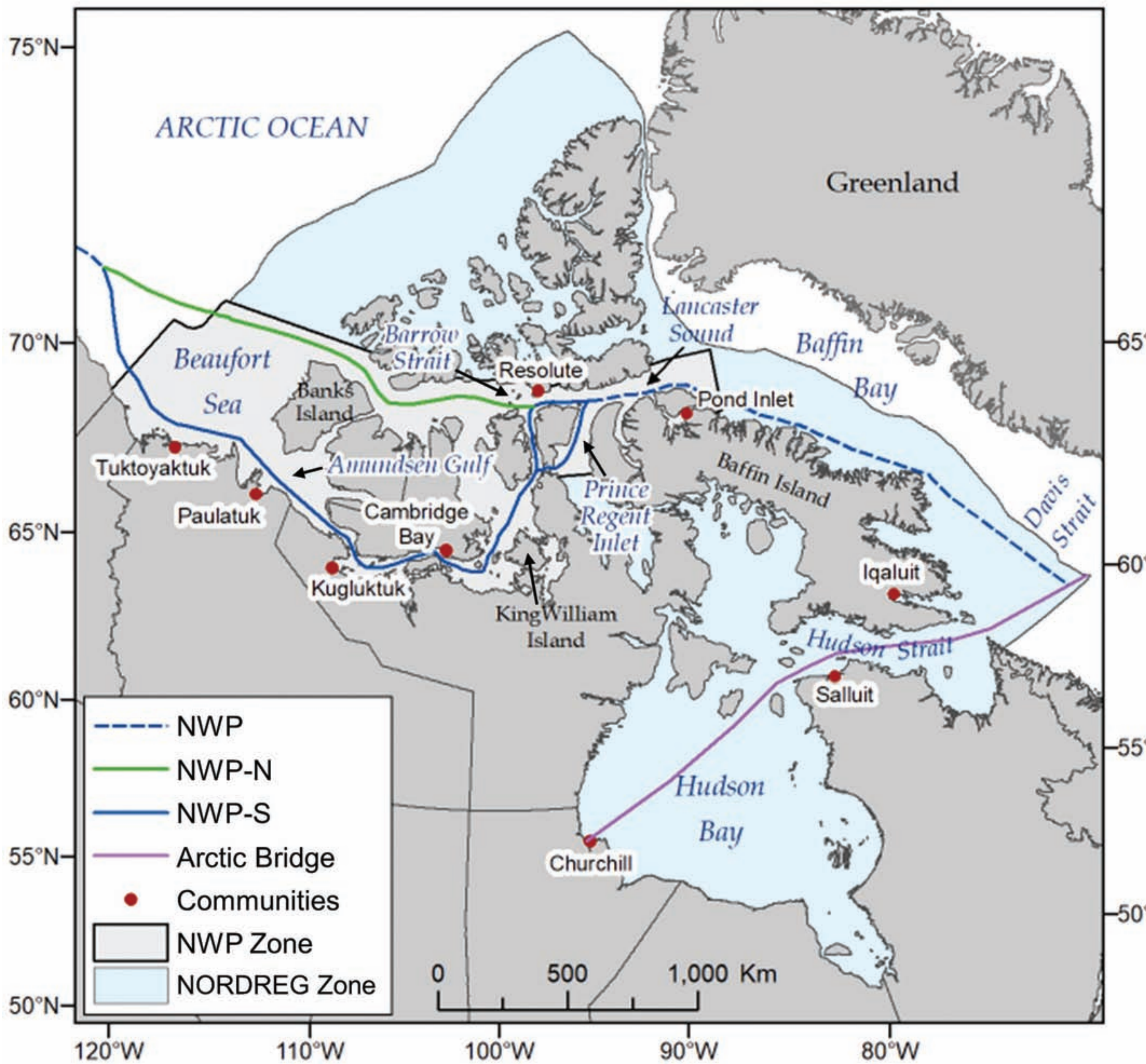


FIG. 1. Map of the Canadian Arctic including the entire NORDREG zone (blue), Northwest Passage zone (light grey), and locations of communities and the primary shipping routes: NWP-N (Northwest Passage-North), NWP-S (Northwest Passage-South), and Arctic Bridge.

When ships do have major incidents or accidents within polar waters, the impacts can be disastrous for the pristine and particularly sensitive environment and for local cultural groups (AC, 2009; CCA, 2016; AMAP, 2017). The direct impacts are also compounded in Arctic Canada due to the remoteness of the region and limited infrastructure, services, and SAR capacity (Ford and Clark, 2019; Kujala et al., 2019). As observed in other regions, long-term ecological impacts were clearly evident after the 1989 *Exxon Valdez* oil spill that devastated Prince William Sound, Alaska (Short et al., 2004; Barron et al., 2020). Other incidents in polar waters include the near sinking of the passenger vessel *Maxim Gorky* near Greenland in 1989, as well as the sinking of the cargo vessel *Finn Polaris* in 1991 in the Canadian Arctic, the passenger vessel M/V *Explorer* in 2007 in Antarctica, and the tour boat *Inuk II* in 2016 near Greenland.

METHODS

Study Area

This study is focused within the Northern Canada Vessel Traffic Services (NORDREG) zone of northern Canada (Fig. 1). The NORDREG zone is the region in which vessels provide reporting of their position and vessel information (e.g., name, flag state, call sign) to the Canadian Coast

TABLE 1. Description of the main vessel types found in the NORDREG zone. After AC (2009) and Dawson et al. (2017).

AMSA 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
General cargo	Carries various types and forms of cargo	Community resupply Roll on/roll off cargo
Bulk carrier	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

Guard. This region encompasses all Canadian Arctic waters, including the Arctic Bridge through Hudson Strait and Hudson Bay, and the NWP through the CAA (Fig. 1). The NWP includes two primary routes: the more commonly used southern shallow water route (NWP-S; Fig. 1) passes to the south of Victoria Island, and the less commonly used northern deepwater route (NWP-N; Fig. 1) extends through Parry Channel. Both routes share the same eastern entrance to the CAA through Lancaster Sound, with most ships (97%) using the southern route.

Analysis of Vessels by Ice Class

In this study, we used over 100,000 ship position reports made to the Canadian Coast Guard Marine Communications and Traffic Services (MCTS) Centres to determine patterns in vessel ice strengthening between 1990 and 2019. According to the Canada Shipping Act (Justice Laws, 2010), the following ships must report their position immediately to the Canadian Coast Guard after first entering the NORDREG 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 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, and
c) vessels carrying as cargo a pollutant or dangerous goods or engaged in towing or pushing a vessel 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 is estimated that 98% of all ships operating in the NORDREG zone notify the Canadian Coast Guard of their presence (Rompkey and Cochrane, 2008), in part because of the advantages accompanied with reporting, such as enhanced SAR response (Johnston et al., 2017).

Ship position reports were obtained from MCTS and collated, duplicates were removed, and the names of ships standardized (e.g., minor typographical errors). Initial quality checking of reported information was undertaken using public databases and websites (e.g., https://www.marinetraffic.com). The primary vessel types (Table 1) were classified according to the Arctic Marine Shipping Assessment (AMSA) (AC, 2009). Inaccuracies may arise from errors within the MCTS reports, inconsistencies between reported values for the same ship, and discrepancies between reported information and the various public databases, but these issues are estimated to affect less than 1% of the total.

MCTS records information on the classification of ice strengthening as provided by individual vessels. This information encompasses a variety of different classification systems (e.g., Arctic Shipping Pollution Prevention Regulations (ASPPR), Lloyd's Register of ice ships, and the Finnish-Swedish ice classes). These

TABLE 2. Conversion table between different ice classification systems for ice strengthening.[1] All ship records in this study were converted to ice class (column 2). FYI is first-year ice, SYI is second-year ice, and MYI is multiyear ice.

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[2]	Arctic ice class	Arctic class[3]
A (Operation in polar waters in at least medium FYI, which may have old ice inclusions)								
PC1 (Year-round operation in all polar waters)	Ice Class A5	–	–	AC3	–	CAC1	5	10
PC2 (Year-round operation in moderate MYI conditions)	Ice Class A4	–	–	AC2	–	CAC2	4	8
PC3 (Year-round operation in SYI; may have MYI inclusions)	Ice Class A3	–	–	AC1.5	–	CAC3	3	6
PC4 (Year-round operation in thick FYI; may have old ice inclusions)	Ice Class A2	–	–	AC1	–	CAC4	2	3
PC5 (Year-round operation in medium FYI; may have old ice inclusions)	Ice Class A1	–	–	1AS	–	CAC4/Type A	1	1
B (Operation in polar waters in at least thin FYI; may have old ice inclusions)								
PC6 (Summer/autumn operation in medium FYI; may have old ice inclusions)	Ice Class A1/A0	1AA	UL	1AS	1ASuper	Type A	A	A
PC7 (Summer/autumn operation in thin FYI; may have old ice inclusions)	Ice Class A0	1A	L1	1A	1A	Type B	B	B
C (Operation in open water or in ice conditions less severe than those in Categories A or B)								
1A Super	B0	1B	L2	1B	1B	Type C	Type C	Type C
1A	C0	1C	L3	1C	1C	Type D	Type D	Type D
1B	D0	1D	L4	1D	Category II	Type E	Type E	Type E
Not ice-strengthened	E0	–	–	100A1	–	–	–	–

[1] Sources of information: Transport Canada, 2003, 2009; Transport Safety Agency, 2010; Canadian Coast Guard, 2012; Vancombe, 2013; ABS, 2016; Baltic Sea Ice Services, 2021. Additional references are available at https://amarineblog.wordpress.com/2017/06/19/ship-ice-class/

[2] CAC = Canadian Arctic Class; "Type" vessels are designed for FYI.

[3] 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 correspond with other classes. Since AIRSS was introduced in about 1996, ASPPR took over as standard.

classifications were standardized into a single class system (Table 2), which conforms to the polar class and ice strengthening of each vessel as defined by the International Association of Classification Societies and International Maritime Organization (ABS, 2016). The conversion between class systems is not exact, but the closest corresponding values were chosen, using information from ABS (2016), Daley (2014), https://amarineblog.com, DNV (2022), and the sources listed in Table 2. Standardization is limited by the accuracy of the data provided and the different criteria used to assign the ice class (e.g., some classifications use engine power while others focus on structural strength, and some report hull ice class based on bow or mid-body whereas others report stern or other areas of design [https://amarineblog.com/2017/06/19/ship-ice-class/]). Inaccuracies may occur where the class system provided to MCTS was not clear. For example, vessels that reported an "Arctic Ice Class" are on an unestablished class system (i.e., this could be either Canadian Arctic Class, Arctic Class, or ABS Ice Class); in these situations, we established a best estimate for the conversion (Table 2). In some cases, where a direct match between different classes was not possible, multiple sources were used to assign the closest possible PC class based on the descriptions of vessel ice strength. Although the conversion is not absolute, it offers a suitable way to compare the ice strengthening of vessels in the Canadian Arctic, which has not been previously investigated.

Analysis of changes in shipping activity and vessel ice strengthening between 1990 and 2019 was conducted, with an emphasis on the spatial patterns across the entire Arctic region (NORDREG zone) and specifically for the NWP. Data are presented in 5-year periods to reduce interannual noise and better show changes over time. The temporal data have been summarized as voyage counts and as unique ship counts. Voyage counts are simply the number of voyages per 5-year period (and if a ship makes several voyages within a year, these are all included). This number was then averaged to get the annual voyage count. For unique ship counts, the number of unique ships within each 5-year time period was totaled (i.e., a ship is counted only once within the period, even if it travelled in several different years). Spatial data are presented as all ship tracks within 5-year periods between 1990 and 2018.

Our analysis focuses on three vessel ice classes that are high, medium, and low

TABLE 3. Average annual voyages of vessels travelling within the NORDREG zone between 1990 and 2019. Total voyage counts in each 5-year increment were averaged to derive annual numbers. "% change" indicates the percentage increase or decrease between 1990–94 and 2015–19. "None" indicates ships with no ice strengthening.

	1990–94	1995–99	2000–04	2005–09	2010–14	2015–19	
Voyage count per year	105	114	105	135	295	380	
Vessel ice class	Average annual voyage counts						% change
PC1	0	0	0	0	0	0	0
PC2	6	5	6	7	11	18	200
PC3	12	10	10	6	7	9	25
PC4	4	1	2	1	1	2	50
PC5	11	7	6	4	1	1	90
PC6	3	6	10	15	20	11	267
PC7	18	23	22	31	66	127	606
1AS	7	9	5	9	37	27	286
1A	13	16	14	12	49	67	415
1B	30	34	29	42	80	84	180
None	1	3	1	8	23	34	3300

ice–strengthened: ice class PC3 (a highly strengthened ship), ice class PC7 (a medium ice–strengthened ship), and ice class 1B (a ship with little to no ice strengthening). These categories represent the highest traffic per ice class in each polar category (see Table 2 for list of polar categories and ice classes) and are representative of the majority of vessel traffic (56%; Table 3). An example of a PC3 ship is the *Amundsen* icebreaker (Fig. 2a), which can navigate throughout the year in ice that is up to two years old and may include multiyear ice inclusions. An example of a PC7 ship is a general cargo vessel, such as a Desgagnés community resupply ship (Fig. 2b), which can only operate in summer and autumn conditions in thin first-year ice with some old ice inclusions. An ice class 1B ship covers vessels that have little ice strengthening and are generally limited to open water operation, such as a bulk carrier carrying grain from Churchill or a pleasure craft (Fig. 2c).

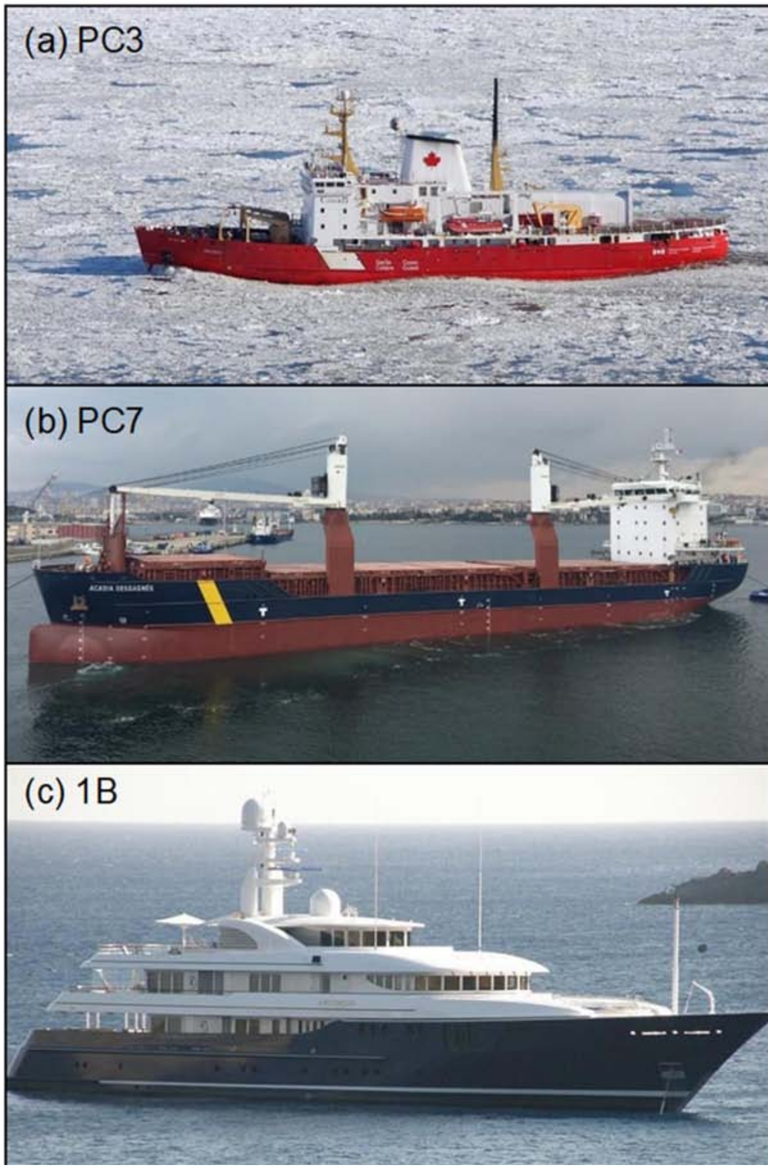
Analysis of Ship Traffic by Ice Class

To analyze ship traffic for the period 1990–2018, we combined position reports for every vessel (n = 1227) that entered the NORDREG zone and converted them into a point shapefile in ESRI ArcGIS 10.6.1. Ship tracks (i.e., the movements of a single vessel along a track for a single trip) were modelled from these ship records using a least-cost path (LCP) approach (Pizzolato et al., 2014, 2016). Tracks were estimated based on the relative impedance of three cost parameters (total sea ice concentration, bathymetry, and distance from land) to a ships safe routing on a scale from 0 to 100, where 100 indicates severe impedance and 0 indicates little impedance. For sea ice concentration, weekly ice charts were extracted from the Canadian Ice Service digital archives (CIS, 2020). The ice chart used to generate the cost surface between two ship position reports was that closest in date to the start point, and a sea ice concentration of 10-tenths was assigned a cost of 100, while 0-tenths was assigned a cost of 0. Bathymetry was derived from the ETOPO2v2 elevation and bathymetry dataset, acquired from the NOAA National Centers for Environmental Information (NCEI, 2006). Bathymetry was assigned a cost of 100 when it exceeded 0 m (as this was considered land), 0 when it surpassed the draft obtained for the vessel from the MCTS ship position report, plus 3 m of safe under keel clearance (maximum draft), 25 for depths between 0 m and the reported draft, and 50 for the reported draft and maximum draft. The distance from land was assigned a cost of 100 at the coast and decreased linearly to 0 at 25 km or more from shore. The final weighted cost surface used the reclassified cost surfaces from the three parameters, with weightings of 50% total sea ice concentration, 25% bathymetry, and 25% distance from land (75% bathymetry and 25% distance from land were used for areas where no ice chart was available). Further details regarding this methodology can be found in Pizzolato et al. (2016). The LCP approach enabled identification of a total of ~5000 individual tracks made by the 1227 vessels. Data processing issues mean that tracks are only available up to 2018.

RESULTS

Changing Levels of Ice Strengthening

Overall, with the addition of 2019 data, there were a total of 1292 unique vessels which reported positions between 1990 and 2019. Of these vessels, 1285 had a reported flag state from a total of 66 different countries, with almost a third (397 vessels) registered in Canada. After this, between 50 and 59 vessels were registered in Panama, Russia, Bahamas, and Cyprus. Between 40 and 48 vessels were registered in the Marshall Islands, United States, Netherlands, Liberia, United Kingdom, France, Denmark, and Malta. Ice-strengthening information was available for 1085 of the 1292 unique vessels (Fig. 3). Of these vessels, 235 (22%) reported no ice strengthening (Fig. 3). Of those that were ice strengthened, most fell into ice class 1B (491 vessels), with the next most common category being PC7 (191 vessels).



REFERENCE BOX: Ship Definitions

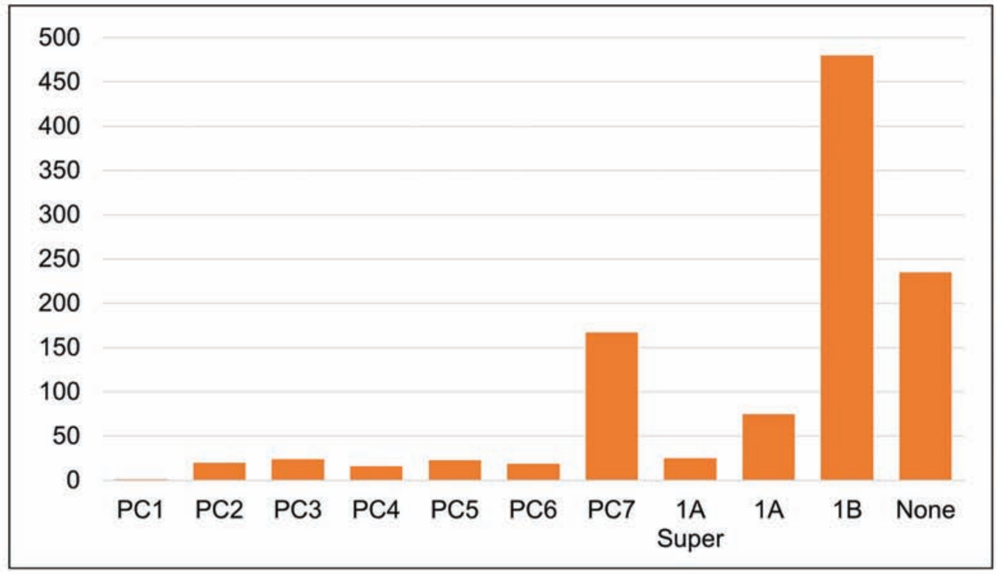
ICE CLASS
PC1: Year-round operation in all Polar waters
PC2: Year-round operation in moderate multi-year ice conditions
PC3: Year-round operation in second-year ice which may include multi-year ice inclusions
PC4: Year-round operation in thick first-year ice which may include old ice inclusions
PC5: 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 operations 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)

FIG. 2. Examples of (a) a highly strengthened ship (CCGS *Amundsen*; ice class PC3), (b) a medium-strengthened ship (*Acadia Desgagnés*; ice class PC7), and (c) a minimally strengthened ship (*Archimedes*; ice class 1B).

For the NORDREG zone as a whole (i.e., all of Arctic Canada), it is clear that there have been large increases in the average annual number of ship voyages between 1990 and 2019, with over three times as many voyages occurring per year in the period 2015 – 19 (n = 381) than 1990 – 94 (n = 104) (Fig. 4; Table 3). In terms of ice strengthening, for the three selected ice classes, there has been a reduction in the annual voyages of highly strengthened PC3 ships (25%), but large increases in the number of voyages of PC7 ships (606%) and 1B ships (180%) (Fig. 4, Table 3). Substantial increases were also observed for classes PC2, PC6, 1AS, and 1A (Table 3). Also of note is the large increase in ships with no ice strengthening, from one voyage per year in 1990 – 94 to 34 in 2015 – 19 (Table 3). Ice classes PC4 and PC5 showed a decrease in ship traffic over time, although these classes typically made few annual voyages. For ice classes that experienced increases in activity, there was a notable increase in voyage counts in 2010 – 14, when several ice classes more than doubled in number (Table 3).

For two of the three ice classes of interest, the number of unique ships per 5-year period has increased between 1990 – 94 and 2015 – 19 (Table 4). This is particularly true for the PC7 ice class, with a similar although smaller increase for ice class 1B. Conversely, the number of unique ships in the PC3 ice class decreased. Bulk carriers in ice class PC7 showed the greatest increase between periods, increasing from four unique vessels over the period 2010 – 14 to 108 over 2015 – 19, a 2600% increase (Table 4). In contrast, bulk carriers in ice class PC3 generally decreased over the recorded period, while there was variability between 5-year periods for bulk carriers in ice class 1B. General cargo and tanker ships in the PC7 ice class also showed large increases between 1990 – 94 and 2015 – 19, by 570% and 323%, respectively. Pleasure



Ice Class	Number
PC1	1
PC2	20
PC3	24
PC4	16
PC5	23
PC6	19
PC7	167
1A Super	25
1A	75
1B	480
None	235
Total	**1085**

FIG. 3. Ice strengthening of unique vessels recorded in the NORDREG zone, 1990–2019, according to ice class. "None" indicates ships with no ice strengthening.

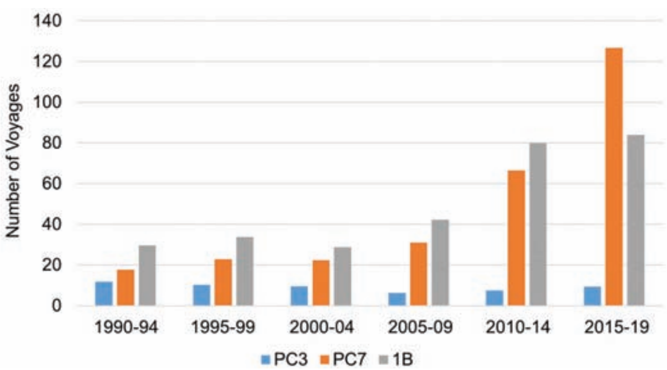


FIG. 4. Average annual voyages of vessels travelling within the NORDREG zone between 1990 and 2019, for highly strengthened ships (ice class PC3), medium-strengthened ships (ice class PC7), and minimally strengthened ships (ice class 1B). Total voyage counts in each 5-year increment were averaged to derive annual numbers.

crafts in ice classes PC7 and 1B showed higher numbers in 2010–14 compared to earlier periods, when only 0 or 1 ship was previously recorded in these categories. Government vessels and icebreakers showed increases in all three ice classes over the recorded period.

For the entire NORDREG zone, there have been significant changes in the spatial distribution of these ships between 1990 and 2018 (Fig. 5). In particular, there has been a marked reduction in the number of voyages of highly strengthened PC3 ships, but large increases in the number of voyages of PC7 and 1B ships with medium and little ice strengthening, with many more voyages of these ship types occurring through the NWP in the recent past than in the 1990s. The largest increases in ship activity have occurred through the southern route of the NWP and also south of Baffin Island through Hudson Strait into northern Hudson Bay via the Arctic Bridge (Fig. 5).

Despite a decrease in activity when looking at NORDREG as a whole, ships in the PC3 ice class have actually increased in the Hudson Strait area, although the number of ships that entered and traveled through Hudson Bay has decreased (Fig. 5). In fact, no vessels in the PC3 ice class entered Hudson Bay during the period 2015–18. For the medium-strengthened PC7 ice class, vessels travelling through both Hudson Strait and Hudson Bay increased between 1995–99 and 2015–18. Vessel traffic in the 1B ice class decreased in both Hudson Strait and Hudson Bay over the recorded period (Fig. 5).

Changing Levels of Ice Strengthening among Vessels in the NWP

Compared to the NORDREG zone as a whole, similar patterns emerge when looking at the NWP, with large increases in the average annual number of ship voyages between 1990–94 and 2015–19 (Table 5). In particular, there have been large increases in the number of voyages of PC7 and 1B ships (Fig. 6). This is especially true for the PC7 ice class, which showed a 610% increase in ship activity over that period (Table 5), a slightly greater increase than observed in the NORDREG zone as a whole. In contrast, there has been a substantial reduction in the voyages of highly strengthened PC3 ships (Fig. 6).

In terms of unique ships travelling in the NWP during the 1990–2019 period, the pattern was similar to that of the NORDREG region as a whole, with large increases in the number of unique ships for the PC7 and 1B classes and a decrease in the PC3 class (Table 6). This pattern is also true when looking at specific vessel types. Bulk carriers in ice class PC7 still showed the greatest increase in the number of unique vessels travelling between 1990 and 2019 (593% increase), followed by general cargo (600% increase). Similarly, pleasure crafts in ice classes PC7 and 1B increased over the study period. The total number of passenger ships doubled between 1990–94 and 2015–19 (Table 6). Further,

TABLE 4. Sum of unique ships per 5-year time period travelling in the NORDREG zone for ice classes PC3, PC7, and 1B. If a vessel type is not listed for a given ice class, then no vessels in that category were recorded over the study period.

Ice class	Vessel type	1990–94	1995–99	2000–04	2005–09	2010–14	2015–19
PC3	Bulk carriers	13	8	7	4	5	5
	Fishing vessels	1	3	0	0	0	0
	General cargo	7	6	5	2	0	0
	Government vessels and icebreakers	0	0	0	0	1	5
	Passenger ships	3	5	5	5	1	1
	Tanker ships	8	2	0	0	0	0
	Tug/barge	1	0	0	0	0	0
	Total	33	24	17	11	7	11
PC7	Bulk carriers	16	12	9	9	4	108
	General cargo	10	11	13	20	46	67
	Government vessels and icebreakers	1	1	4	1	10	6
	Passenger ships	1	5	8	12	14	23
	Pleasure crafts	0	0	0	0	4	0
	Tanker ships	13	21	20	16	41	55
	Tug/barge	2	9	7	11	17	14
	Total	43	59	61	69	136	273
1B	Bulk carriers	24	46	47	35	81	14
	Fishing vessels	35	12	6	22	37	33
	General cargo	10	11	10	3	1	17
	Government vessels and icebreakers	1	3	6	26	29	30
	Oil/gas exploration/exploitation	2	0	0	2	1	0
	Passenger ships	4	1	0	8	5	7
	Pleasure crafts	1	0	1	0	4	4
	Tanker ships	15	6	8	6	6	2
	Tug/barge	29	41	40	58	57	49
	Other	0	0	0	1	0	0
	Total	121	120	118	161	221	156

the percent composition of these vessels with less ice strengthening has increased dramatically, with only one highly strengthened PC3 vessel in recent years. There was an 1800% increase in unique passenger ships with the PC7 ice class, but only a 100% increase for those of the 1B ice class, and PC3 passenger ships decreased by 67% (Table 6).

As with the NORDREG zone as a whole, there have been substantial changes in the spatial distribution of ships in the NWP between 1990 and 2018 (Fig. 7). There has been a large reduction in the voyages of highly strengthened PC3 ships, and increases in the number of voyages from ships with medium-strengthened PC7 ships and minimally strengthened 1B ships. For the latter two classes, there have been many more voyages through the NWP in the recent past than in the 1990s, particularly for PC7 vessels, and all vessels transited the southern route (Fig. 7). Specific areas of increase for PC7 and 1B ships include through Prince Regent Inlet, surrounding King William Island, as well as through the Amundsen Gulf and into the Beaufort Sea (Fig. 7). Despite increases overall in the NWP, the number of PC7 vessels in Lancaster Sound and Barrow Strait did not change between 1990 and 2018, but rather remained at a consistently high level (Fig. 7).

DISCUSSION

Changes in Ship Ice Strength over Time

There are now fewer highly strengthened PC3 vessels and more non-strengthened vessels operating in the Canadian Arctic compared to the past (Figs. 4, 5, and 7; Tables 3–6). For the entire NORDREG zone, there was more than a quadrupling of PC7 vessel voyages between 1990–94 (n = 18) and 2015–19 (n = 127) (Table 3). Only one vessel reported no ice strengthening in the 1990s, but about 10% of vessels (34 out of 380) fell into this category in the 2015–19 period (Table 3). The increasing pattern is particularly apparent in the NWP in the 2010s compared to the 1990s (Figs. 6 and 7). In the early 1990s, over 30% of all vessels transiting the NWP were in classes PC2 and PC3, compared to less than 6% in those classes over 2015–19 (Table 5). It is important to note that not all highly strengthened ice classes have decreased, and that the general pattern for Category A (PC1-PC5) shows a slight reduction from 32 in 1990–94 to 30 in 2015–19 (Table 3).

The NWP provides the most important route for shipping across the Canadian Arctic and a large number of northern communities depend upon it for resupply as well as cultural and economic activities (Brooks and Frost, 2012; Dawson et al., 2020). Previous studies have shown that the NWP is likely to experience an increase in ship traffic in the upcoming decades (Stephenson and Smith, 2015; Melia et al., 2016). However, the increased mobility and variability of sea ice conditions that occur from year to year (Howell et al., 2013; Haas and Howell, 2015), even in recent years, means that ships can still experience significant risk when interacting with ice (e.g., “Even small boats are tackling the fabled Northwest Passage. The ice doesn’t always cooperate” [Mooney, 2017]). This continued and prevalent risk to ships from ice is particularly important given our finding that there are many ships

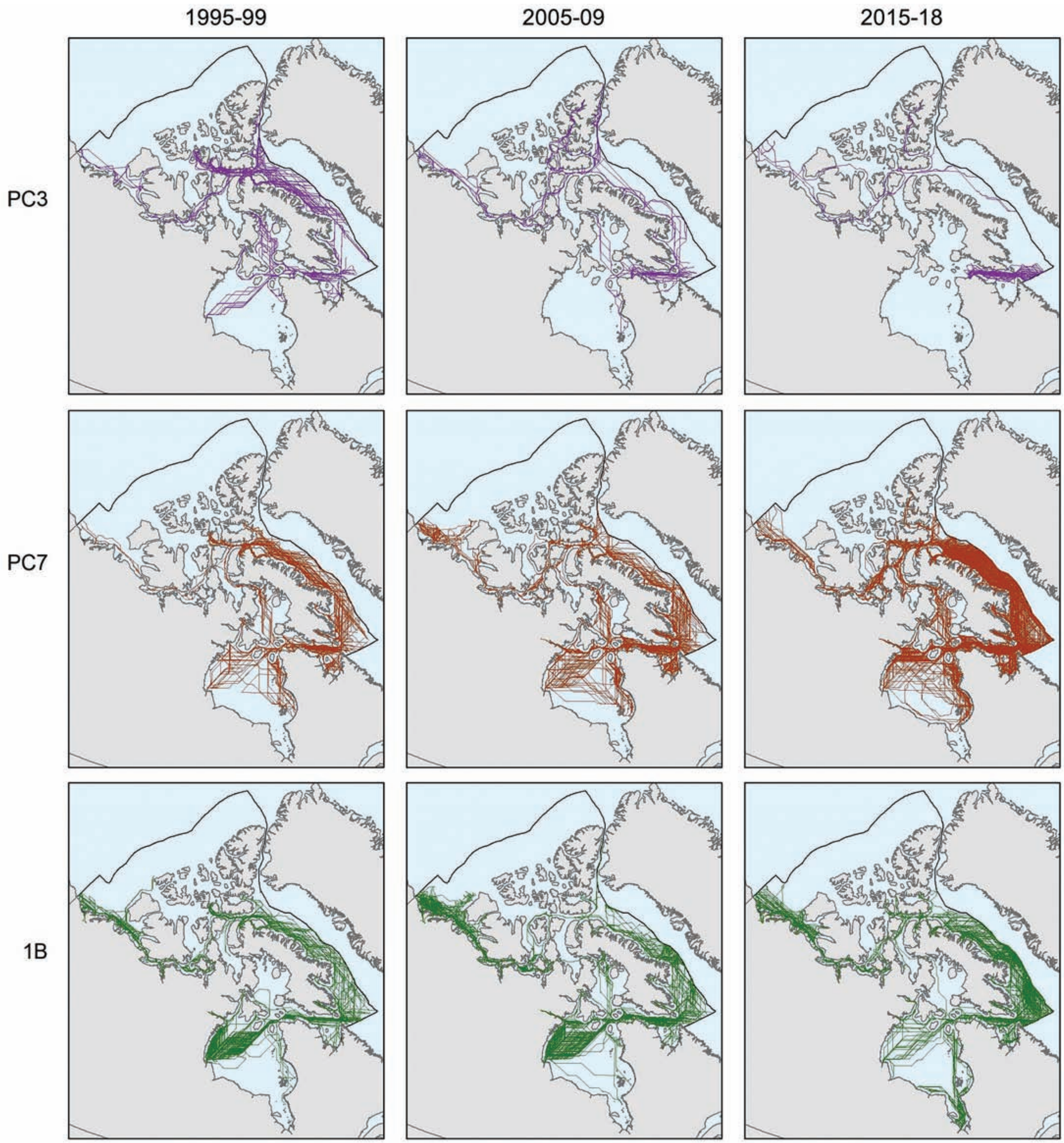


FIG. 5. Changes in vessel track distribution between 1995–99, 2005–09, and 2015–18 for highly strengthened ships (ice class PC3), medium-strengthened ships (ice class PC7); minimally strengthened ships (ice class 1B). Note the large reduction in PC3 ships towards the present day, in comparison to the large increase in PC7 and 1B vessels over the same period.

operating there with little to no ice strengthening (Tables 5 and 6; Figs. 6 and 7).

The largest increase in ship activity in the Canadian Arctic occurred after 2005–09 (Table 4; Fig. 4). This period corresponds with dramatic changes in sea ice conditions throughout the CAA, including a reduction of 105 km^2 in sea ice extent between 2005 and 2006 and a record-setting sea ice minimum in 2007 (Tivy et al., 2011; Mudryk et al., 2018). This period also saw a reduction in sea ice thickness and multiyear ice coverage (Mudryk et al., 2018) and an increase in mean navigability for shipping (Copland et al., 2021). During this time, ships with medium

TABLE 5. Average annual voyages of vessels travelling through the NWP between 1990 and 2019. Total voyage counts in each 5-year period were averaged to derive annual numbers. "% change" indicates the percentage increase or decrease between 1990–94 and 2015–19. "None" indicates ships with no ice strengthening.

	1990–94	1995–99	2000–04	2005–09	2010–14	2015–19	
Voyage count per year	42	42	33	42	78	152	
Vessel ice class	Average annual voyage counts						% change
PC1	0	0	0	0	0	0	0
PC2	5	5	5	6	8	7	40
PC3	9	6	5	2	1	1	89
PC4	2	1	2	1	1	1	50
PC5	4	2	1	1	0	0	100
PC6	1	2	2	5	4	4	300
PC7	10	9	7	9	19	71	610
1AS	0	0	0	0	1	0	0
1A	1	4	2	1	2	11	1000
1B	9	13	9	12	23	32	256
None	1	0	0	5	19	25	2400

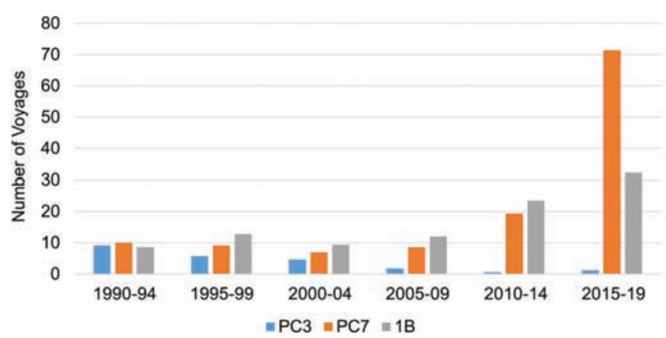


FIG. 6. Average annual voyages of vessels travelling through the Northwest Passage between 1990 and 2018, for highly strengthened ships (ice class PC3), medium-strengthened ships (ice class PC7), and minimally strengthened ships (ice class 1B). Voyage counts in each 5-year increment were averaged to derive annual numbers.

and low levels of ice strengthening were able to travel in increasing numbers in the NORDREG region (Fig. 4, Table 4). However, for the NWP, the dramatic increase occurred slightly later, after 2010–14 (Fig. 6), likely because there was no significant reduction in sea ice extent for both the northern and southern routes until after 2008 (Tivy et al., 2011).

Within the three ice classes presented here, cargo ships and bulk carriers have shown the largest overall increase in terms of the number of unique vessel counts (211% and 140%, respectively) between 1990 and 2019 within the NORDREG zone (Table 4), similar to results from previously published work (Johnston et al., 2017; Dawson et al., 2018). The increase is particularly prevalent for PC7 ships with medium ice strengthening, with a 570% increase in cargo ships and 575% increase in bulk carriers over that time. Notably, 1B bulk carriers with little ice strengthening peaked at 81 unique ships during the 2010–14 period, before declining substantially. The peak during the 2010–14 period is primarily due to the opening of the Baffinland Mary River Mine in 2015, after which bulk carrier activity near Pond Inlet increased considerably, mostly in the PC7 ice class (Fig. 7). The increase in PC7 bulk carriers is especially evident by the fact that bulk carriers travelling within the NWP comprised 96% of traffic for that vessel type for all of Arctic Canada in the 2015–19 period calculated by dividing the 104 bulk carriers, which travelled in the NWP in 2015–19, by the 108 bulk carriers that travelled in the entire Arctic in 2015–19 (Tables 4 and 6). Similar increases for cargo ships travelling in the NWP occurred between 1990 and 2019, where unique ships increased by 600% for PC7 vessels and 100% for 1B vessels (Table 6). These increases are related to community resupply, as the local Inuit population is increasing at a rate nearly three times faster than that of the rest of the Canadian population, thereby increasing the need for goods delivered by cargo ship (Statistics Canada, 2016).

Despite the total number of passenger ships remaining relatively constant over time, as previously reported (Johnston et al., 2017; Dawson et al., 2018), there are marked changes in the ice strengthening of these ships. Passenger ships are the vessel type that has had the biggest relative change in ice strength over time (Tables 4 and 6), with these ships commonly highly strengthened until 2009 (ice class 3, $n = 5$ per period), but in 2015–19 there was a total of only one passenger ship with this level of ice strengthening. PC7 passenger ships with medium ice strengthening are now the most common. Medium-strengthened ships are generally only able to navigate in thin first-year ice, so these vessels are travelling in the NORDREG zone despite the presence of multiyear ice in at least part of that region for some of the summer season (ECCC, 2019). In general, cruise ship tourism has moved northwards from Hudson Bay to the NWP over the past several decades (Dawson et al., 2018). Notable examples were the successful voyages of the IB ice class *Crystal Serenity* through the southern route of the NWP in 2016 and 2017. To date, major cruise ship accidents have been avoided in Arctic Canada, but there have been several groundings, and a situation similar to the sinking of the M/V *Explorer* in Antarctica (Stewart and Draper, 2008) could arise given the observed reductions in ice strength (Tables 4 and 6).

TABLE 6. Sum of unique ships per 5-year time period, travelling through the Northwest Passage, for ice classes PC3, PC7, and 1B. If a vessel type is not listed for a given ice class, then no vessels in that category were recorded over the study period.

Ice class	Vessel type	1990–94	1995–99	2000–04	2005–09	2010–14	2015–19
PC3	Bulk carriers	13	5	4	0	0	0
	Fishing vessels	0	0	0	0	0	0
	General cargo	5	1	1	0	0	0
	Government vessels and icebreakers	0	0	0	0	1	5
	Passenger ships	3	5	5	5	1	1
	Tanker ships	3	1	0	0	0	0
	Tug/barge	1	0	0	0	0	0
	Total	25	12	10	5	2	6
PC7	Bulk carriers	15	11	3	0	1	104
	General cargo	6	8	9	11	31	42
	Government vessels and icebreakers	0	1	2	0	6	2
	Passenger ships	1	4	5	7	11	19
	Pleasure crafts	0	0	0	0	4	0
	Tanker ships	5	5	4	4	23	24
	Tug/barge	2	4	3	7	6	13
	Total	29	33	26	29	82	204
1B	Bulk carriers	0	5	3	1	0	5
	Fishing vessels	1	0	0	0	2	6
	General cargo	6	5	4	1	1	12
	Government vessels and icebreakers	0	1	1	7	13	18
	Oil/gas exploration/exploitation	2	0	0	1	0	0
	Passenger ships	2	0	0	1	1	4
	Pleasure crafts	1	0	1	0	4	3
	Tanker ships	2	0	0	3	1	2
	Tug/barge	20	29	28	38	37	34
	Other	0	0	0	1	0	0
	Total	34	40	37	53	59	84

Pleasure craft with little or no ice strengthening are also increasingly common in Arctic Canada. The number of unique vessels with ice class 1B increased, although overall numbers remained low, rising from one in 1990–94 to four in 2015–19 (Table 4).

Changes in Spatial Patterns of Shipping Activity by Ice Class

Of the three ice classes presented here, the largest increases in ship activity have been for PC7 and 1B vessels travelling through the southern route of the NWP (Fig. 7) and also south of Baffin Island through Hudson Strait into northern Hudson Bay via the Arctic Bridge (Fig. 5). The NWP has experienced a doubling in ship traffic over the period 2015–19 (152 vessels/yr) compared to the prior period 2010–14 (78 vessels/yr; Table 5). The increase in traffic is particularly apparent for the number of bulk carriers in the PC7 ice class which increased by 10,300% between 2010–14 and 2015–2019 (Table 6). Interestingly, no vessels transited the full northern route of the NWP in either 1990–94 or 2015–18 (Fig. 7). Several started, but then diverted south of Banks Island to join the southern route.

Although the overall trend is towards a decrease in activity for ships in the PC3 ice class when looking at the NORDREG zone as a whole, ships of this type have actually increased in the Hudson Strait area due to traffic supporting Raglan and Nunavik Nickel mines in northern Nunavik (Fig. 5). In fact, the vast majority of traffic in the PC3 ice class through Hudson Strait for the 2015–18 period was into the port of Deception Bay near Salluit (Fig. 5). While traffic from highly strengthened vessels has been amplified in this region, there has been a decrease in ice class 1B vessels travelling in Hudson Strait, and even more so for Hudson Bay (Fig. 5).

Overall, ship traffic has increased substantially in the southern route of the NWP (Fig. 7). This was mostly for PC7 and 1B vessels with medium and little ice strengthening (Fig. 7), which increased overall by 603% and 147%, respectively, between 1990 and 2019 (Table 6). Interestingly, all but one pleasure craft that operated in the NORDREG zone travelled within the NWP (Tables 4 and 6). As with pleasure craft, 1B fishing vessels with little strengthening have increased in the NWP, with unique ships increasing by 500% (from one to six between 1990–94 and 2015–19; Table 6). Fishing vessels operating in the NWP, however, do not represent a large portion of the total within the NORDREG zone (6% overall; Tables 4 and 6). Due to the continuing presence of sea ice in the CAA and its mobile nature, there are still significant risks from ice for non-strengthened vessels (Babb et al., 2013; Kwok et al., 2013; Howell et al., 2013; Moore and McNeil, 2018; Howell and Brady, 2019). Rescues of private pleasure craft vessels with little or no ice strengthening have occurred several times in the NWP over the past couple of years, such as several in the Bellot Strait in August 2018 (CBC, 2018; Toth, 2018). Overall, there appears to be a false sense of optimism for safe travel through the NWP (Mudryk et al., 2021).

Changing Levels of Risk from Ice to Ships

Given the rapid recent shift towards vessels with medium or less ice strengthening as the dominant ship

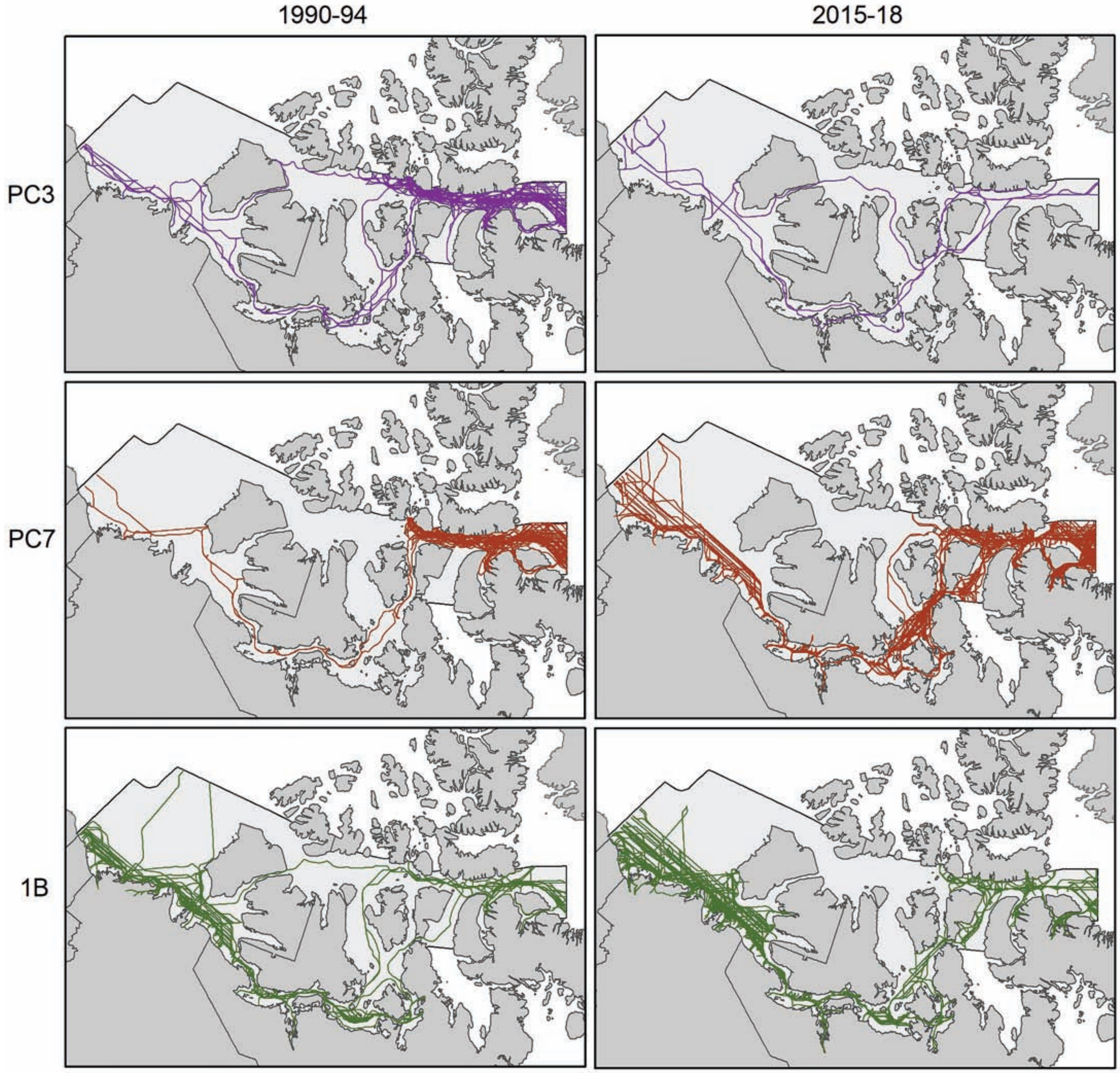


FIG. 7. Vessel track distribution in 1990–94 (left) and 2015–18 (right) in the NWP (light grey area) for highly strengthened ships (ice class PC3), medium-strengthened ships (ice class PC7), and minimally strengthened ships (ice class 1B).

type now operating in the Canadian Arctic, the relatively narrow time window and limited region in which these vessels can safely operate mean that significant risks still exist for their operation in waters where ice is present. The large variability and sometimes sudden changes in sea ice conditions mean that they can still experience navigational hazards and get stuck (e.g., Mooney, 2017). Further, when incidents occur, there are few primary SAR resources stationed north of 60° N, which requires SAR crews to travel great distances in order to reach vessels in remote Arctic areas (Russell, 2011; CCA, 2016). Although the likelihood of the occurrence of a major incident is low, when an incident does occur, it can be a high consequence event, and the risk from ice may be increasing over time as the proportion of vessels, particularly passenger vessels with low ice strength, increases in Canadian Arctic waters (Tables 4 and 6). Groundings, mechanical breakdowns, and running out of fuel are common incidents, particularly for pleasure craft with inexperienced crew, but can be dangerous and costly in remote Arctic regions for both the vessel and for any rescue crews. The type of data presented in this study is necessary to develop region-specific management policies in terms of SAR, but also a safety strategy for Canadian Arctic shipping as a whole.

In summary, despite recent easing of navigational conditions in the Canadian Arctic due to reductions in sea ice (Copland et al., 2021), there is no clear evidence of a coincident reduction in ice 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 SAR services for vessels (Drewniak and Dalaklis, 2018).
2. The increased mobility of sea ice, particularly in areas of hazardous multiyear ice, which is now able to enter the interior channels of the Canadian Arctic from the Arctic Ocean (e.g., Howell et al., 2013).
3. A rapid increase in the occurrence of non-strengthened vessels; for example, only four reported in this class in the 1990s, but 57 reported in this class in the past decade (Table 3).
4. No clear evidence that the reduction in average ice strengthening is occurring at the same rate as the easing in sea ice navigability.

CONCLUSION

Shipping in the Canadian Arctic is undergoing profound change. Vessel numbers are rapidly increasing, with a shift towards many more ships with little to no ice strengthening. Specifically, between 1990 and 2019, voyages from highly strengthened PC3 ships decreased by 25%, while PC7 and 1B vessels with medium to low ice strengthening increased by 606% and 180%, respectively. Further, traffic from ships with no ice strengthening increased by 3300%. Bulk carriers and cargo ships showed large increases in the PC7 ice class (575% and 570% increases, respectively). However, one of the largest changes has occurred in relation to passenger vessels, with only one highly strengthened PC3 vessel in recent years, compared to the majority of vessels being of this ice class in the 1990s, even though the annual number of passenger vessels has remained relatively constant over time.

In some warm summers over the past decade, vessels with no ice strengthening have been able to easily pass through the southern route of the NWP, many more than in the 1990s. However, sea ice conditions are still highly variable from one year to the next, meaning that a voyage through the region can quickly turn to disaster for poorly strengthened vessels, particularly pleasure craft, with inexperienced crew. Future work needs to be done to establish whether sea ice navigability is easing as quickly as the reduction in ship strength.

There is limited infrastructure and a lack of shipping support services in Arctic Canada, which compounds any risks that exist 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-strengthened vessels, increased mobility of sea ice, and the limited infrastructure and support services will create additional risks for the region.

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