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Understanding changes in iceberg–ship coexistence throughout the eastern Canadian Arctic: 2012–2019

Abigail Dalton[a], **Luke Copland**[a], **Wesley Van Wychen**[b], **Jackie Dawson**[a], **Alison Cook**[c,a], **Adam Garbo**[a], **Derek Mueller**[d], and **Adrienne Tivy**[e]

[a]Department of Geography, Environment, and Geomatics, University of Ottawa, Ottawa, ON , Canada; [b]Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON, Canada; [c]Scottish Association for Marine Science, Oban, Scotland; [d]Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, Canada; [e]Environment and Climate Change Canada, Ottawa, ON, Canada

Corresponding author: **Abigail Dalton** (email: abigail.dalton@uottawa.ca)

Abstract

Icebergs present a known hazard to ships operating in ice-infested waters. As iceberg production rates vary, potentially compounded by climate change, it is becoming increasingly important to understand the extent to which icebergs pose navigational hazards. In this study, we explore the relationship between historic ship tracks derived from Automatic Identification System and iceberg drift locations obtained from in situ satellite trackers and the Canadian Ice Island Drift, Deterioration, and Detection Database. Using an iceberg–ship coexistence index we quantify this relationship throughout the eastern Canadian Arctic (ECA) from 2012 to 2019. Comparing 2012–2015 to 2016–2019, the total number of unique vessels operating in the ECA more than doubled. At the same time, icebergs were consistently observed throughout the entire ECA, specifically in Nares Strait, eastern Lancaster Sound, and east of Baffin Island. Regions where the largest increases in both icebergs and ships occurred were along the east coast of Baffin Island and east of Bylot Island, most often involving dry bulk vessels, and in Smith Sound between Ellesmere Island and NW Greenland involving passenger vessels. Recent reductions in the mean ice strengthening of ships operating in the ECA means the seriousness of any potential iceberg collision is likely increasing towards present day.

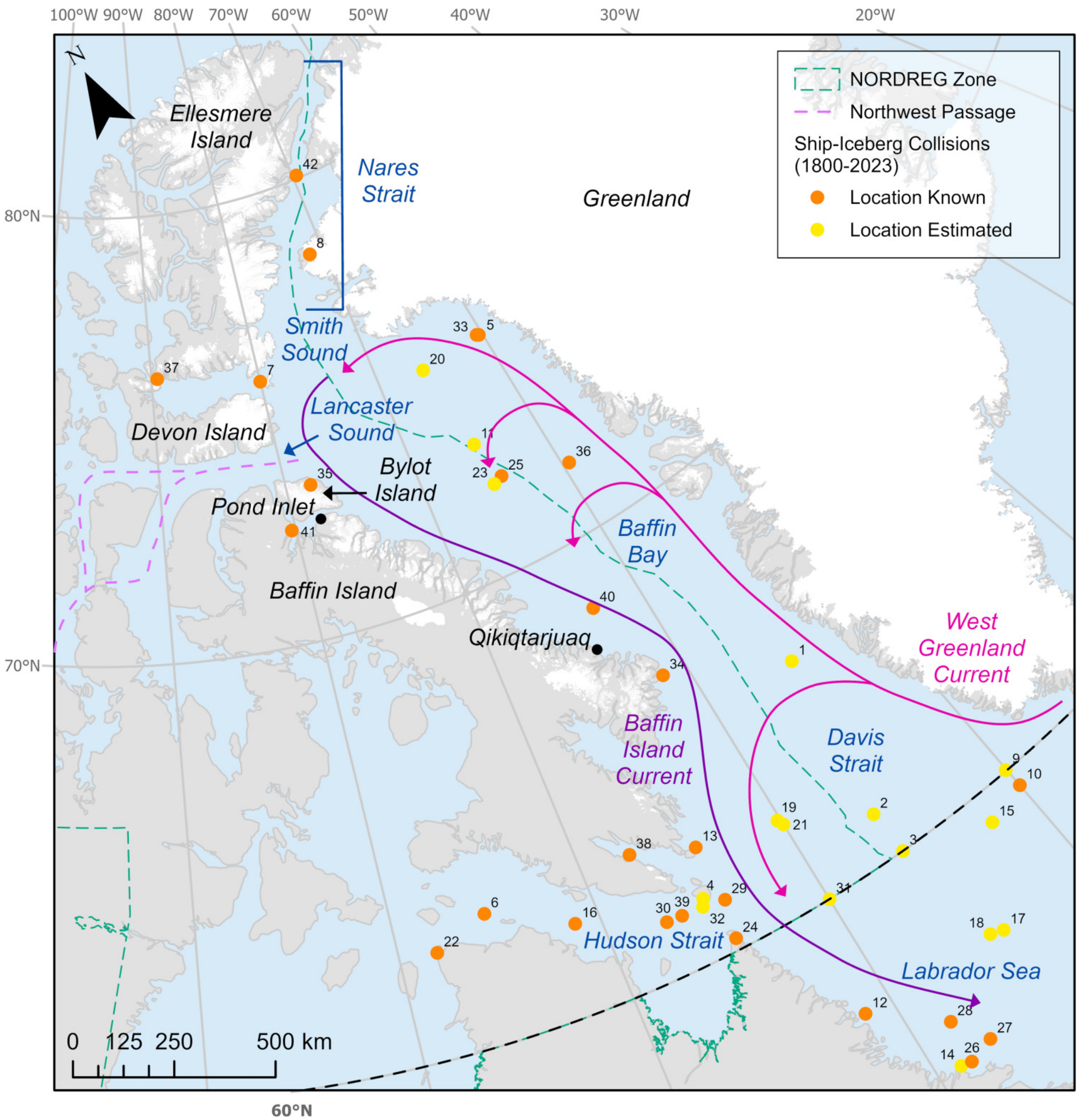
Key words: icebergs, Arctic shipping, shipping risk, Canadian Arctic

1. Introduction

Ship traffic throughout the Canadian Arctic Archipelago (CAA) has more than tripled in recent decades, with the average number of voyages increasing from 104 year^{-1} from 1990 to 1994 to 381 year^{-1} from 2015 to 2019 (Dawson et al. 2022). Many communities in the North are inaccessible by road and therefore heavily reliant on shipping, meaning that the primary purpose of much of the shipping is related to resupply, although many voyages are dedicated to mineral resource extraction (Stephenson and Smith 2015; Dawson et al. 2018). The greatest increase in ship traffic has been observed in Hudson Strait, where many mines are located on adjacent lands, followed by the Beaufort Sea and Baffin Bay. While shipping season length varies spatiotemporally throughout the CAA (Haas and Howell 2015; Copland et al. 2021; Mudryk et al. 2021), the entrance of the Northwest Passage (NWP) in eastern Lancaster Sound has shown some of the most significant increases in season length since 2007 (Cook et al. 2024). Since 1990, the fastest-growing shipping sector, by kilometres travelled, has been pleasure crafts, such as recreational sailboats and private yachts (Dawson et al. 2018).

Icebergs that calve from tidewater glaciers in the CAA and western Greenland frequently drift into these same areas where ships are operating, including throughout Baffin Bay, where the icebergs typically transit in a counterclockwise direction before drifting southwards along the east coast of Canada (Valeur et al. 1996). There is a great deal of inter-annual variability in terms of the number of icebergs that reach the regions termed "Iceberg Alley," i.e., the area between Baffin Bay and the Grand Banks of Newfoundland, which is a region that has several offshore oil platforms and a large numbers of vessel movements (Sudom et al. 2014). Icebergs within Iceberg Alley have been monitored since 1913, one year after the sinking of the *RMS Titanic* following an iceberg collision on 14 April 1912. The International Ice Patrol (IIP) works in conjunction with the Canadian Ice Service (CIS) to monitor iceberg presence in the North Atlantic Ocean and provide iceberg warnings and charts to those navigating off the coast of Newfoundland and Labrador. However, north of 60°N in the eastern Canadian Arctic (ECA), ice charts lack detailed iceberg information and only indicate that icebergs are present

Fig. 1. Map of study area, including location of main ocean currents and historical ship-iceberg collisions from 1800 to 2023 (Hill 2010) throughout eastern Canada. Additional details on collisions are included in Table 1. Black dotted line shows the iceberg chart limit of 60°N, above which iceberg charts are not regularly issued. Dotted green line represents Canadian Coast Guard NORDREG Zone (Justice Laws 2010). Glacier outlines: Randolph Glacier Inventory (RGI) 6.0 (RGI Consortium 2017). Projection: NAD83 / Statistics Canada Lambert.



with the broad designation of "bergy waters" (Fig. 1; CIS 2005).

The Arctic Ice Regime Shipping System and Polar Operational Limitation Assessment Risk Indexing System (POLARIS) are used to manage operational limitations for ships in Arctic Canada based on current sea ice conditions and level of vessel ice strengthening. Presently, the ice numeral used in POLARIS to assess risk only considers sea ice type and concentration, but not icebergs. The lack of inclusion of icebergs in current navigational risk assessments in combination with the remoteness of the Canadian Arctic, limited search and rescue (SAR) capabilities (Ford and Clark 2019), and lack of bathymetric data (Chénier et al. 2017), highlights the need for improved long-term monitoring of icebergs and improved assessment of their potential risk to navigation (AC 2009; Arctic Monitoring and Assessment Programme (AMAP) 2017; Kujala et al. 2019; Dawson et al. 2022).

While several previous studies have focused on the relationships between sea ice and Arctic shipping (e.g., Pizzolato et al. 2014, 2016; Dawson et al. 2018; Copland et al. 2021, 2022; Cook et al. 2024), there has been little analysis completed on characterization of iceberg–ship coexistence. This study therefore presents the first known overview of spatial and temporal patterns in iceberg–ship coexistence throughout the ECA between 2012 and 2019. Using a comprehensive database of Automatic Identification System (AIS) ship locations and a multi-year dataset of known iceberg drift tracks, this study:

i) identifies spatial and temporal patterns in iceberg drift and ship traffic throughout the ECA during the shipping season (July–October);
ii) establishes areas of coexistence between icebergs and ships; and
iii) quantifies changes in iceberg–ship coexistence along ECA shipping routes from 2012 to 2019.

2. Study area

2.1. Baffin Bay

Baffin Bay is an oceanic basin located in the Arctic, connecting the Arctic Ocean to Davis Strait and the Labrador Sea (Fig. 1). Sea ice and icebergs drifting in Baffin Bay are influenced by two main ocean currents: the West Greenland Current (WGC) and the Baffin Island Current (BIC). The WGC flows northward along the west coast of Greenland until Smith Sound where it bends westward, and then begins moving southward along the eastern coast of Baffin Island, merging with the BIC (Melling et al. 2001; Tang et al. 2004). Icebergs and sea ice can be carried by this current around Baffin Bay and may eventually drift south past Davis Strait and into the Labrador Sea (Valeur et al. 1996; Tang et al. 2004; Münchow et al. 2015).

In Baffin Bay, minimum sea ice cover occurs in September when remaining sea ice is only present near the coast of Baffin Island due to the relatively warm northward flowing WGC in the east (Tang et al. 2004). Sea ice begins to form in mid-October and is typically present in Baffin Bay throughout the year, reaching a maximum cover in March when it extends into Davis Strait (Valeur et al. 1996). Along the ECA coast, icebergs can often become frozen in sea ice as they follow the BIC close to the shores of Baffin Island (Marko et al. 1982; Tang et al. 2004) and will remain static until the sea ice is free to move again. Given the presence of sea ice throughout Baffin Bay from approximately November to June (Tang et al. 2004), we identify the shipping season as July to October (Stephenson et al. 2013; Eguíluz et al. 2016).

2.2. NORDREG zone

The NORDREG zone (Fig. 1) is the region north of 60°N in the Canadian Arctic in which vessels above a certain size threshold are required to report their position and vessel characteristics (e.g., name, call sign) to the Canadian Coastguard. Other vessels (e.g., small pleasure crafts) may voluntarily report their position. It has been stated that approximately 98% of all ships operating in the NORDREG zone notify the Canadian Coast Guard of their presence (Rompkey and Cochrane 2008), even if not required to by law, in part due to the advantages accompanied with reporting such as enhanced SAR response (also see Johnston et al. 2017). Here, we use the NORDREG zone to define the eastern and southern extent of analysis for iceberg–ship coexistence.

3. Data

3.1. Ship collision with iceberg database

Since the sinking of the RMS *Titanic*, several collisions between icebergs and ships navigating the polar regions have been documented, including the sinking of the *Finnpolaris* cargo vessel in 1991 in Baffin Bay and the *M/V Explorer* passenger vessel in Antarctica in 2007 (Fig. 1; Table 1). Hill (2010) compiled a database of over 200 years of historical iceberg and ship collisions throughout the northern hemisphere, which is available for download (https://newicedata.com/the-ship-iceberg-collision-database/). Collision details were compiled from a variety of sources, ranging from newspaper reports and shipping gazettes to official inquiries. Based on this database, a total of 42 ship iceberg collisions occurred between 1800 and 2006 in our study area. We searched the Transportation Safety Board Marine Safety Information System (MARSIS) database between 2006 and 2023 (https://www.tsb.gc.ca/eng/stats/marine/data-6.html) to identify any other collisions in our study area, but no additional collisions were reported during that period. Ship-iceberg collisions occurred throughout eastern Canada and are shown in Fig. 1. Table 1 describes the vessel type, damage, and severity of each collision. Over 1/3 of all collisions resulted in the sinking of a vessel and four incidents resulted in confirmed fatalities, most recently in 1975 with the sinking of the *Aigle d'Ocean* in the Labrador Sea. A total of 8 collisions have occurred since 1990, four of which were located north of 72°N.

3.2. Iceberg climatology

Data from a combination of in situ drift locations collected through the deployment of satellite tracking beacons, and the Canadian Ice Island Drift, Deterioration, and Detection (CI2D3) database, were compiled to create a climatology of known iceberg locations in the ECA between 2008 and 2019. For analysis in subsequent sections, each dataset is plotted on a 50 × 50 km grid to provide an overview of patterns across the ECA. Both datasets are described further below.

3.2.1. Iceberg Beacon Track Database (IBTD)

This study uses a dataset of iceberg tracks compiled from beacons deployed by the Canadian Ice Service (CIS), along with other government, academic, and industry collaborators to characterize iceberg drift on a regional scale throughout Baffin Bay, including Nares Strait, Lancaster Sound, and

Table 1. List of historical ship–iceberg collisions from 1800 to 2023 (Hill 2010; Transportation Safety Board (TSB) 2023) throughout the eastern Canadian Arctic.

No.	Vessel name	Vessel type	Date	Latitude (°N)	Longitude (°W)	Damage	Fatalities
1	Thomas*	Whaling Vessel	1812-01-01	65	55	No damage	No
2	Royalist*	Whaling Ship	1814-04-05	61.07	56.13	Sinking	Yes
3	London*	Whaling Vessel	1817-01-01	60	56	Sinking	Yes
4	Prince of Wales*	Sailing Ship	1821-07-24	61.42	65.12	Hole	Unknown
5	Progress	Whaling Brig	1830-07-02	75.1	60.3	Sinking	Unknown
6	Terror, HMS	Sailing Bomb Vessel	1837-07-13	63	75.3	Puncture	No
7	Intrepid, HMS	Steam Discovery Sloop	1851-08-27	76	80	Denting	Unknown
8	Advance	USS Brigantine	1853-08-21	78.36	71.5	Unknown	No
9	Fluorine*	Bark	1882-10-01	60.02	50.04	Denting	Unknown
10	Alumina	Bark	1884-05-01	59.55	50	Sinking	Unknown
11	Alert*	HMS Sloop (powered)	1884-08-01	73	65	No damage	No
12	Ethel	Sailing Vessel	1908-07-25	57.34	61.23	Sinking	Unknown
13	Snowdrop	Whaling Vessel	1908-09-18	62.54	64.3	Sinking	Unknown
14	Erik*	Wooden Steamer	1908-09-21	55.2	59	Denting	Unknown
15	Hugo*	Steam Schooner	1927-05-05	59.3	52	Sinking	Yes
16	Bright Fan	SS Cargo	1932-10-01	62.09	71.23	Sinking	No
17	Maia*	Schooner	1933-10-11	57.2	54.45	Sinking	Unknown
18	Saint Coulomb*	Fishing Schooner	1935-04-11	57.3	55	Sinking	Unknown
19	Maria Preciosa*	M/V Fishing Vessel	1944-06-14	62.15	60.15	Sinking	Unknown
20	Sappa Creek*	M/V Tanker	1951-08-01	75	66	Crushed	Unknown
21	Rio Caima*	M/V Fishing Schooner	1952-09-01	62	60	Sinking	Unknown
22	Kastela	SS Cargo	1963-08-03	62.45	78.1	Sinking	No
23	Westwind, USCG*	Cutter	1970-07-01	72	65	Unknown	No
24	Aigle d'Ocean	M/V Cargo	1975-08-20	60.27	64.59	Sinking	Yes
25	Arctic	M/V Bulk Carrier	1978-10-17	72.08	64.25	Hole	Unknown
26	Escort Protector	M/V Tug	1979-06-10	55.15	58.56	Unknown	Unknown
27	Pacnorse I	Drillship	1982-07-25	55.35	57.45	Cracks	Unknown
28	Kristina Logos	M/V Stern Trawler	1983-06-22	56.17	58.4	Hole	No
29	Mesange	M/V Cargo	1983-07-21	61.17	64.22	Hole	No
30	Evangelia C	M/V Bulk Carrier	1984-07-31	61.3	67.15	Unknown	Unknown
31	Ocean Prawns*	M/V Stern Trawler	1984-08-16	60	60	Sinking	No
32	Lucien Paquin*	M/V Cargo	1985-07-20	61.25	65.3	Denting	No
33	Terra Nova	M/V Cargo	1989-07-31	75.12	60.46	Unknown	Unknown
34	Des Groseilliers	CCGS Icebreaker	1989-08-29	66.34	61.4	Unknown	No
35	Terra Nova	M/V Cargo	1990-10-03	73.48	78.04	Puncture	No
36	Finnpolaris	M/V Cargo	1991-08-11	71.59	59.52	Sinking	No
37	Hubert Gaucher	M/V Product Tanker	1991-08-31	76.42	89.44	Cracks	Unknown
38	Alla Tarasova	Cruise/Passenger	1995-07-19	63.05	67.42	Small puncture	No
39	Reduta Ordona	M/V Bulk Carrier	1996-07-21	61.28	66.38	Large hole	No
40	Lucien Paquin	M/V Cargo	1998-08-20	68.46	63.03	Unknown	Unknown
41	Arctic Viking	M/V Cargo	1998-10-01	72.59	80.32	Denting	Unknown
42	Louis S. St-Laurent, CCGS	Icebreaker	2001-08-17	80.07	69.53	No damage	No

Note: His/Her Majesty's Ship (HMS), Canadian Coast Guard Ship (CCGS), United States Coast Guard (USCG) *Location estimated.

Davis Strait. This dataset is publicly available at the Polar Data Catalogue (PDC) (Garbo et al. 2025). Of the 40 beacons used in this study, we deployed 25 between July and September each year from 2016 to 2019 onto icebergs throughout the ECA (Dalton et al. 2025). These beacons were deployed by helicopter from the *CCGS Amundsen* onto icebergs and ice islands and transmitted their position using the Iridium satellite network. Iceberg drift tracks from the Iceberg Beacon Track Database were identified for use from 2012 to 2019, selected based on the following criteria:

i) observations were located within the NORDREG zone;
ii) observations occurred during the shipping season (July–October);
iii) observation transmission interval did not exceed 6 h; and
iv) drift track duration was ≥ 10 days.

Drift tracks were limited to the NORDREG zone north of 60°N, which extends approximately from Nares Strait to the Labrador Sea. Beacons which transmitted data for fewer than 10 days, or which had a transmission interval exceeding 6 h, were excluded due to their limited coverage. Observations were plotted based on the number of times a unique iceberg tracking beacon was present within each 50 × 50 km grid cell.

3.2.2. Canadian Ice Island Drift, Deterioration, and Detection (CI2D3) Database

Ice islands are large, tabular icebergs that calve from ice shelves and floating ice tongues in the Arctic (Dowdeswell and Jeffries 2017). The flux of ice island fragments from ice tongues on northwestern Greenland was quantified by Desjardins et al. (2018) using synthetic aperture radar (SAR) imagery from the CIS archive of RADARSAT-1 and -2 scenes between July 2008 and December 2013. This dataset is publicly available at the PDC (https://www.polardata.ca/pdcsearch/PDCSearch.jsp?doi_id=12678). Ice islands were manually digitized as polygons between northwestern Greenland (Petermann, Ryder, Steensby, and C.H. Ostenfeld glaciers) and Newfoundland. The use of repeat imagery allowed for re-observation of >900 individual ice islands and fragments totalling >25 000 positions. For the purpose of this study, we limit the ice island observations to the NORDREG zone north of 60°N and during the shipping season (July–October; Fig. 2).

To analyze the spatial distribution of ice islands and the hazard they represent to ship traffic, we considered all ice islands that were first observed calving from ice tongues or were found in the open ocean. These ice islands were given a unique identifier, which was retained during subsequent observations, to avoid including repeat observations in our analysis. As smaller fragments broke away from these ice islands, they were given a new unique identifier, and so on. We then counted the number of unique ice islands that were observed within each of the 50 × 50 km grid cells, to create an iceberg climatology of known ice island locations throughout the ECA from 2008 to 2013. These results from the CI2D3 database were then added to the database of known iceberg drift tracks described in the previous section to characterize the distribution of known iceberg drift locations throughout the ECA.

3.3. AIS ship data

Most vessels operating in Canadian waters are equipped with AIS transponders, which send messages to terrestrial (land-based) (T-AIS) and satellite (S-AIS) receivers (Nicoll et al. 2024). These messages provide voyage information, including position, speed, course, vessel name, size, and destination. There are two types of AIS transponders, Class A and Class B. Class A transponders broadcast messages more frequently and at a stronger transmission power than Class B transponders, resulting in Class A messages being more easily received. As per regulation 19 of the International Convention for the Safety of Life at Sea (SOLAS) Chapter V (31 December 2004), the following vessels are required to carry Class A transponders internationally:

- i) vessel is 150 gross tons or more, is carrying more than 12 passengers, and is engaged on an international voyage;
- ii) vessel is 300 gross tons or more and is engaged on an international voyage (excluding fishing vessels);
- iii) vessel is 500 gross tons or more and is not engaged on an international voyage (excluding fishing vessels); or
- iv) vessel is certified to carry more than 12 passengers, or is eight or more metres in length and is carrying passengers.

Class B transponders are voluntary and are generally equipped on smaller vessels such as pleasure craft and fishing boats. This study uses S-AIS data transmitted by Class A and B transponders provided by exactEarth Ltd. (Spire, 2023), and processed courtesy of The Marine Environmental Observation, Prediction and Response Network (MEOPAR). Given that Class B transponders are voluntary for smaller vessels, they may be underrepresented in this dataset. However, as Class B transponders have become more affordable in recent years, it is possible that increases in small vessel traffic (e.g., pleasure crafts) could be due in part to an increase in small vessels using AIS transponders (Nicholl 2024). For this analysis, positional AIS messages from the NORDREG zone (i.e., north of 60°N) were converted into spatial points using a custom Python script and stored in a geodatabase by year, following the methodology of Nicoll et al. (2024). Points with invalid Maritime Mobile Service Identity (MMSI; unique nine-digit identifier outside the range of 201 000 000 to 775 999 999) were removed. Known ship location points were then converted into track lines using NOAA's Track Builder tool. For each MMSI, the track lines were generated from points where the next point was within 80 km and 5 h. These thresholds were chosen based on the inconsistent nature of AIS message transmission and reception within remote regions of the Arctic. Where points exceeded these values, a new vessel track line was produced, creating independent vessel transits over time.

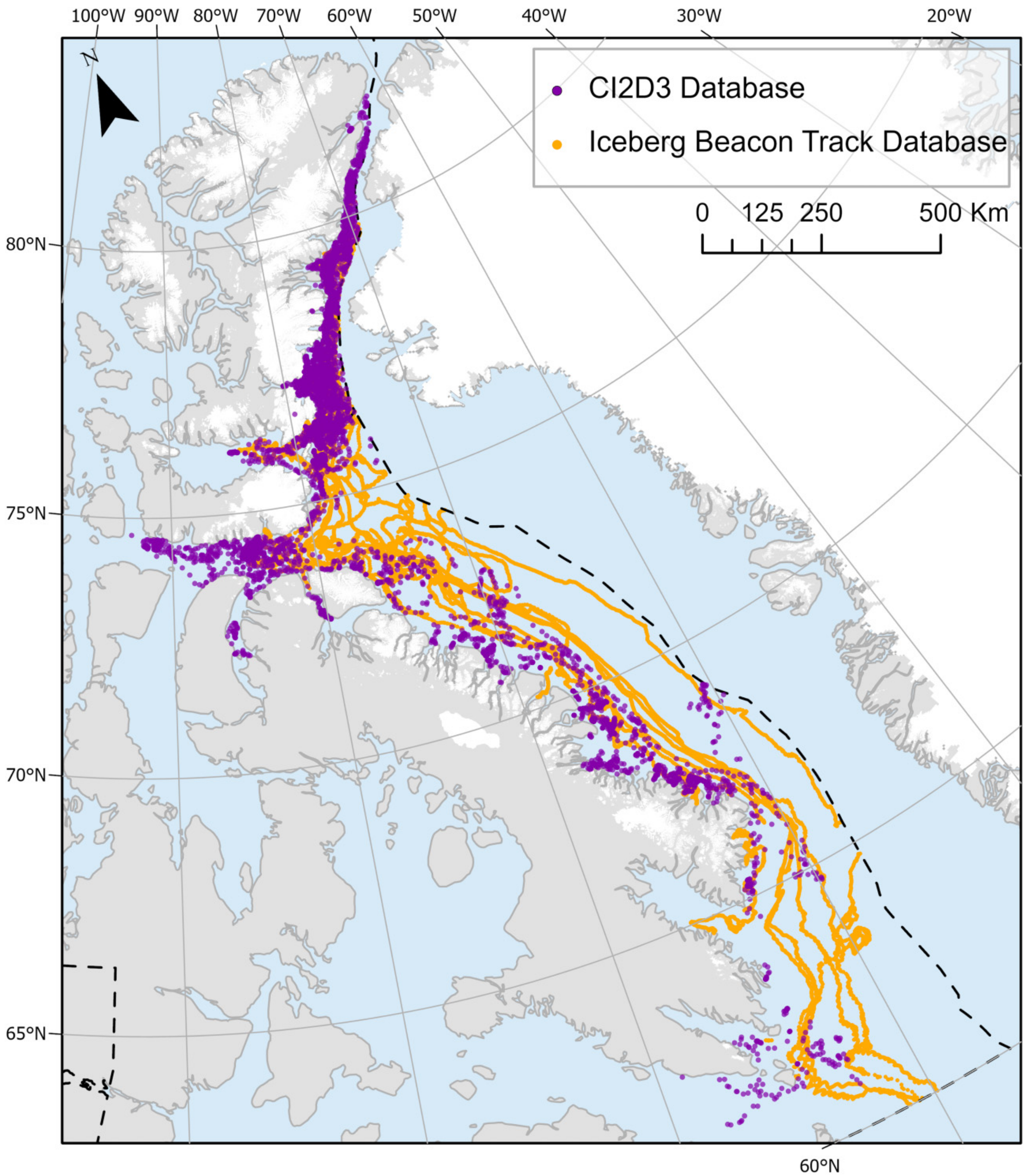
There are ten types of vessels operating in the ECA that were used in this report (Table S1). Additional corresponding static vessel information (e.g., MMSI, ship name, ship type) was collected from a combination of online sources (e.g., MarineTraffic.com, MyShipTracking.com, and Industry Canada). Unique number of vessels (MMSI) per 50 × 50 km grid cell was plotted to display the spatial and temporal distribution of vessel traffic throughout the ECA during the shipping season (July–October) between 2012 and 2019.

4. Methods

4.1. Iceberg ship coexistence index (ISCI)

To quantify the overlap between known iceberg and ice island drift locations and vessel traffic throughout the ECA, we computed an Iceberg Ship Coexistence Index (ISCI). The number of unique observations within each grid cell for the iceberg beacon track and CI2D3 databases were first summed

Fig. 2. Location of iceberg tracks (2012–2019) and Canadian Ice Island Drift, Deterioration, and Detection (CI2D3) Database (2008–2013) ice island fragment observations across the eastern Canadian Arctic used in this study. Projection: NAD83 / Statistics Canada Lambert.



(2008–2019) for all months of the shipping season (July–October) to create a climatology of known iceberg and ice island occurrences throughout the ECA. The ISCI was then determined by multiplying the iceberg climatology (i.e., unique number of iceberg track and CI2D3 Database observations per 50 $\times$ 50 km grid cell for 2008–2019) by the number of vessel trips within that grid cell. For analysis, we then calculated the average annual ISCI for two time periods, 2012–2015 and 2016–2019.

It should be noted that the ISCI provides a conservative estimate of iceberg–ship coexistence as we only have a partial measure of the number of icebergs in our study area; however, the spatial patterns in our iceberg climatology likely provides a realistic measure of their relative distribution as they are based on a large number of observations. Iceberg and ice island observations are used in this study as a climatology, which we assume describes average conditions and locations of icebergs throughout the shipping season. In our analysis, observations from the iceberg climatology are fixed, resulting in any changes in ISCI being solely due to changes in the number and distribution of ships throughout the ECA.

5. Results

5.1. Known iceberg locations: 2008–2019

5.1.1. IBTD

A total of 40 beacons transmitted their position during the shipping season throughout the ECA (Fig. 3A). The highest concentration of tracked icebergs occurred in the area north of 65°N along the east coast of Baffin Island and into Nares Strait. Observations south of this point are limited, with the exception of the area on SE Baffin Island near Qikiqtarjuaq and into Davis Strait (Fig. 1), where icebergs commonly become grounded and remain in a single location for long periods of time. The greatest concentration of beacons was throughout Nares Strait and in eastern Lancaster Sound, with the maximum number of nine beacons per 50 × 50 km grid cell transmitting in Kane Basin and in Smith Sound near Coburg Island.

5.1.2. CI2D3 database

In total, 452 unique ice islands were detected during the shipping season (July–October) from 2008 to 2013 (Fig. 3B). During the observation period, the distribution of ice islands extended throughout the ECA from northern Nares Strait, and into the entrance of Hudson Strait. Ice islands also drifted into the entrance of Lancaster Sound. The highest concentration of observations reached a maximum of 48 in one grid cell in Smith Sound near SE Ellesmere Island. Over the entire period, ice islands drifted south along the east coast of Baffin Island, often entering narrow inlets and fiords.

5.2. Shipping traffic: 2012–2019

5.2.1. Temporal patterns

Between 2012 and 2019, the total annual number of unique ships operating in the ECA more than doubled from 108 to 271 (Table 2; Fig. 4). Overall, the unique number of individual ships increased by 22.4 per year ($R^2 = 0.85$, $p < 0.05$) between 2012 and 2019. While increases were observed in nearly every type of vessel, the greatest changes were seen in dry bulk, pleasure crafts, passenger vessels, and other/special ships while container, government/research, and tanker vessel types remained largely consistent from 2012 to 2019 with inter-annual fluctuations. The number of dry bulk vessels more than tripled from 13 in 2012 to 46 in 2019, while the number of other/special ships and pleasure crafts increased by 307% and 571%, respectively.

There was also a clear increase in the number of vessels operating in the ECA since 2016 (Fig. 5). From 2012 to 2015, the total number of unique ships increased from 108 to 134, while from 2016 to 2019 the total number of unique ships increased from 134 to 271, indicating a recent influx of new traffic to the ECA.

5.2.2. Spatial patterns

5.2.2.1. All vessel types

There has been a clear shift in spatial distribution of vessel traffic between 2012 and 2019. The total number of trips by all vessels increased from 6570 between 2012 and 2015 (Fig. 5A) to 10966 between 2016 and 2019 (Fig. 5B). The area with the greatest observed increase in traffic occurred along the east coast of Baffin Island and into Pond Inlet towards the entrance of Lancaster Sound, where many vessels are travelling to Pond Inlet for community resupply and cruise ship visits, and to adjacent Milne Inlet to load iron ore produced from the Mary River Mine. Traffic from Davis Strait through Hudson Strait remained largely consistent from 2012 to 2019. Given the increase in the unique number of vessels operating in the ECA from 2012 to 2019 and historical precedent for collisions (Fig. 1; Table 1), we focus our analysis on dry bulk, cargo, pleasure crafts, and passenger vessels.

5.2.2.2. Dry bulk

From 2012 to 2019, there was a marked shift in navigation of dry bulk vessels throughout the ECA. In 2012, a total of 13 unique dry bulk vessels operated in the ECA, compared to 46 by 2019 (Table 2). From 2012 to 2015, the number of trips taken by dry bulk vessels reached a maximum of 326, concentrated mainly throughout Hudson Strait (Fig. 6A). From 2016 to 2019, dry bulk traffic through Hudson Strait decreased and 1438 trips were recorded, predominantly along the east coast of Baffin Island into Pond Inlet, with a particularly large increase since 2018 when Mary River Mine reached full production (Fig. 6B).

5.2.2.3. Cargo

Cargo vessels were involved in 7 of the 16 collisions between ships and icebergs since 1980 (Table 1; Fig. 1). The number of unique cargo vessels operating in the ECA more than doubled from 13 in 2012 to 28 in 2019. Between 2012 and 2015, cargo vessel traffic totalled 1107 trips and was distributed across the ECA, with the highest number of trips occurring through Hudson Strait (Fig. 6C). Between 2016 and 2019, the number of trips increased to 1487, with a greater concentration of trips occurring along the east coast of Baffin Island, and into Pond Inlet and the entrance to Lancaster Sound (Fig. 6D).

5.2.2.4. Pleasure crafts

From 2012 to 2019, the unique number of pleasure crafts operating in the ECA more than tripled from 14 to 43 per year (Table 2). Between 2012 and 2015, pleasure craft traffic was dispersed throughout the ECA, with 816 trips operating throughout Baffin Bay, Lancaster Sound, and into Hudson Strait (Fig. 6E). By 2016–2019 the total number of trips had only increased to 864, with a decrease in traffic through Hudson Strait and instead a concentration throughout the entrance to the Northwest Passage, reaching between 50 and 100 trips over the same period near Pond Inlet and Lancaster Sound (Fig. 6F).

Fig. 3. (A) Unique number of icebergs tracked between 2012 and 2019 and (B) unique number of ice island observations between 2008 and 2013, per 50 × 50 km grid cell. Projection: NAD83 / Statistics Canada Lambert.

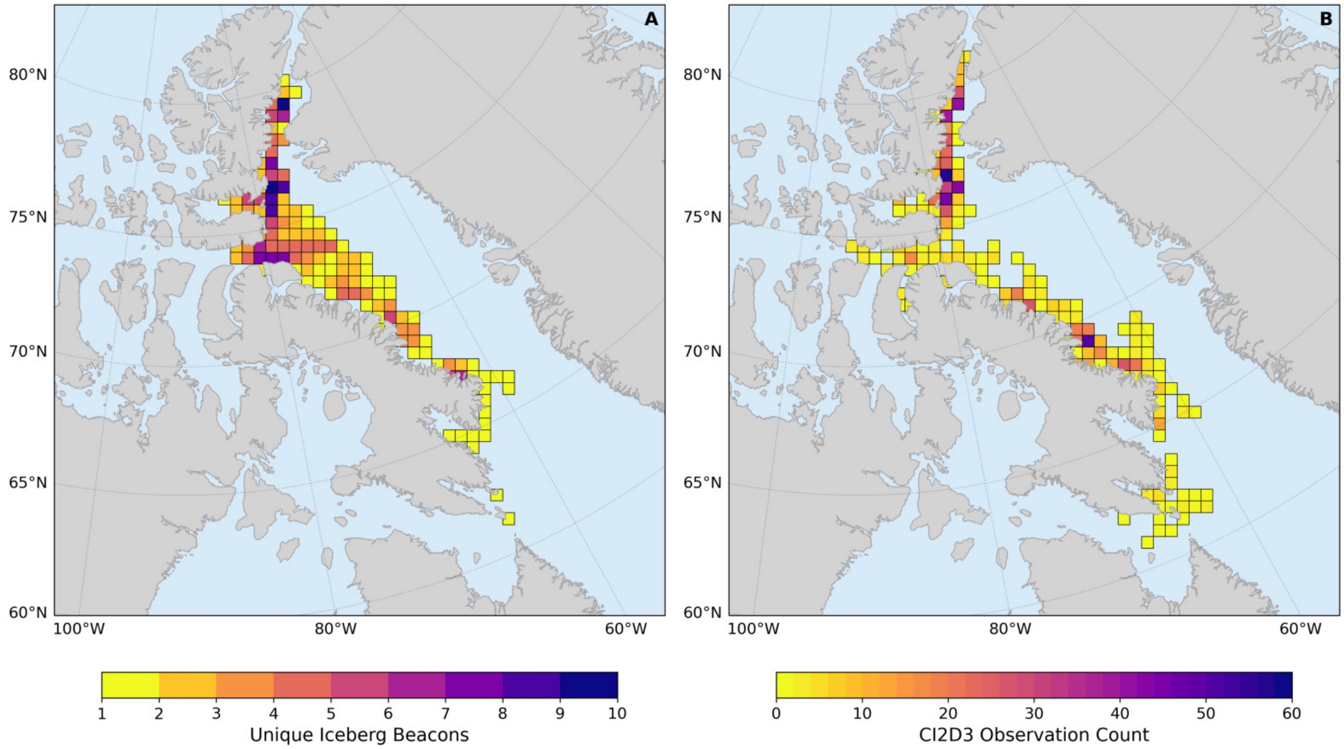
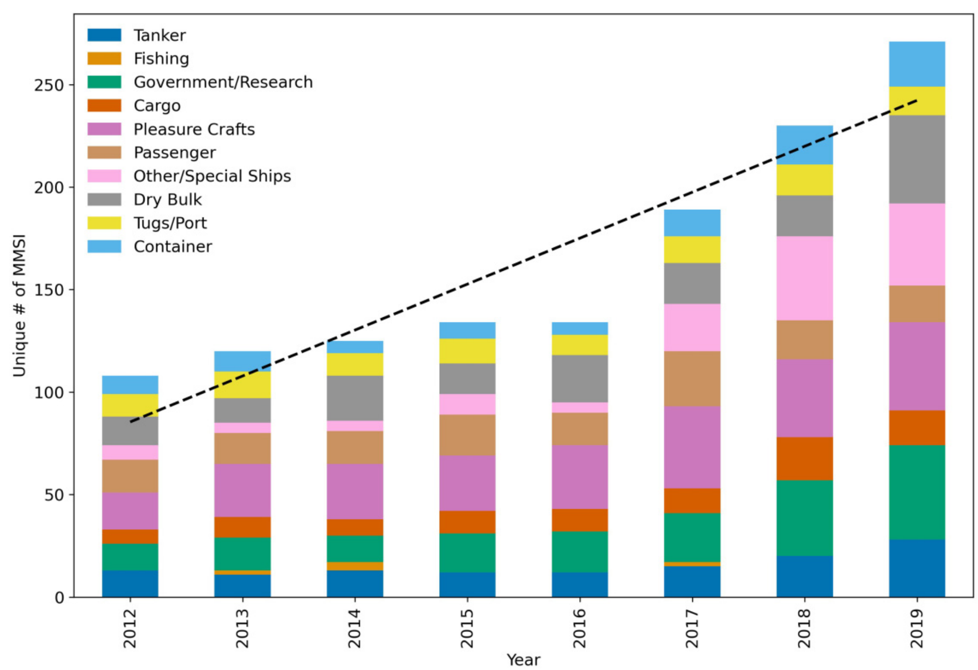


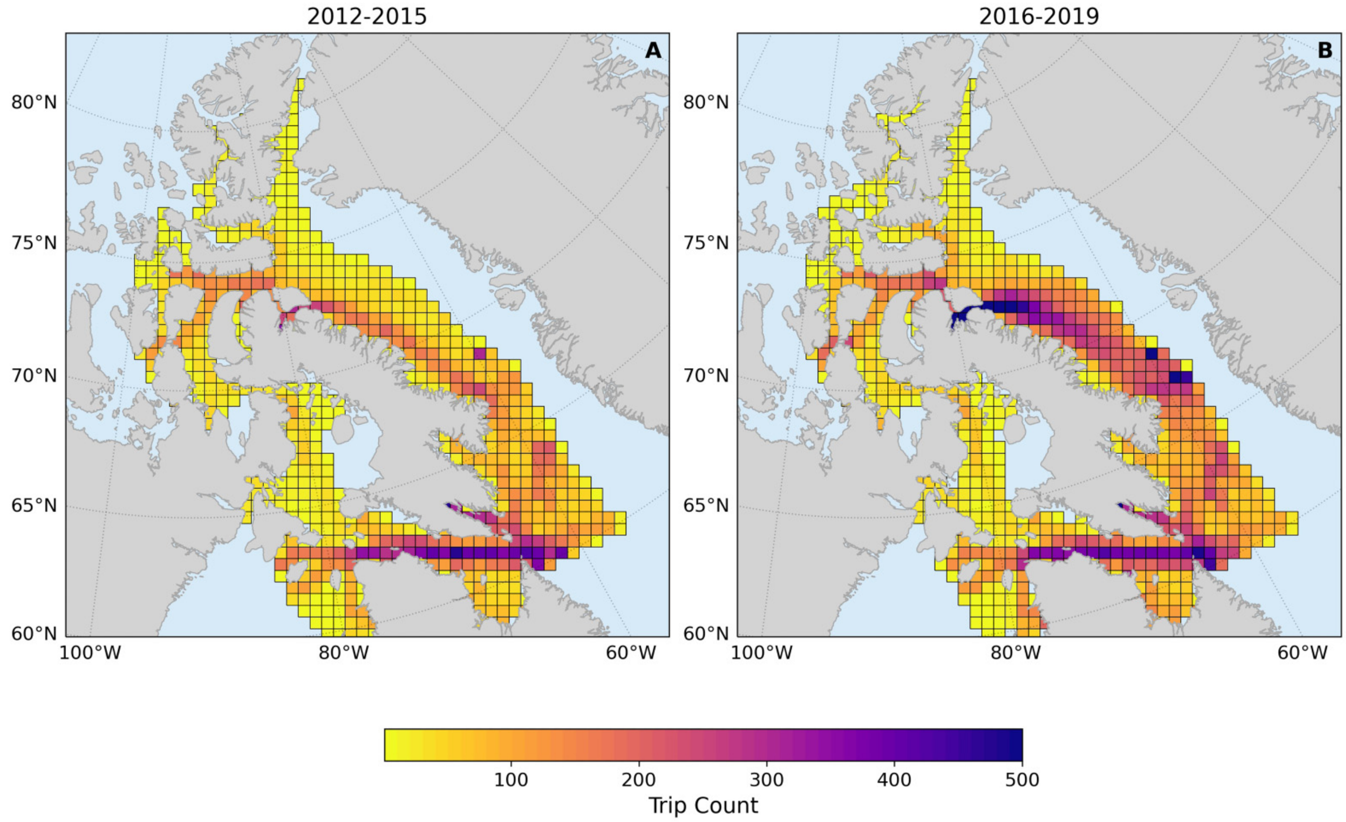
Fig. 4. Unique number of individual ships operating in the eastern Canadian Arctic by all vessel types from 2012 to 2019. Dashed line represents the trend line over time.



5.2.2.5. Passenger vessels

The unique number of passenger vessels increased from 7 to 17 between 2012 and 2019 (Table 2; Fig. 4). During the earlier period, 2012–2015, these vessels accounted for 441 trips which, similar to pleasure crafts, were distributed throughout the ECA. This included navigation through Hudson Strait, along the east coast of Baffin Island, and into Lancaster Sound and the Northwest Passage (Fig. 6G). From 2016 to 2019 the

Fig. 5. Total number of vessel trips per 50 × 50 km grid cell for: (A) 2012–2015, and (B) 2016–2019 throughout the shipping season (July–October). Projection: NAD83 / Statistics Canada Lambert.



total number of trips decreased slightly to 406, but traffic became more concentrated in the area around Bylot Island and the Northwest Passage.

5.3. Iceberg ship coexistence index (ISCI)

5.3.1. All vessel types

For all vessel types over the periods 2012–2015 and 2016–2019, annual ISCI showed similar spatial patterns, with maximum values occurring along the east coast of Baffin Island (Fig. 7). Moderate values occurred in the entrance to Lancaster Sound and Jones Sound, and around Bylot Island, with values decreasing further east into Baffin Bay and north into Nares Strait.

5.3.2. Individual vessel types

For each individual vessel type, we calculated the difference in annual ISCI between the earlier, 2012–2015, and later 2016–2019, time periods (Fig. 8). For dry bulk vessels (Fig. 8A), coexistence between icebergs and vessels was limited to the east coast of Baffin Island and the entrance of Hudson Strait. The greatest increase in ISCI (504) was observed along the east coast of Baffin Island and east of Bylot Island.

For cargo vessels (Fig. 8B), coexistence of icebergs and vessels extended from southern Ellesmere Island to Hudson Strait with increases in most regions. The greatest increase in ISCI (105) occurred within Lancaster Sound, and reached ~57 in the area east of Bylot Island and along the coast of Baffin Island.

The coexistence of icebergs and pleasure crafts was observed from southern Kane Basin to Hudson Strait (Fig. 8C). Overall, average annual ISCI decreased from 2012–2015 to 2016–2019 in Davis Strait and along the east coast of Baffin Island and in northern Baffin Bay/Smith Sound. The largest increase in average annual ISCI, from 108 to 284, was observed in Lancaster Sound.

Coexistence between icebergs and passenger vessels was observed between northern Nares Strait and Hudson Strait from 2012 to 2019 (Fig. 8D). Overall, ISCI increased along the coast of Baffin Island, Devon Island, and within Jones Sound. However, there were marked regional differences: in southern Baffin Bay and Davis Strait, average annual ISCI decreased by up to 30. In contrast, in areas to the north of Bylot Island and in Smith Sound and east of Ellesmere Island, increases in average annual ISCI ranged from reached 133, nearly doubling near Jones Sound.

6. Discussion

Historically, interactions between ships and icebergs in the ECA have resulted in outcomes ranging from no damage to sinking resulting in loss of life (Table 1). Iceberg ship collisions since 1800 have occurred in most regions of the ECA,

Fig. 6. Total number of vessel trips per 50 × 50 km grid cell for: (A, B) dry bulk, (C, D) cargo, (E, F) pleasure, and (G, H) passenger vessels for 2012–2015 and 2016–2019, respectively. Projection: NAD83 / Statistics Canada Lambert.

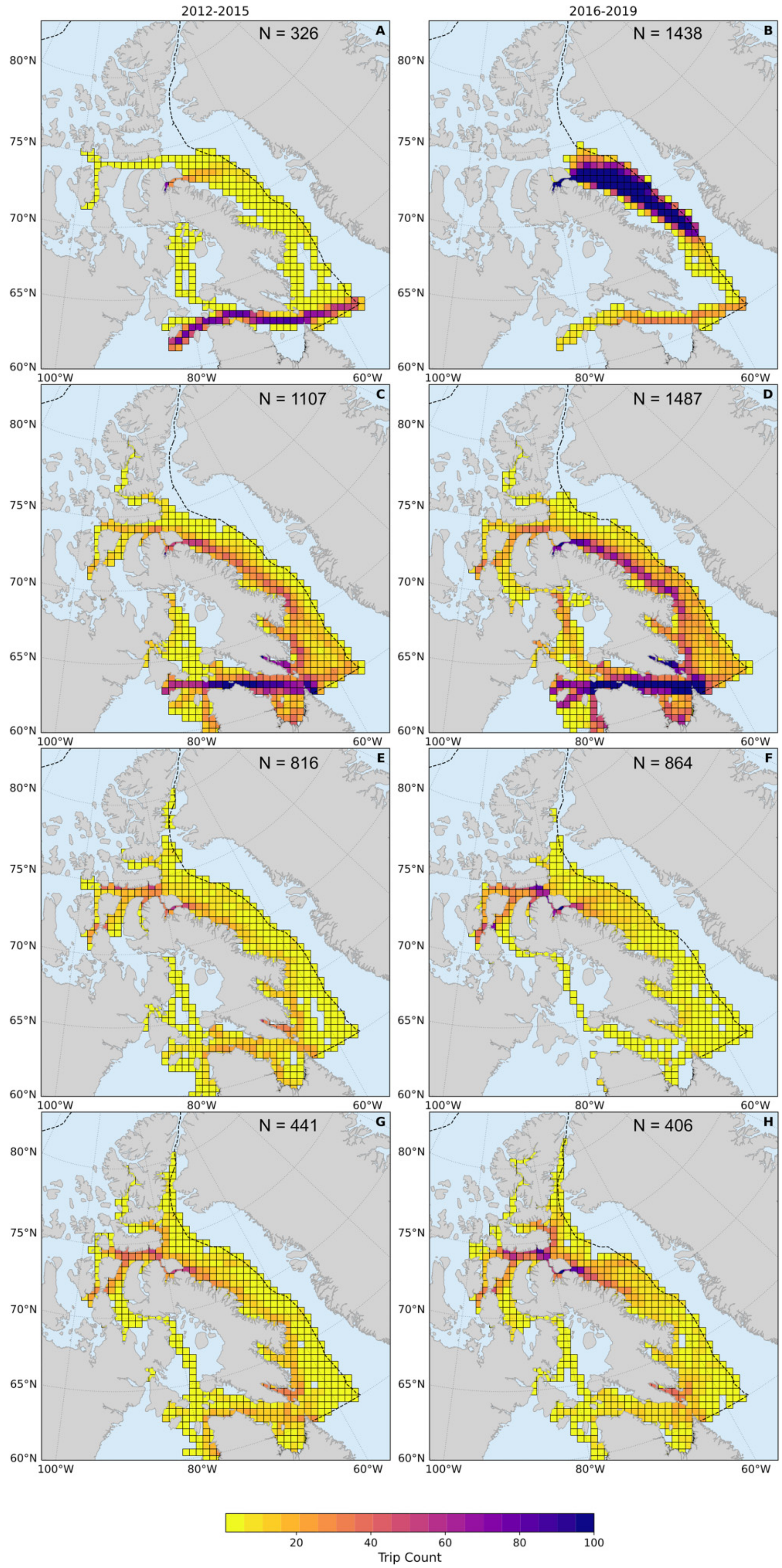
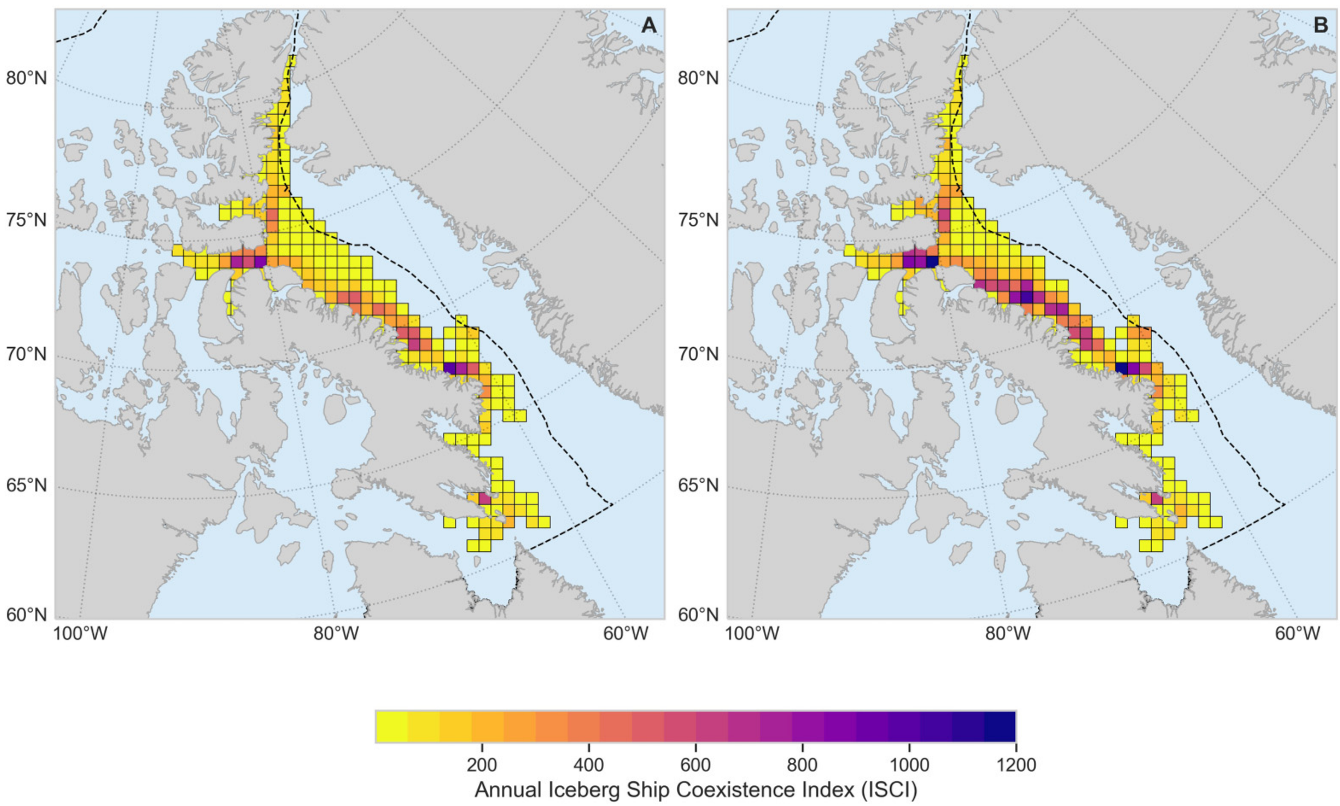


Table 2. Total number of individual ships operating in the eastern Canadian Arctic by vessel type from 2012 to 2019.

Vessel type	2012	2013	2014	2015	2016	2017	2018	2019	Total
Cargo	13	11	13	12	12	15	20	28	124
Container	0	2	4	0	0	2	0	0	8
Dry bulk	13	16	13	19	20	24	37	46	188
Passenger	7	10	8	11	11	12	21	17	97
Fishing	18	26	27	27	31	40	38	43	250
Government/research	16	15	16	20	16	27	19	18	147
Others/special ships	7	5	5	10	5	23	41	40	136
Pleasure crafts	14	12	22	15	23	20	20	43	169
Tanker	11	13	11	12	10	13	15	14	99
Tugs/port	9	10	6	8	6	13	19	22	93
Total	108	120	125	134	134	189	230	271	

Fig. 7. Average annual iceberg ship coexistence index (ISCI) for: (A) 2012–2015 and (B) 2016–2019 for all ship types. Projection: NAD83 / Statistics Canada Lambert.

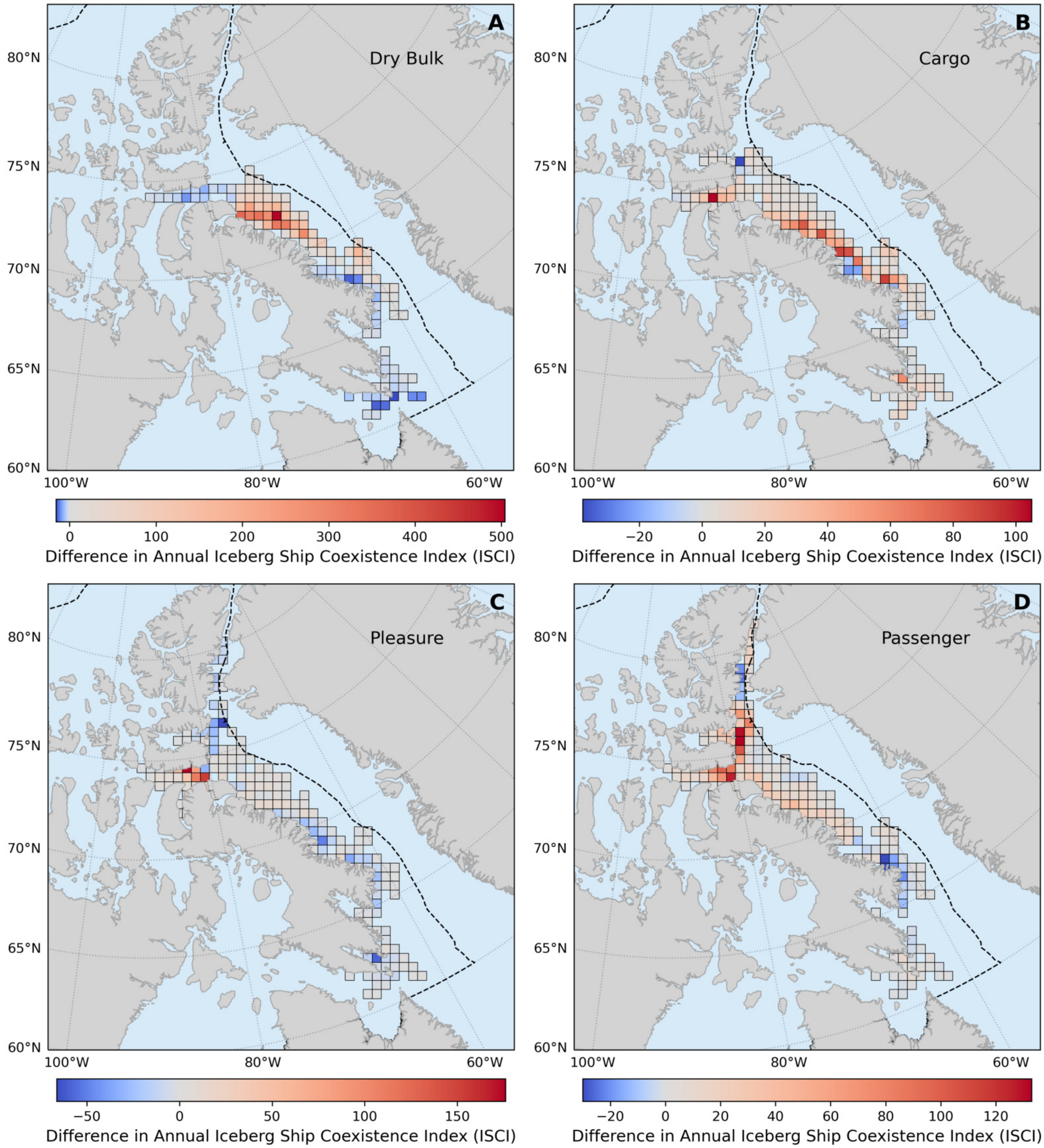


from Nares Strait to Davis Strait (Fig. 1; Hill 2010). In this study, we combined the two most comprehensive datasets available of iceberg and ice island locations throughout the ECA to produce a climatology of known iceberg presence between 2008 and 2019. While the iceberg climatology presented here is limited both spatially and temporally given the challenges involved in tracking icebergs using in situ and remote sensing methods, it provides the first assessment of iceberg distribution throughout the ECA. From these results, it is clear that ships have consistently been navigating through areas of known iceberg and ice island locations between 2012 and 2019. Here, we provide the first estimation of the coexistence of icebergs and ships throughout the ECA, quantify how coexistence has changed during 2012–2019, and present considerations for future navigation.

6.1. Presence of icebergs throughout the ECA

Production of icebergs from glaciers in the CAA has remained relatively consistent in the recent past, with frontal ablation (i.e., primarily iceberg production, as well as subaerial frontal melting and sublimation, and subaqueous frontal melting) accounting for $\sim$4.28 $\pm$ 1.18 Gt a^{-1} of mass loss over the period 2010 to 2020, compared to $\sim$4.14 $\pm$ 1.11 Gt a^{-1} from 2000–2010 (Kochtitzky et al. 2022). In western

Fig. 8. Difference in average annual Iceberg Ship Coexistence Index (ISCI) from 2012–2015 to 2016–2019 for: (A) dry bulk, (B) cargo, (C) pleasure, and (D) passenger vessels. Note the difference in scales. Projection: NAD83 / Statistics Canada Lambert.



Greenland, ice discharge from tidewater glaciers into Baffin Bay and surrounding waters has increased recently, totalling ~76 Gt a^{-1} from 2010 to 2018, compared to ~47 Gt a^{-1} from 2000 to 2010 (Mouginot et al. 2019; Mankoff et al. 2020). Icebergs have both an above-water (sail) and below-water (keel) portion and can range in size from smaller fragments called growlers (<5 m length) and bergy bits (5 to <15 m length) to large tabular ice islands several km^2 in area (Bigg et al. 1996; CIS 2005). In the ECA, icebergs can often become frozen in sea ice in the winter as they follow the shore of eastern Baffin Island, posing a threat to ships, as they are difficult to detect within the sea ice pack (Marko et al. 1982; AC 2009).

Ice islands, very large tabular icebergs, are discharged episodically through the disintegration of ice shelves and ice

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tongues For example, Petermann Glacier in NW Greenland underwent five major calving events from the floating glacial ice tongue at its terminus between 1959 and 2012, producing large ice islands on the order of 100 km^2 (Johannessen et al. 2013). Given the frequency of major events like these over the last several decades, the presence of ice islands and ice island fragments throughout the ECA is episodic. These events are likely to diminish given the significant loss of ice shelves in northern Greenland since the 1990s (Higgins 1991; Falkner et al. 2011) and from the CAA since the early 20th century (Mueller et al. 2017; White and Copland 2019). When ice islands are present in the ECA they are considered hazards to navigation, as well as a potential medium-term source of additional icebergs as fragments calve from the main pieces (Scambos et al. 2005; 2008; Wagner et al. 2014; Crawford et al. 2016). For example, ice island PII-B which calved from Petermann Glacier in 2010, produced 3.8 Gt of ice island fragments over 22 months during periods of drift and grounding (Crawford et al. 2016). Ice islands are capable of providing a source of icebergs to areas where few tidewater glaciers exist that would regularly produce icebergs, such as eastern Baffin Island (Van Wychen et al. 2015; Crawford and Mueller 2022).

Icebergs and ice islands identified in this study using satellite tracking beacons and remote sensing methods were observed to consistently drift south from Nares Strait along the east coast of Baffin Island, with frequent intrusions into Jones Sound, eastern Lancaster Sound, and Hudson Strait (Marko et al. 1982). The greatest concentration of ice island fragments was located within Nares Strait and Smith Sound, as their drift is restricted by topographic constraints between Ellesmere Island and Greenland (Fig. 4).

6.2. Navigation of vessels throughout the ECA: 2012–2019

Shipping throughout the CAA is dependent on environmental factors such as sea ice conditions and the length of the open water season. It is also controlled by demand, as shipping in the CAA is primarily destinational and vessels which navigate this region are there for a purpose such as resource extraction, community resupply, or tourism (Stephenson et al. 2015). Ships navigating within the Arctic are equipped with varying classifications of hull strengthening which allows them to operate in a range of ice conditions. Highly ice strengthened vessels such as icebreakers can operate in year-round sea ice conditions, including through floes with multiyear sea ice inclusions. Medium strength vessels, commonly cargo vessels, bulk carriers and some passenger ships, operate in summer and autumn conditions including through thin first-year sea ice with some multiyear ice inclusions, whereas minimally ice strengthened vessels such as pleasure crafts are designed for operation in mostly open water conditions with little to no ice presence (Dawson et al. 2022).

Overall, shipping traffic throughout the ECA increased both in number of unique vessels operating and the total number of trips taken by vessels between 2012–2015 and 2016–2019. Of the four specific vessel types highlighted in this study, the greatest overall increases in unique numbers were observed for dry bulk vessels, which nearly tripled between 2012 and 2019, and pleasure crafts, which more than tripled over the same period. While there was little increase in the number of trips taken by pleasure crafts from 2012 to 2019, trips by dry bulk vessels more than tripled with operations concentrated along the east coast of Baffin Island and towards Pond Inlet. Increases in unique number of ships was also observed in both cargo ships and passenger vessels. Consistent with the results of previous studies (Johnston et al. 2017; Dawson et al. 2018, 2022), while the number of trips taken by pleasure and passenger vessels throughout the ECA remained relatively stable over time, the unique number of vessels more than doubled, with vessels beginning to operate more northward than before. Our results indicate that not only did existing ships operating in the ECA take more trips from 2016 to 2019 compared to 2012–2015, but that new vessels have begun operating in these areas and extending their range northward into Nares Strait and westward into the Northwest Passage.

While icebergs are considered potential hazards for all vessels navigating in the Arctic, they are of particular concern for vessels with minimal or no ice strengthening. Overall, the average annual voyage count of ships with no ice strengthening operating in the NORDREG zone increased by 3300% between 1990 and 2019 (Dawson et al. 2022). Dawson et al. (2022) also found that in addition to the influx of new passenger, dry bulk, and cargo vessels operating in more northern regions of the ECA, the ice strengthening of these vessels had decreased between 1990 and 2019. Spatially, traffic of dry bulk vessels shifted out of Hudson Strait from 2012 to 2015 to almost exclusively along the east coast of Baffin Island in 2016–2019, where icebergs and ice islands are known to drift, resulting in an increase in the ISCI in the same region from 2012–2015 to 2016–2019. Due to cargo and passenger vessel traffic (with generally medium to minimal ice strengthening; Dawson et al. 2022) increasing in northern Baffin Bay and the entrance to the Northwest Passage, the ISCI also increased in these regions as icebergs are known to drift within eastern Lancaster Sound (Marko et al. 1982; Dalton et al. 2025) before continuing south along Baffin Island. Icebergs and ice islands which calve from NW Greenland (e.g., Petermann Glacier) and the QEI typically drift south through Smith Sound, often times becoming temporarily grounded near Coburg Island (Crawford and Mueller 2023). The greatest increase in ISCI in Smith Sound was observed for passenger vessels, which, as of 2016–2019, have begun operating in higher rates in more northern regions compared to 2012–2015.

6.3. Considerations for coexistence of icebergs and ships in the ECA

Glaciers from Greenland and the CAA remain a continuous source of icebergs for Baffin Bay (Kochtitzky et al. 2022), while vessels operating throughout the region over the past decade have changed both in quantity and the total number of trips taken, during which their level of ice strengthening has been reducing (Dawson et al. 2022). The Ice Navigation in Canadian Waters Manual is published by the Canadian Coast Guard and the CIS and provides operational requirements and guidelines for vessels operating within Canadian waters.

This manual identifies icebergs and their fragments, especially growlers and bergy bits, as extreme local hazards to vessels operating in ice infested waters. Glacial ice is very hard and severe damage can result from collision with a ship (CCG 2022). While the use of AIS transponders has become useful for differentiating between ships and icebergs (ABS 2016), ship radar cannot be solely relied upon for iceberg detection due to variable iceberg geometry and environmental conditions such as heavy snow, fog, and high waves (CCG 2022). Additionally, icebergs drifting or frozen within a sea ice pack can result in the formation of leads (open water areas) downstream of the iceberg (Hunke and Comeau 2011). While sea ice leads can offer a navigable passage for surface vessels, they can end suddenly at an iceberg, bergy bit, or growler (CCG 2022).

Although icebergs have been widely identified as posing a significant hazard to ships operating in the Arctic (ABS 2016; CCG 2022), few formal recommendations exist about navigation in iceberg-infested waters with the exception of planning routes through polar waters that take into account the current extent and type of icebergs in the vicinity of the planned route. However, ice charts produced for the CAA tend to broadly classify the limit of icebergs as "bergy waters," with little to no information on size, shape, or specific location. Presently, iceberg charts produced by CIS and the IIP only provide detailed information on iceberg conditions through shipping lanes south of 60°N.

The ISCI presented here indicates that the coexistence of icebergs and ships occurs for nearly all regions of the ECA north of 60°N. For dry bulk vessels from 2012–2015 to 2016–2019, which typically have minimal to medium ice strengthening (Dawson et al. 2018), average annual ISCI increased by up to 2700% in areas along the east coast of Baffin and Bylot Islands. For passenger vessels, ISCI has increased not only along the east coast of Baffin Island, but also in Smith Sound, as traffic from these vessel types moves northward. As shipping traffic increases through the ECA, the findings of this study clearly indicate the need for additional monitoring and reporting of iceberg and ice island locations for shipping lanes in the ECA.

7. Conclusion

Using a climatology of known iceberg drift locations in combination with AIS ship location data, we provide the first known quantification of the coexistence between ships and icebergs throughout the ECA. While we cannot conclude from this study that iceberg presence has increased throughout the ECA from 2012 to 2019, it is clear from our results that the number of unique ships and voyages has increased over this period. We are therefore able to use the ISCI to assess the changing relative likelihood of iceberg and ship coexistence throughout the ECA. This climatology indicates that icebergs and ice islands are consistently present during the shipping season throughout Nares Strait, eastern Lancaster Sound, and within Baffin Bay following the east coast of Baffin Island. When we look at the coexistence of ships and icebergs throughout the ECA between 2012 and 2019, our findings show that the greatest increases occurred along the east coast of Baffin Island, eastern Lancaster Sound, and Smith Sound. In particular, the coexistence of dry bulk and cargo vessels and icebergs has increased along the east coast of Baffin Island and east of Bylot Island. For passenger vessels, the greatest increases in coexistence were observed in Smith Sound, as operation by these types of vessels moves northward.

Icebergs present a known hazard to navigation in the Arctic around which ship operators are recommended to take caution. Operators are encouraged when planning to mark areas known to have significant concentrations of icebergs on charts, such as off the coast of Greenland (CCG 2022). The results of this study could be used in the planning stage to expand areas of known iceberg drift and grounding in the ECA. The hazards posed by icebergs to ships is likely increasing over time due to the observed recent increases in the number of vessels operating in the ECA, with the seriousness of any potential collision also increasing due to the recent reduction in mean ice strengthening observed in vessel types such as dry bulk, passenger, and pleasure crafts (Dawson et al. 2022). For vessels such as passenger ships, icebergs are also presented as an attraction or feature during navigation, so these vessels sometimes purposely navigate close to them.

Considering these increases in shipping navigation through areas of known iceberg presence, it is important to address issues that may arise with potential future increases in vessel traffic. Given the existing framework for iceberg analysis off the Newfoundland and Labrador coasts, it is recommended that iceberg charts be expanded to cover primary shipping lanes in the ECA during the shipping season. By including detailed analysis of iceberg location and size, icebergs could then be included in the ice numeral calculation for POLARIS, further refining the estimate of risk to ships navigating in the ECA.

The results of this study highlight the need for improved iceberg monitoring, both in situ for validation of iceberg drift forecast models, and through remote sensing, to allow for greater spatial and temporal coverage of their distribution. Collection of data on environmental variables through known iceberg areas will help us to better understand the forces controlling their drift and deterioration, especially through shipping lanes in the ECA. This study will provide foundational information for policy decisions surrounding vessel navigation through known iceberg locations.

Acknowledgements

We thank the Natural Sciences and Engineering Research Council of Canada, Canada Foundation for Innovation, Ontario Research Fund, ArcticNet Network of Centres of Excellence Canada, Amundsen Science, Environment and Climate Change Canada, University of Ottawa, Northern Scientific Training Program, and Polar Knowledge Canada for funding. Thank you to MEOPAR for permitting access to Satellite AIS data which were provided by exactEarth Ltd. (Spire) (2023) and processed courtesy of MEOPAR.

Article information

Editor(s)

Irene Gregory-Eaves, Raid Al-Tahir

History dates

Received: 9 October 2024
Accepted: 9 September 2025
Version of record online: 24 November 2025

Data availability

The Ship Iceberg Collision Database compiled by Hill (2010) can be accessed online (https://newicedata.com/the-ship-iceberg-collision-database/). The Transportation Safety Board Marine Safety Information System (MARSIS) is accessible online (https://www.tsb.gc.ca/eng/stats/marine/data-6.html). The CI2D3 Database of ice island locations from 2008 to 2013 is available for download through the Polar Data Catalogue (https://www.polardata.ca/pdcsearch/PDCSearch.jsp?doi_id=12678). The IBTD is available for download through the Polar Data Catalogue (https://www.polardata.ca/pdcsearch/PDCSearch.jsp?doi_id=13340). Access to Satellite AIS data was given through a joint project agreement with MEOPAR-processed ship data provided by exactEarth Ltd. (Spire) (2023).

Author information

Author ORCIDs

Abigail Dalton https://orcid.org/0000-0002-6787-2116
Luke Copland https://orcid.org/0000-0001-5374-2145
Wesley Van Wychen https://orcid.org/0000-0002-4275-6768
Jackie Dawson https://orcid.org/0000-0002-3532-2742
Alison Cook https://orcid.org/0000-0003-0374-9167
Adam Garbo https://orcid.org/0000-0002-7312-7390
Derek Mueller https://orcid.org/0000-0003-1974-319X
Adrienne Tivy https://orcid.org/0000-0001-5764-3232

Author contributions

Conceptualization: AD, LC, WV, JD, AG, DM, AT
Data curation: AD, JD, AG, DM
Formal analysis: AD
Funding acquisition: LC, WV, AT, JD
Investigation: AD
Methodology: AD, LC, WV, JD, AC, AG, DM
Project administration: AD, LC
Resources: LC, WV, JD, AT
Software: LC
Supervision: LC, WV
Visualization: AD, AG
Writing – original draft: AD
Writing – review & editing: AD, LC, WV, JD, AC, AG, DM, AT

Competing interests

The authors have declared that no competing interests exist.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/facets-2024-0232.

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