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Analysis of ice navigational risks by level of ice strengthening among vessels in the Canadian Arctic (1990-2019)

Prepared for the Northern Transportation Adaptation Initiative Team of Transport Canada – March 2021

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NOTICES

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EXECUTIVE SUMMARY

Climate change has caused a substantial reduction in sea ice extent and thickness over the last few decades, but has also increased ice mobility and inter-annual variability. These variable and unpredictable sea ice conditions still present significant navigational challenges for most shipping in the Canadian Arctic, during a period when there have been large increases in ship traffic since the 1990s. The operational risks associated with the combined increase in ship traffic and occurrence of hazardous sea ice varies, depending on the Ice Class (i.e. level of ice strengthening) of the vessel, and on the ice conditions it encounters. To date there has been no systematic study undertaken that evaluates the changes in navigational risk using actual shipping records with a statistically significant duration (30+ years) and observed changes in sea ice conditions.

To address this knowledge gap, sea ice charts were converted into navigational threshold maps using the Risk Index Outcome (RIO) values outlined in the Polar Code, and then compared with reports of ship positions for 1990-2019. A positive RIO value indicates an acceptable risk level where operations may proceed, while a negative RIO indicates increased risk, potentially to levels where it is not recommended that the vessel advances. RIO values were obtained from ice charts close to the date of each ship position report, and calculated for the specific Ice Class of each ship. This resulted in a dataset of 37,520 ship position reports with RIO attributes for the NORDREG zone, which were then used for the analysis of ice navigational risks encountered by ships of different ice strengths since 1990.

Results reveal that a small proportion (<4%) of ship position reports with RIO values occurred in areas of increased ice risk (RIO <0) between 1990-2019 in the NORDREG zone. The vast majority of ship position reports (>96%) travelled under conditions that can be considered normal and safe, and many travelled well within the limits of safe operation with respect to ice conditions. Over the period of record there was a significant increase in the total number of ship position reports in elevated risk areas (RIO < 0 to -10), and a slight increase in the number of ship position reports in high risk areas (RIO < -10). There was a similar increase over time in the number of tracks in both high and elevated risk thresholds. Considering that we expect an overall increase in ship traffic in the future, it is likely that we will continue to see a small but still present proportion of ship position reports and tracks in higher risk ice regimes.

There has been a larger increase in risk for specific ship types towards the present day, most notably for fishing vessels and pleasure craft. Of particular importance is that low ice strengthened vessels, including many ships with no ice strengthening at all, make up the largest proportion of ship position reports and track counts found in high ice-risk

thresholds. The number of non-ice strengthened ship position reports from areas of increased risk grew substantially beginning in 2004.

Three geographic areas were identified as regions where the prevalence of higher ice-risk ship position reports have occurred: 1) Franklin Strait, 2) Frobisher Bay, and 3) Lancaster Sound. In each of these regions, certain vessel types were more frequently observed to operate in areas of increased risk (RIO < 0), most often bulk carriers, tanker ships, and pleasure craft. The specific location of risk events changed over time, as did the type of ship that contributed to these events, with notable recent increases in the number of ship position reports from pleasure craft operating in high risk areas in Franklin Strait and Lancaster Sound.

Overall, our results show that since 1990, there have been a generally small number of ship position reports and tracks with increased risk in the Canadian Arctic. However, the total number of ship position reports and tracks in these risky conditions is increasing over time, particularly for pleasure craft, which creates concerns when combined with the increased mobility of sea ice. This is a region with limited infrastructure and support services, including critical search and rescue services, which can compound any risks that exist for ship-ice interactions.

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DEFINITIONS AND GLOSSARY

Egg Code: convention for classifying all sea and lake ice, describing concentration, stages of development (age) and form (floe size) of ice. The data are contained in a simple oval form

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

IMO: International Maritime Organization

MCTS: Marine Communications and Traffic Services, a branch of the Canadian Coast Guard which coordinates the collection of ship location information in the NORDREG zone

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

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

POLARIS: Polar Operational Limit Assessment Risk Indexing System

RIO: Risk Index Outcome

1.0 INTRODUCTION

Over the past several decades, there have been extensive reductions in sea ice extent in the Arctic Ocean (Cavalieri and Parkinson, 2012; Stroeve et al., 2012), including in the Canadian Arctic (ECCC, 2019; Serreze and Stroeve, 2015; Kwok, 2018). In the Canadian Arctic Archipelago, sea ice extent declined by 1.3% per decade between 1979-2010 (Cavalieri and Parkinson, 2012). Further, the onset of icepack melt is occurring significantly earlier in the season, and the freeze-up period is beginning later (Stroeve et al., 2014). This means that the historically sought-after voyage through the Northwest Passage (NWP) is now often possible, for at least some portion of the year. Observed changes in sea ice extent are coupled with losses of thick, multiyear ice, and an increased abundance of thin, first year ice (Comiso, 2012; Mudryk et al., 2018; Stroeve et al., 2012). This increases ice pack mobility (Howell et al., 2013; Howell and Brady, 2019), and means that ice conditions are highly variable from one year to the next (Haas and Howell, 2015).

Over this same period, there have been rapid increases in ship traffic in the Canadian Arctic (Pizzolato et al., 2014; Dawson et al., 2018). Notably, this includes vessels with little to no ice strengthening (Copland et al. in press; Dawson et al. 2020). These ordinary vessels can encounter a wide range of challenges while navigating ice infested waters, which can easily lead to incidents, including, for example, damage to the ship from ice impact, vessels becoming beset in sea ice, or issues due to inexperience of the captain and crew navigating hazardous ice conditions (Kujala et al., 2019). This was evident by the sinking of several pleasure craft in the summers of 2017 and 2018 (Mooney, 2017; CBC, 2018; Toth, 2018; Coast Guard, 2018). Risk during these types of incidents is further exacerbated by the limited search and rescue capabilities in these remote areas.

Despite reduced sea ice extent, increased ice mobility and annual variability present significant navigational challenges for most shipping in the Canadian Arctic, particularly in more northerly regions and throughout the NWP (Howell and Yackel, 2004; Tseng and Cullinane, 2018). In fact, it is possible that risks to shipping are higher now than in the past, and may continue to increase as conditions change. The operational risks vary depending on the Ice Class of the vessel (i.e. level of ice strengthening) and on the level to which sea ice is prevalent and changing in the regions where ships operate. To address these risks there needs to be informed policy made surrounding Arctic shipping, both generally and in terms of safety. However, to date there has been no systematic study undertaken evaluating the changes in navigational risk using actual shipping records with a statistically significant duration (30+ years). Therefore, this study was designed to inform policy by addressing this important gap in knowledge by:

a. Providing details about how many unique ships, and which types of ships, transited the NORDREG zone between 1990-2019, as well as trends for ship tracks;
b. Detailing what ice navigational risks were encountered by vessels, including by different types of ships and with different ice strengths;
c. Examining the spatial patterns in risk encountered by ships, including specific areas of high risk; and,
d. Discussing the changing level of risk for ships operating in the Canadian Arctic.

2.0 METHODS

Past ice navigational risks to ships within the Canadian Arctic can be determined using historical weekly regional ice charts and ship records that include the Polar Code classification of the ship's hull strength. The International Maritime Organization (IMO) developed a methodology for assessing the operational limitations of vessels travelling in ice infested waters called the Polar Operational Limit Assessment Risk Indexing System (POLARIS). The system assesses ice conditions by determining the Risk Index Value (RIV) based on the Polar Code ship classification and each sea ice type within a region, and then summing those values to produce a Risk Index Outcome (RIO) for that region:

$$RIO = (C_1 \text{ x } RIV_1) + (C_2 + RIV_2) + (C_3 \text{ x } RIV_3) + \ldots (C_n \text{ x } RIV_n) \qquad \text{(eq. 1)}$$

Where $C_1 \ldots C_n$ are the concentrations (in tenths) of ice types within a region, and $RIV_1 \ldots RIV_n$ are the corresponding Risk Index Values provided in Appendix A. A positive RIO value indicates an acceptable risk level where operations may proceed, while a negative RIO indicates increased operational risk, potentially to levels where it is not recommended that the vessel advances (e.g. due to regulatory penalties, legal liability, insurance issues) (IMO, 2016) (Table 1).

Table 1: IMO Polar Code Risk Index Outcome (RIO) Criteria

RIO Value	**Ice classes PC1-PC7**	**Ice classes below PC7 and ships not assigned an ice class**
RIO ≥ 0	Normal operation	Normal operation
-10 ≤ RIO < 0	Elevated operational risk	Operation subject to special consideration
RIO < -10	Operation subject to special consideration	Operation subject to special consideration

In this study we assign RIO values to ship position reports and use these to quantify the level of operational risk that was encountered by ships operating in the Canadian Arctic over the period 1990 to 2019. The RIO values are calculated from ice charts that were issued close to the date of the ship record, for a total of 37,520 ship position reports. A full description of the methodology can be found in Appendix A, and a summary is provided below.

In the first stage, all ship position reports were obtained from the Marine Communications and Traffic Services (MCTS) office for each individual year between 1990 and 2019. The data was quality controlled, converted into a point shapefile for further editing in ESRI ArcGIS 10.6.1, and merged to create one shapefile with a total of 115,173 ship position reports for 1990-2019. This included clipping the shapefile to the NORDREG boundary and joining non-spatial attributes (e.g., Polar Code classification of the ship's hull strength) from a ship characteristics database, with further editing to remove erroneous values. This provided the foundation for the RIO analysis within the NORDREG Zone, which was undertaken over sequential 5-year periods (1990-1994, 1995-1999, etc.) to reduce inter-annual noise and better show changes over time. The data in the main text is mainly discussed in terms of **ship position reports**, which reflect the typically daily locations reported by ships operating in the NORDREG zone, and are indicative of the intensity of regional navigational risk. For a single general cargo ship on a month-long community resupply run, for example, this vessel would provide approximately 30 ship position reports. In places we also provide **unique ship counts** and **track counts** to indicate of how many different ships have operated in the NORDREG Zone over time. Unique ship counts refer to the counting of each ship only once within each annual period, even if it travelled in the NORDREG zone multiple times that year. Track counts refer to the counting of each ship when it enters and exits the NORDREG zone. Other results are also available in the Appendices.

The second stage of analysis involved a comparison of each ship position report with sea ice conditions at that location, as recorded in weekly regional ice charts produced by the Canadian Ice Service (CIS; downloaded from https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions/archive-overview.html). These ice charts were converted into RIO values using equation (1), based on the type and concentration of sea ice within each region defined by a single Egg Code. This produced polygon shapefiles for each ice chart, with a RIO value for each separate ship ice class.

The ship position reports were typically available daily, while ice charts were only available weekly, so the ship records were filtered to only include those positions recorded close to an ice chart issue date. This is to ensure that the RIO value calculated for each ship position report provides an accurate representation of the sea ice conditions at that time and location. Each shapefile includes the date that the ice chart was issued (a ‘Date_carte’ attribute), which was compared to that of the ship position report. At the CIS, ice charts were created manually using radar satellite imagery typically taken between 1 and 3 days before the chart issue date between 1990 and 2007, and between 0 and 2 days before the chart issue date between 2008 and 2019[1]. For this analysis, we therefore only included ship position reports up to three days before the ice chart issue date for 1990-2007, and two days for 2008-2019.

The discrepancy between ice chart and ship position report dates was considered when assessing the results, as were other changes over time, such as the improving digitization precision of ice charts towards the present day. Similarly, adjacent regional ice charts sometimes had differing ice conditions listed at their boundaries, so we always prioritized the ice chart with the date closest to the ship position report. Full descriptions of the specific ArcGIS methods used and descriptions of ice charts and Risk Index Values are included in Appendix A, and data limitations are explained in Appendix B.

The completed dataset consists of an ArcGIS point shapefile with 37,520 ship position reports, each of which has an assigned RIO value. An example of ship position reports overlying a regional ice chart from one week in 2018 are shown in Figure 1. This shows that several Polar Code Ice Class 1AS ships reported in a region that is considered normal operation only for ships with PC6 ice strength or stronger. These records therefore occur within a ‘risk’ zone.

The final step involved assigning risk thresholds based on the RIO values. Following a discussion with personnel at Transport Canada and CIS, it was decided to define risk thresholds according to the IMO Polar Code RIO operational risk criteria. In line with the ship operation table from the IMO Polar Code Report (Table 1), the three thresholds used in this study are defined as follows:

- Normal Operation (RIO ≥ 0)
- Elevated Risk (RIO <0 to -10)
- High Risk (RIO < -10)

This final dataset was used for numerical analyses to address the questions of how navigational risks encountered by ships of different types and hull strengths have changed over time.

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[1] This discrepancy is due to the launch of Radarsat-2 in December 2007, which increased the frequency and availability of satellite imagery for ice chart production from 2008 onwards. More information is provided in Appendix B.

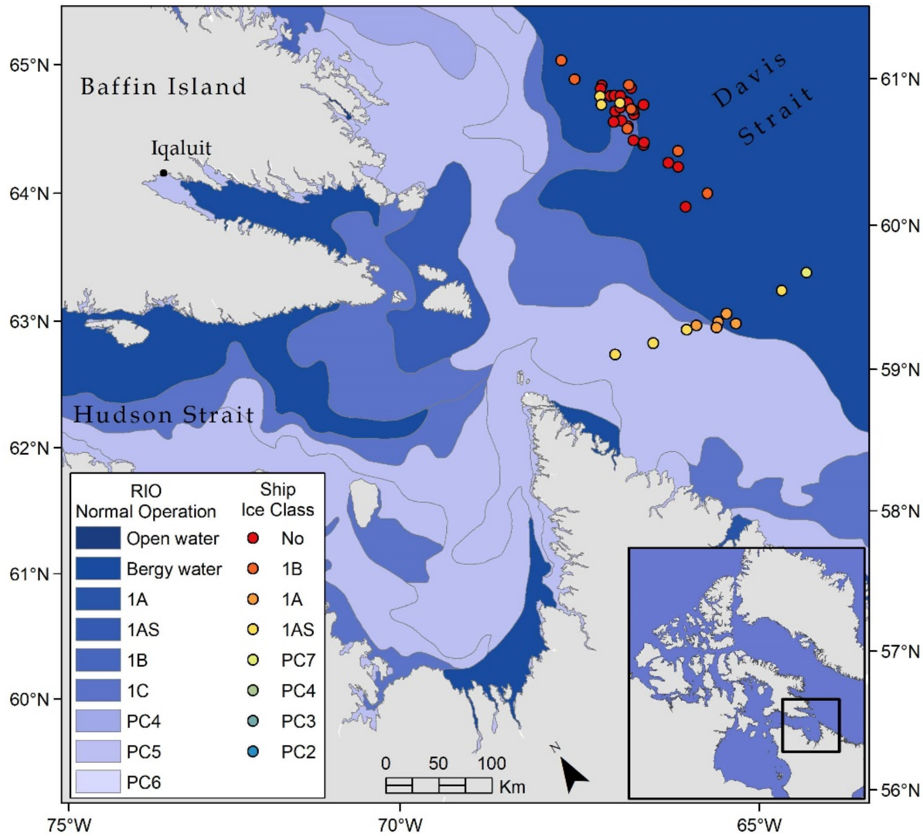

Figure 1: An example showing one weekly regional ice chart issued on 25 June 2018 converted to RIO Normal Operation values (i.e., RIO is ≥ 0 for each given ship class). Overlain are dots which show the ship position reports, including the Polar Code Ice Class, that correspond to this chart (23-25 June 2018).

3.0 CHANGES IN TEMPORAL PATTERNS OF SHIP TRAFFIC IN ARCTIC CANADA (NORDREG ZONE)

In this section, we include all ship position reports provided by MCTS for the NORDREG Zone for 1990-2019 to show the overall trends in unique ship counts and track counts, as a background for the analysis of the subset of ship position reports that have RIO values in Section 4. In total, 115,172 ship position reports were available within the NORDREG zone between 1990-2019.

Figure 5 and Table 2 show the overall increase in the total number of ship position reports, in 5-year intervals. The most significant increases occurred between 2010-2014, when a total of over 11,000 ship position reports occurred within the NORDREG zone compared to the previous time period (Figure 5; Table 2). In 2015-2019, over 37,000 ship positions were reported within the NORDREG zone (Figure 5, Table 2).

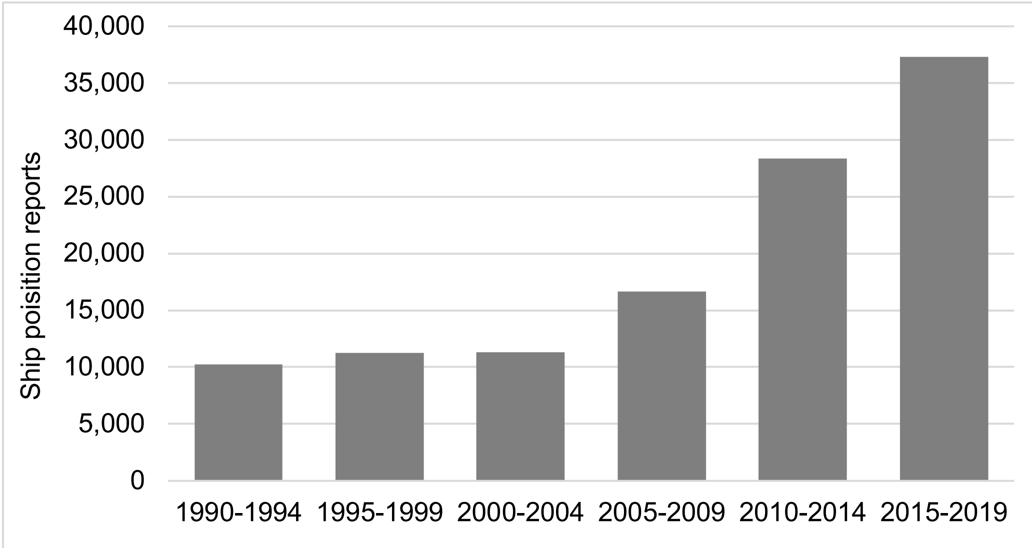

Figure 2: Total number of ship position reports in the NORDREG Zone, by 5-year time intervals.

Table 2: Total number of ship position reports in the NORDREG Zone, by 5-year time intervals.

Time Period	Ship Position Reports
1990-1994	10,242
1995-1999	11,238
2000-2004	11,338
2005-2009	16,672
2010-2014	28,370
2015-2019	37,310
Grand Total	**115,172**

3.1 Trends in Unique Ship Counts

In terms of unique ship counts, the number vessels has been increasing since 2005, including substantial increases between 2016 and 2019 (Figure 2). In 2019, 198 unique ships travelled within the Canadian Arctic, more than double the average of 85 unique ships that travelled between 1990 and 2006.

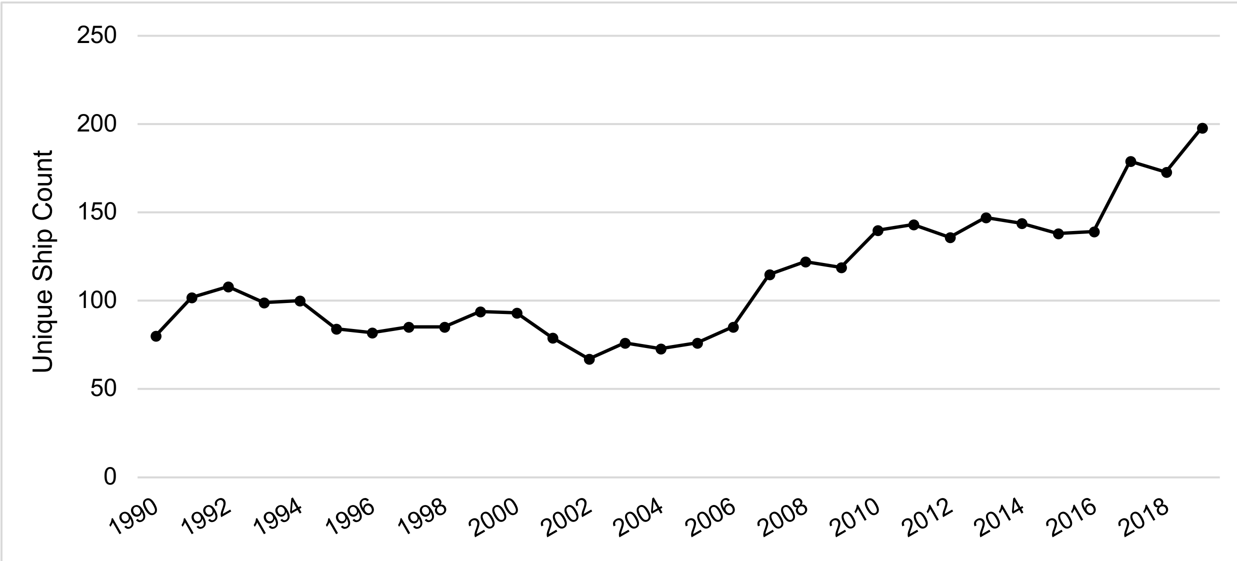

Figure 3: Mean annual unique ship counts in the NORDREG Zone.

There has been a gradual increase in unique ship counts for almost all ship types (Figure 3). Bulk carriers show the most growth, and made up over 25% of unique ships that travelled within the NORDREG zone in 2019 (Figure 3). This is followed by fishing vessels, and general cargo. However, the number of fishing vessels was highest in 1992, decreased in the early 2000s, and has been generally increasing since 2006. The number of pleasure craft travelling in Canadian Arctic waters has also increased substantially, from 2 in 1990 to a peak of 30 in 2016.

In terms of change in hull strength over time for unique ships travelling in the NORDREG zone, there is a clear difference between high/medium ice strengthened vessels (Polar Class Categories A and B; Figure 4A), and low ice strengthened vessels (Category C; Figure 4B). There has been little to no increase in the number of highly ice strengthened (PC1 to PC6) ships, but a remarkable increase in medium ice strengthened (PC7) ships since 2008 (Figure 4A). There have always been a large number of ships with little ice strengthening (Polar Class 1B), but these have also shown an overall increase (Figure 4B). There has been a significant increase in ships with no ice strengthening since 2006 (Figure 4B). More discussion surrounding the changes in ship ice strengthening can be found in Dawson et al. (2020), and for further information on trends in non-unique ship counts, please see Appendix D. Appendix D also includes information on ship type and ice class.

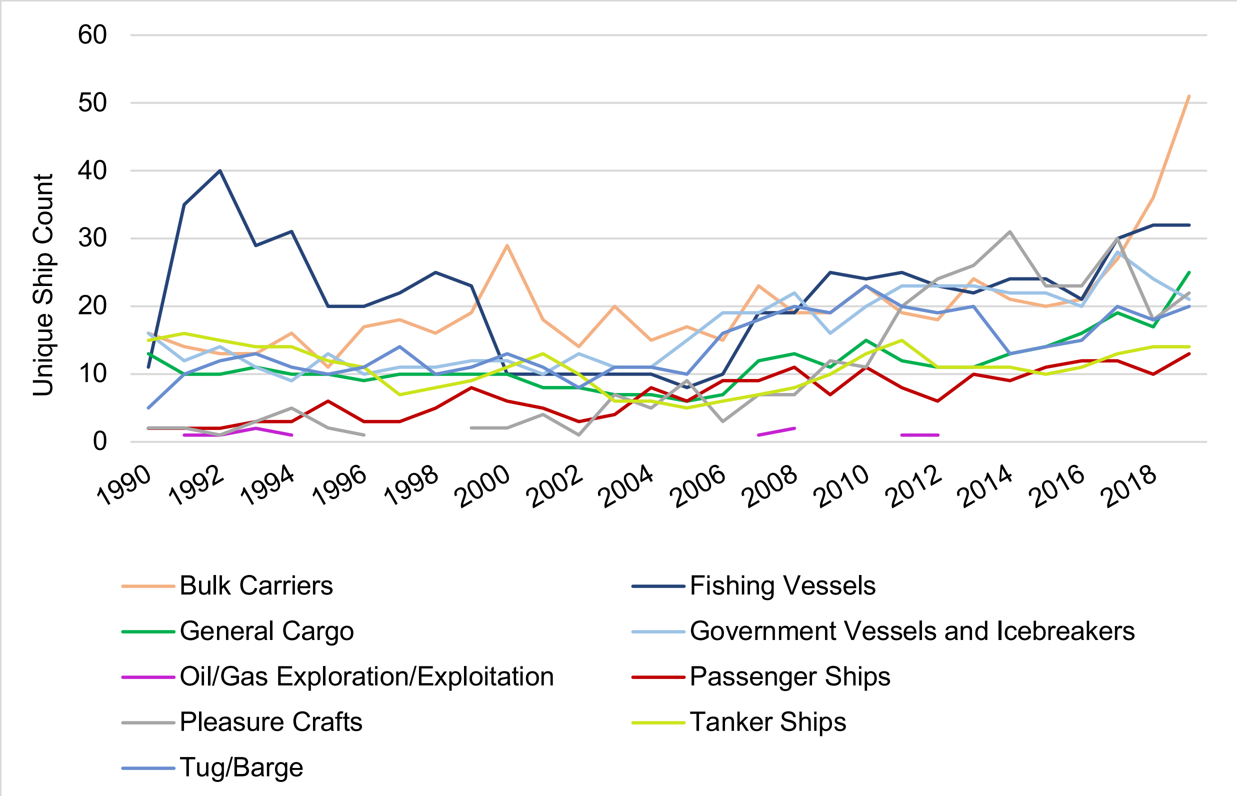

Figure 4: Mean annual unique ship counts in the NORDREG Zone by ship type.

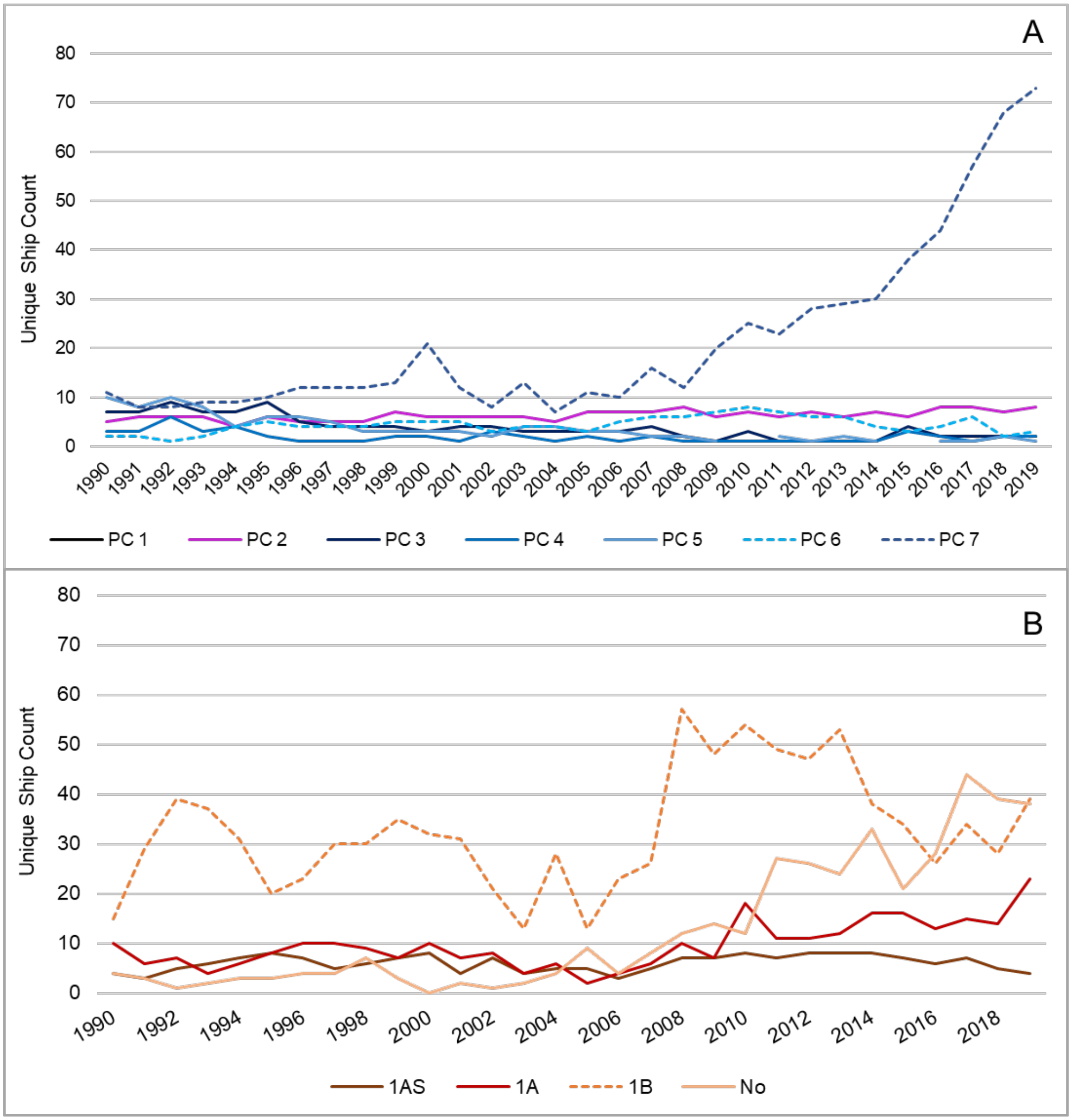

Figure 5: Mean annual unique ship counts in the NORDREG Zone by Ice Class in: (A) Polar Class hull strength categories A and B (PC1 to PC7); (B) Polar Class hull strength category C (1AS to no ice strengthening, indicated by "No").

3.2 Trends in Track Counts

For tracks, the number counts remained fairly stable from 1990 to 2006, and has been increasing since (Figure 6). Between 2006 and 2019, the track count more than quadrupled, increasing from 118 tracks in 2006 to over 500 tracks in 2019 (Figure 6).

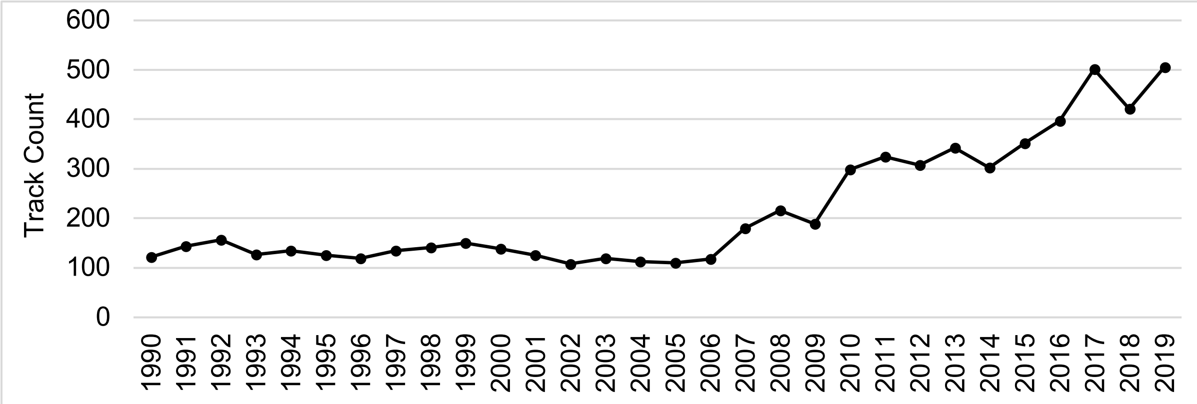

Figure 6: NORDREG Zone total annual track counts.

As with unique ship counts, there has been a gradual increase in track counts for almost all ship types (Figure 7). Fishing vessels made up 29% of track counts in 2019, and showed a substantial increase in track counts after 2006, including a large spike of over 72 track counts between 2009 and 2010 (Figure 7). Track counts for bulk carriers also increased substantially after 2014, from 31 to 143 in 2019 (Figure 7). Tracks also increased for general cargo (Figure 7).

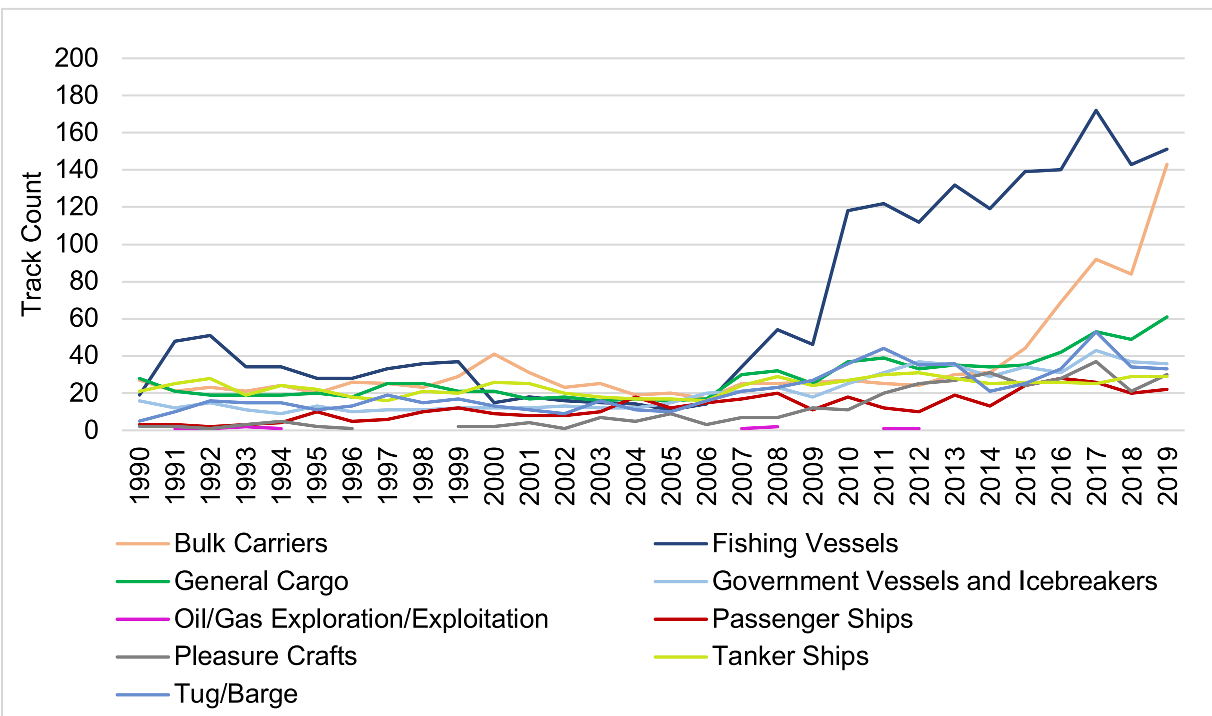

Figure 7: NORDREG Zone annual track counts by ship type.

When examining how the hull strength of vessels has changed over time in relation to the track count, the trend is similar to that of unique ships (Figure 8). Medium ice strengthened vessels (PC7) had the highest overall track count, and showed the greatest increased over time, particularly from 2014 to 2019 where they almost tripled (Figure 8A). As with unique ships, there has been little to no increase in the number of highly ice strengthened (PC1 to PC6) ships (Figure 8A). There were more track counts for ships with little ice strengthening (Polar Class 1B) than highly ice strengthened ships (PC1 to PC6), and the number of tracks stayed fairly consistent over the record, increasing slightly since 2006 (Figure 8B). Notably, this includes an increase in ships with no ice strengthening (Figure 8B). More discussion surrounding the changes in ship ice strengthening can be found in Dawson et al. (2020), and for further information is available in Appendix D.

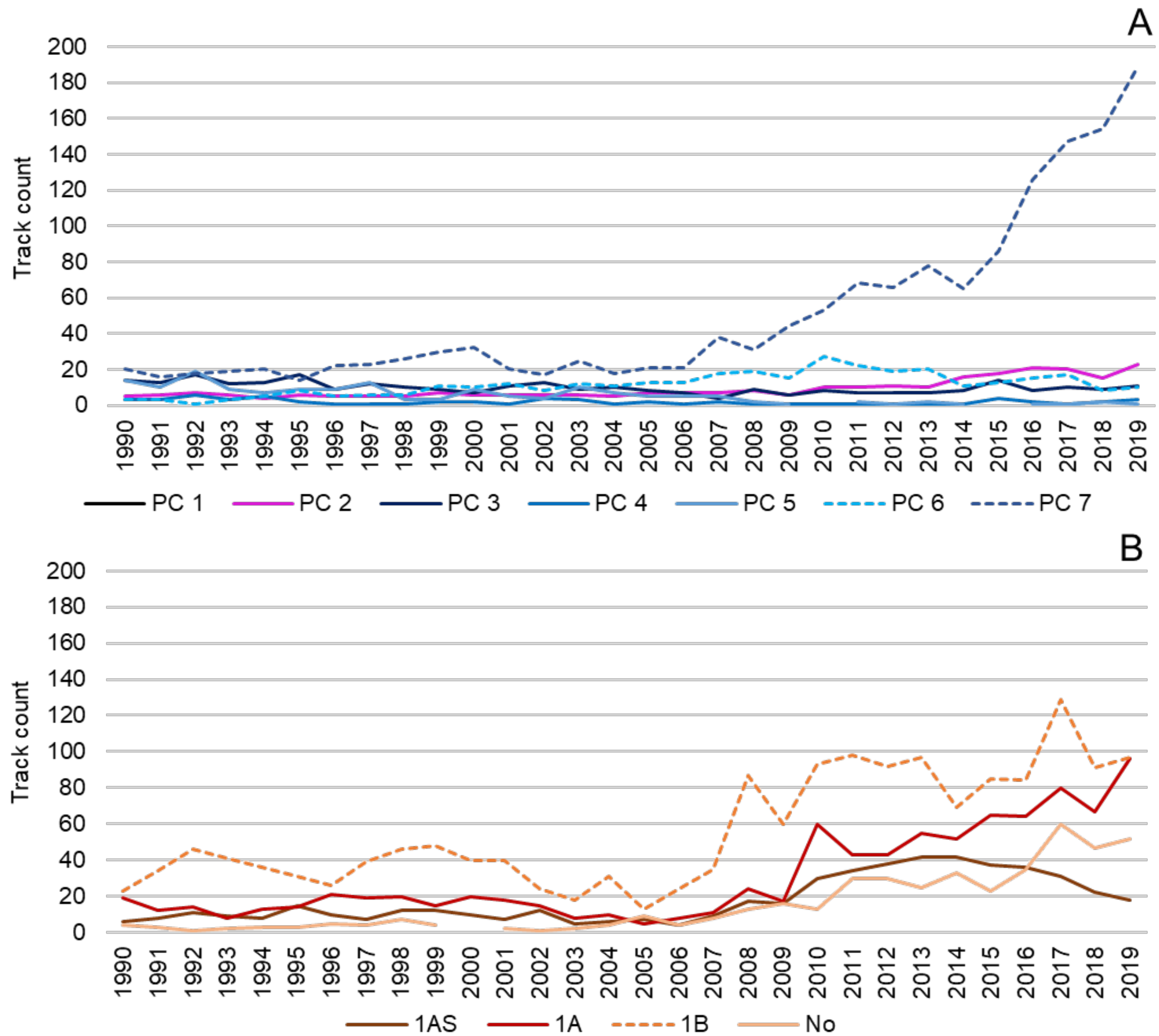

Figure 8: NORDREG Zone annual track counts by Ice Class in: (A) Ship Category A and B, and (B) Category C.

4.0 TEMPORAL ANALYSIS OF OPERATIONAL RISK BASED ON SHIP STRENGTH AND ICE TYPE

In section 3.0, we identified patterns in all ship traffic in the NORDREG zone between 1990 and 2019. In this section and later, we focus only on ship position reports with assigned RIO values (i.e., those within 2-3 days of the issue date of an ice chart; Section 2.0), to assess changing levels of operational risk experienced by ships over that same time frame. Since RIO values could only be assigned to approximately a third of total ship position reports, the ship position reports listed as 'high risk' or 'elevated risk' in the following sections need to be regarded as minimums, with actual numbers potentially up to ~3 times higher.

4.1 RIO Results from Ship Position Reports

For the time periods studied, the number of ship position reports to which RIO values could be assigned progressively increased, from almost 3,500 in 1990-94 to over 12,000 in 2015-19 (Figure 9A and Table 3). This increase matches the increase in overall number of ship position reports described in Section 3, as both records increased by about 3-4 times between 1990-1994 and 2015-2019 (Figure 2 and Table 2). This indicates that although only ~33% of ships could have RIO values assigned to them, that subset provides a representative sample with no temporal bias. Most notably, the number of ships in the elevated risk category (RIO < 0 to -10) and high risk category (RIO < -10) is a low percentage of the total count in each time period (Table 3). In every 5-year period analysed, over 96% of ships reported risk in the normal operation category (RIO ≥ 0).

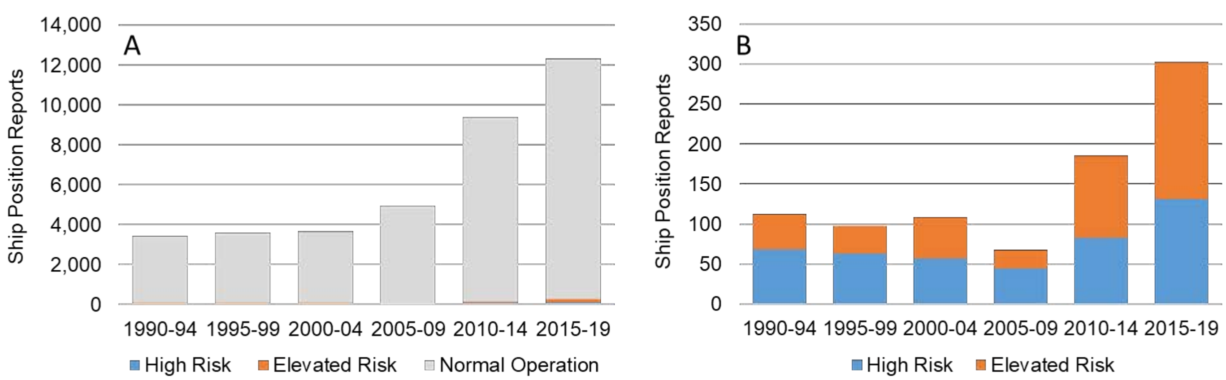

Figure 9: (A) Total count of ship position reports with RIO values for 5-year time intervals between 1990 and 2019, categorized by risk thresholds; (B) highlighting only high and elevated risk categories.

Table 3: Count of ship position reports with RIO values within each risk threshold at 5-year time intervals. The percentage of the total count is indicated in brackets.

	High Risk	Elevated Risk	Normal Operation	
	RIO < -10	**RIO < 0 to -10**	**RIO ≥ 0**	**Total Count**
1990-94	69 (2.0%)	44 (1.3%)	3,341 (96.7%)	3,454
1995-99	64 (1.8%)	35 (1.0%)	3,496 (97.3%)	3,595
2000-04	58 (1.6%)	51 (1.4%)	3,595 (97.1%)	3,704
2005-09	46 (0.9%)	22 (0.4%)	4,900 (98.6%)	4,968
2010-14	119 (1.3%)	115 (1.2%)	9,214 (97.5%)	9,448
2015-19	132 (1.1%)	171 (1.4%)	12,048 (97.6%)	12,351
Total	**488 (1.3%)**	**438 (1.1%)**	**36,594 (97.5%)**	**37,520**

Overall, the number of ship position reports that occurred in conditions of increased operational risk (RIO <0) has generally increased over time, both for 5-year periods (Figure 9B) and for individual years (Figure 10). This includes both high and elevated risk categories. In the high risk category, there was a slight decrease in the number of ship position reports from the period 1990-94 to 2005-09, followed by a sharp increase from 2005-09 to 2015-19 (Figure 9B). There was a similar trend for the elevated risk category, with an even more dramatic increase after 2005-09 (Figure 9B). Figure 10 shows the significant increasing trend in the annual number of elevated risk ship position reports between 1990 and 2019, from less than 5 to almost 30 (R^2 = 0.39, p-value < 0.05). Conversely, there was a slight increase in the annual number of ship position reports in the high risk category, although this trend is not statistically significant (R^2 = 0.10, p-value > 0.05). However, there is a large amount of inter-annual variability for both the high and elevated risk categories (Figure 10).

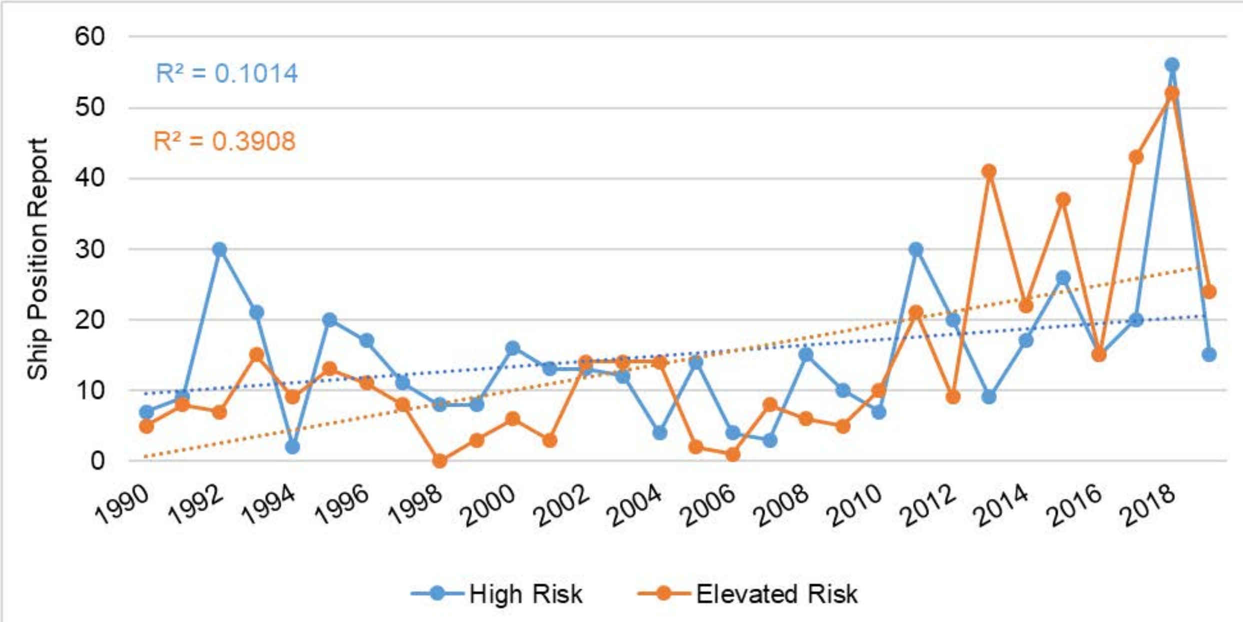

Figure 10: Annual number of ship position reports with RIO values that occurred within areas of increased operational risk (RIO < 0).

For ship position reports from areas of increased operational risk, both high and elevated, there are clear differences based on ship type (Figure 11). Bulk carriers accounted for the highest number of ship position reports in areas of increased risk between 1993 and 2002, but since then their occurrence has been negligible. This is contrary to the pattern observed for the total unique ship counts, where bulk carriers made up the largest proportion of vessels in both 2018 and 2019 (Figure 3) (also see section 4.2 for possible explanation). Ship position reports from fishing vessels made up a high proportion of vessels operating under increased risk conditions in recent years (2011-2019), but, perhaps surprisingly, did not account for a substantial proportion in earlier years, despite having the largest number of unique ship counts throughout the region in 1990-2000 (Figure 3). Ship position reports from pleasure craft operating in areas of increased operational risk showed a large increase since 2005, comprising over 25% of ship position reports from vessels that travelled in areas of increased risk in 2018, and 18% in 2019 (Figure 11). Ship position reports from general cargo ships and tugs/barges operating in areas of increased risk have decreased in their numbers since about 2003.

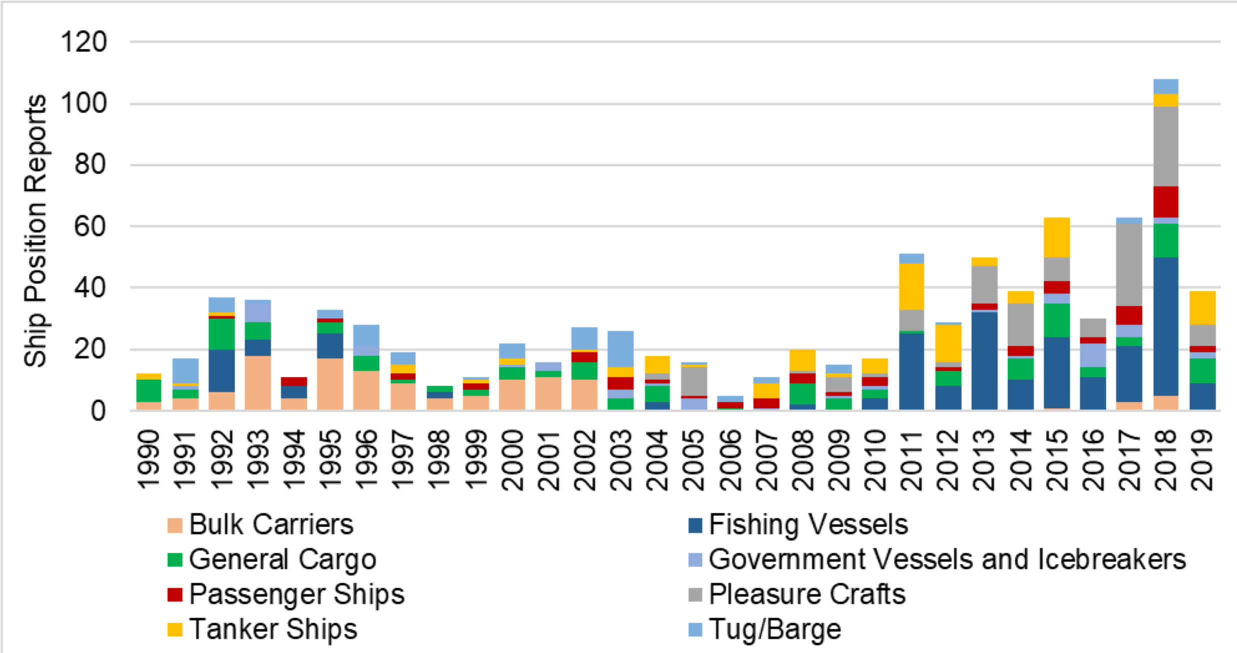

Figure 11: The total number of ship position reports with RIO values that occurred within areas of increased operational risk (RIO < 0), by ship type.

Figure 12 shows the total number of ship position reports from areas of increased operational risk separated by Ice Class. As with unique ship counts (Figure 4), vessels with little to no hull strengthening (Category C = 1AS, 1A, 1B or No ice strengthening) made up the largest proportion of ship position reports that encountered risks (Figure 12). Notably, the number of ship position reports from vessels with no ice strengthening in areas of increased risk grew substantially after 2004, accounting for the largest proportion of records in 2017 and 2018. For ship position reports with high/medium ice strengthening (Categories A and B; PC3 to PC7), PC7 ships make up the largest proportion that operated in areas of increased operational risks.

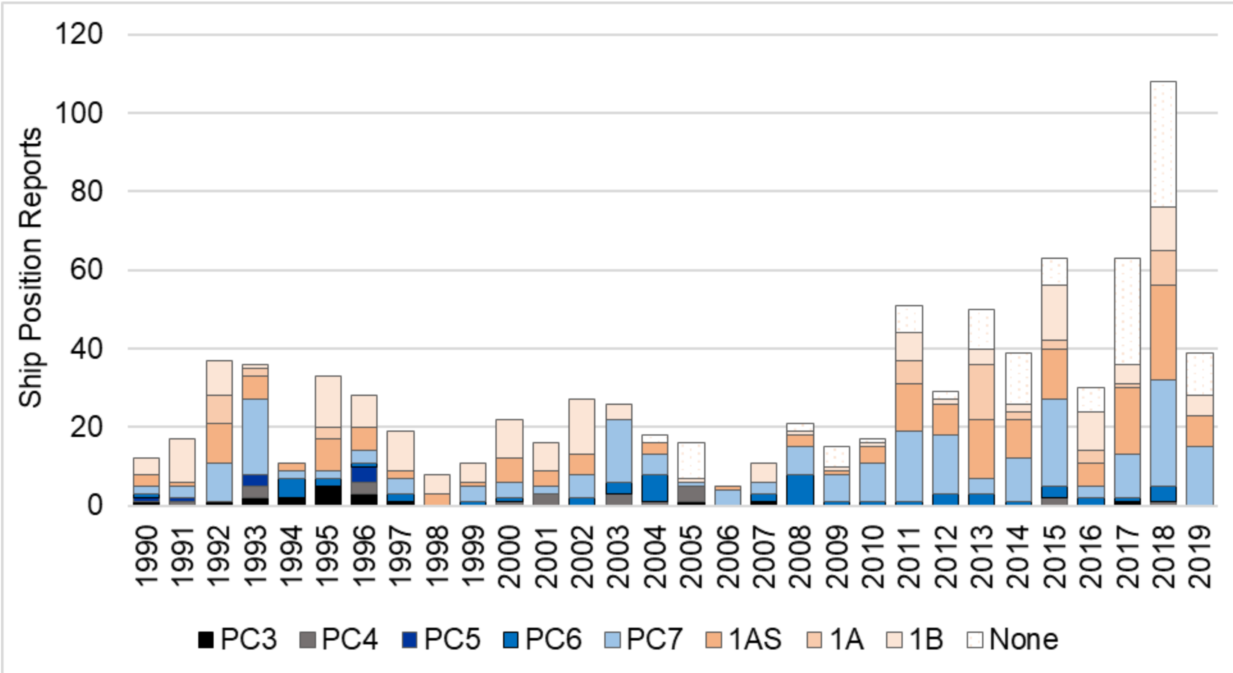

Figure 12: The total number of ship position reports with RIO values that occurred within areas of increased operational risk (RIO < 0), by ice class.

4.2 RIO Results for Track Counts

Over the recorded period, the total track count progressively increased, from almost 600 in 1990-94 to nearly 2,000 in 2015-19 (Figure 13). The number of tracks in the elevated risk category (RIO < 0 to -10) and high risk category (RIO < -10) were both fairly consistent between 1990-2009, and both experienced a substantial increase following that (Figure 13). However, the number of tracks in increased risk categories is a low percentage of the total count in each time period, only about 5% for both at the maximum number in 2015-19 (Figure 13).

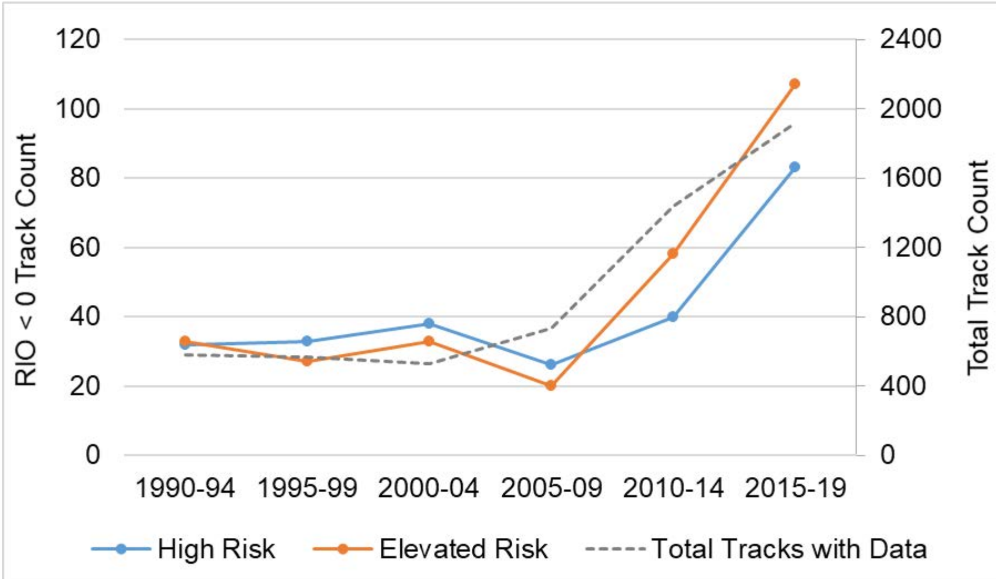

Figure 13: Number of tracks with records in each risk threshold for 5-year periods. The dashed line shows the total track count.

4.3 Changes in Risk Thresholds by Ship Types

Although the general trend over time is an increase in the number of ship position reports in areas of risk, both high and elevated (Figure 9 and Figure 10), each ship type shows a slightly different pattern (Figure 14). For bulk carriers, early in the record there was a large percentage of ship position reports in both elevated and high risk thresholds, before a rapid drop to almost nil from 2005-09 onwards (Figure 14A). This is possibly due to ships encountering operational risks through Lancaster Sound to reach the Polaris Mine on Cornwallis Island, which closed in 2002. There appears to be no change over time for fishing vessels for either risk threshold, all remaining below 2% (Figure 14B). For general cargo ships, there has been a decrease in the percentage of ship position reports in the high risk threshold (from 4% to 1%), but little change for elevated risk (Figure 14C). Government vessels and icebreakers have never operated in conditions of increased operational risk (Figure 14D), which is not surprising as they usually have higher ice strengthening (PC3 or stronger). In the passenger ship type, there is a relatively low percentage of ship position reports for both risk thresholds in all time periods, although in the earliest period over 4% were in the elevated risk category (Figure 14E). Pleasure craft are a unique category, as there is a peak in the high risk category in 2005-09 (Figure 14F). This is mainly caused by 3 out of the 6 unique pleasure craft in 2005 reporting 9 high risk ship position reports out of the total 22 ship position reports in that year. Ship position reports from pleasure craft in the elevated risk category have been increasing since 2005. Further, between 2015-19 pleasure craft have the highest percentage of ship position reports, in both elevated and high risk categories, out of all the ship types (between 4-7%). For tanker ships, there is no clear trend, but there is a higher percentage in the high risk threshold in 2010-14 (Figure 14G). There has been a decrease in the percentage of ship position reports from tugs/barges in both risk thresholds, with a drop to almost nil since 2010 (Figure 14H).

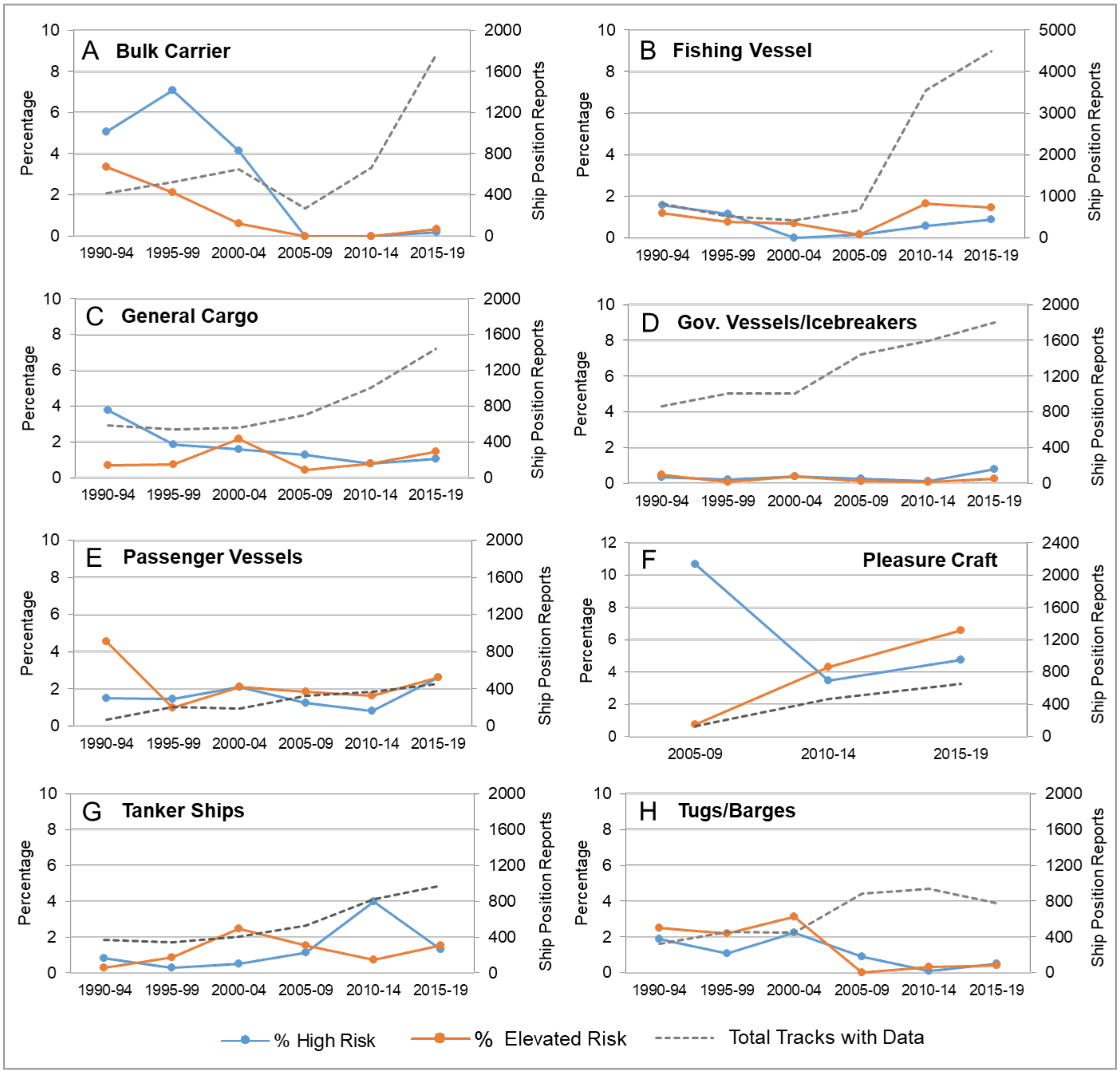

Figure 14: Percentage and total number of RIO ship position reports in areas of increased operational risk (RIO < 0) by ship type, for: (A) bulk carriers, (B) fishing vessels, (C) general cargo, (D) government vessels and icebreakers, (E) passenger vessels, (F) pleasure craft, (G) tanker ships, and (H) tugs/barges. For additional information, see Table D1.

As with unique ship counts, for track counts, each ship type shows a slightly different pattern in changes to operational risk over time (Figure 15). For bulk carriers, early in the record there was a large percentage of tracks in both elevated and high risk thresholds, before a rapid drop to almost nil from 2005-09 onwards (Figure 15A). There appears to be no change over time for fishing vessels for either risk threshold, all remaining around 4% (Figure 15B). For general cargo ships, there has been a decrease in the percentage of track counts in the high risk threshold (from 13% to 5%), but elevated risk has remained fairly constant, with a maximum of 10% in 2000-04 (Figure 15C). There is a relatively low percentage of government vessels and icebreakers operating under conditions of increased risk, but the percentage slightly increased over time for the high risk threshold, but an overall decrease for elevated risk, from 5% in 1990-04 to 3% in 2015-19 (Figure 15D). In the passenger ship type, there is a slight increase in the percentage of track counts for both risk thresholds, including a spike from 4-10% between 2010-14 and 2015-19 for the high risk threshold (Figure 15E). Pleasure craft show a dramatic increase in the elevated risk category from 4% in 2005-09 to 26% in 2015-19, while peaking in the high risk category in 2005-09 (Figure 15F). Tanker ships show a slight increase in the percentage of track counts over time in both risk thresholds (Figure 15G). There has been a decrease in the percentage of track counts from tugs/barges in both risk thresholds, with a drop to less than 4% since 2005-09 (Figure 15H).

Further information regarding ship position reports and track counts by ship type and by Ice Class are available in Appendix D, including tables summarizing the results.

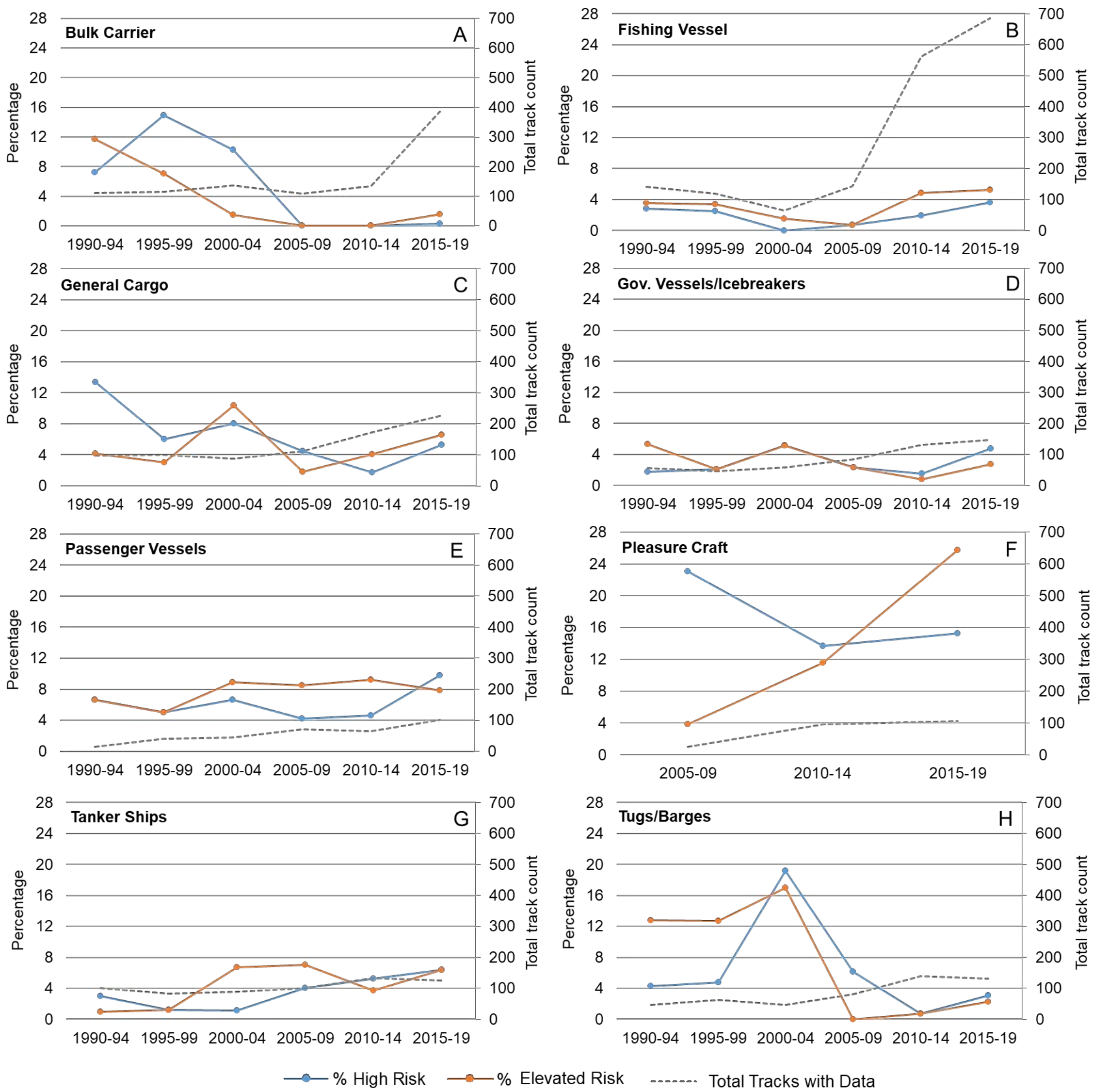

Figure 15: Percentage of tracks in each risk threshold for each ship type: (A) bulk carriers, (B) fishing vessels, (C) general cargo, (D) government vessels/icebreakers, (E) passenger vessels, (F) pleasure craft, (G) tankers, and (H) tugs/barges.

5.0 SPATIAL ANALYSIS OF OPERATIONAL RISK BASED ON SHIP-STRENGTH AND ICE TYPE

The significance of temporal patterns in ship navigational risks, described above in Section 4, can be difficult to interpret when grouped together for the NORDREG zone as a whole. Spatial analysis of the data was therefore undertaken, which shows distinct clusters of ship position reports within the two risk categories. In particular, three areas where ships experienced increased operational risk conditions stand out when all ship position reports with RIO values are displayed: Lancaster Sound, Franklin Strait and Frobisher Bay (Figure 16). These regions are discussed in detail in Section 6.

The spatial data can further be separated by ship type, to identify which vessel types contributed most to the greatest number of ship position reports that experienced increased risk conditions in these regions (Figure 17). Bulk carriers, tankers and pleasure craft comprised the primary ship types operating in the elevated/high risk categories in the three geographical regions outlined in Figure 16, so we focus our discussion on them here. General cargo and passenger ships also contributed to elevated/high risk ship position reports in these regions, but to a lesser extent, so we present information for those ship types and others in Appendix E.

Across the whole period of record (1990-2019), bulk carriers mainly travelled one of two routes: a southern route through Hudson's Bay (often called the 'Arctic Bridge' route), or a northern route along the north side of Baffin Island and into Lancaster Sound. The bulk carriers that travelled the southern route hardly ever experienced conditions of increased operational risk, with the few examples mainly occurring in Hudson Strait. In contrast, ship position reports from bulk carriers travelling the northern route encountered many more elevated risk conditions, particularly to the south of Devon Island and Cornwallis Island, where many high risk events (RIO < -10) were recorded (Figure 17A).

Tanker traffic was more spatially dispersed throughout most of the Canadian Arctic (Figure 17B), although ship position reports from this vessel type encountered many high risk conditions in Frobisher Bay, and to a lesser extent in Cumberland Sound.

The number of ship position reports from pleasure craft was least of the three primary ship types over the period 1990-2019, with most of these traversing the southern route of the NWP to the south of Victoria Island (Figure 17C). Pleasure craft often experienced elevated risk conditions upon entering Lancaster Sound, with a particular focus in Franklin Strait. Several ship position reports from pleasure craft showed increased operational risk conditions on the east coast of Ellesmere Island (Figure 17C). It is important to note that the majority of pleasure craft travelling in the Canadian Arctic have little to no ice strengthening (Dawson et al., 2020), so encountering high risk conditions can be potentially catastrophic (CBC, 2018; Coast Guard, 2018).

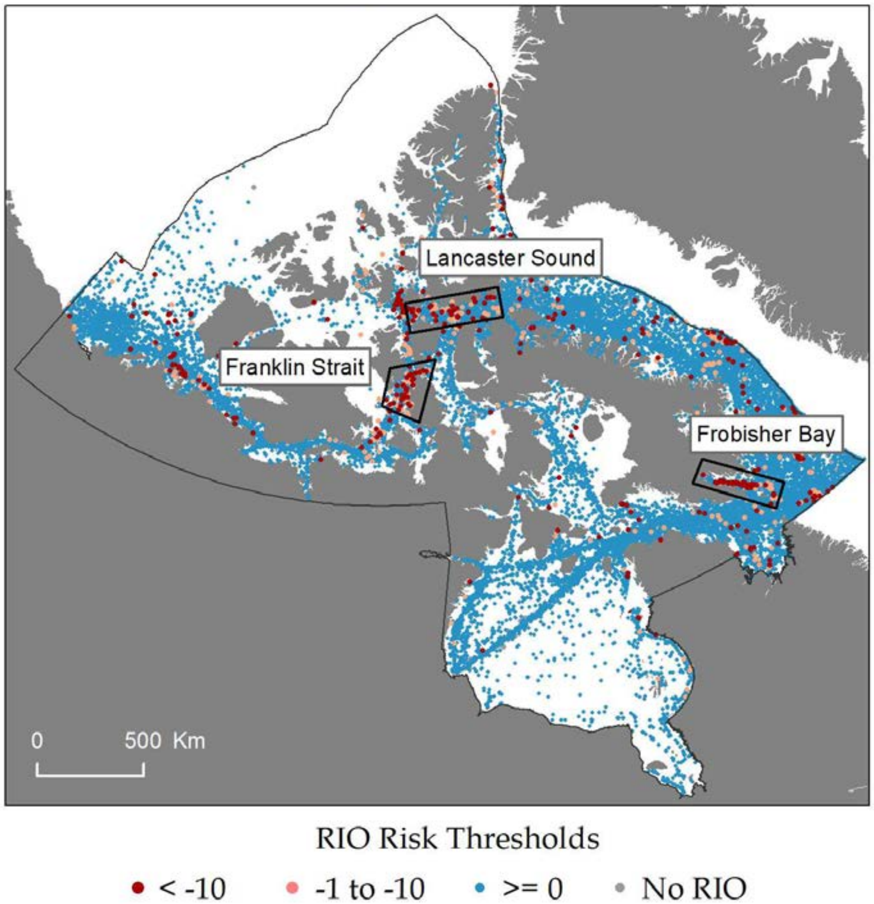

Figure 16: Spatial distribution of all ship position reports with RIO values from 1990-2019.

When the spatial data is analyzed by 5-year period, it is evident that the location of ship position reports with increased risk conditions changed over time (Figure 18). First, when the spatial and temporal patterns for ship position reports from all ship types combined is analyzed, it shows that during the early periods of the record, instances of increased risks were generally concentrated in Lancaster Sound (Figure 18). The total number of ship position records increased over time, but there was no clear spatial pattern for those which experienced operational risks in 2000-04. In 2005-09 and 2010-14, the occurrences of increased risk were mainly in Franklin Strait and Frobisher Bay, and by 2015-19 all three regions had a larger number of ship position reports with increased risks than in surrounding regions.

Second, when the spatial and temporal trends in ship position reports are analyzed by the primary ship types of bulk carriers, tankers and pleasure craft (other ship types available in Appendix E), different patterns are evident between them. Bulk carriers experienced increased operational risk early in the record (between 1990-2004), particularly in Franklin Strait (Figure 19A, B, and C). There were no risk events between

2005-09 possibly due to the Polaris Mine closure (Figure 19D), and limited events later in the record, mostly near Pond Inlet and Eclipse Sound for 2015-19 (Figure 19F). The pattern was quite different for ship position reports from tankers, which experienced limited operational risk earlier in the record (1990-1999; Figure 20A and B), but which increased substantially after 2004 (Figure 20C). Of particular interest is the considerable increase in high risk events experienced by tankers in Frobisher Bay over the last decade (Figure 20E and F).

Investments in maritime infrastructure, such as the planned port in Iqaluit, may help to reduce future risk events to some degree, although the region is commonly plagued with icebergs and areas of thick sea ice imported from regions to the north. As climate change continues it is highly likely that high risk ship-ice events will continue or increase in Frobisher Bay, considering the ice dynamics and the requirements for re-supply and development in the territory’s capital city of Iqaluit. The planned port development, including other infrastructure investment, may help to reduce future risk events. Ship position reports from pleasure craft showed increased operational risk mostly from 2005 onwards, dispersed throughout the NORDREG region (Figure 21). Notably, there was a dramatic increase in high risk events for this ship type between 2010 and 2019 in Lancaster Sound and Franklin Strait (Figure 21E and F).

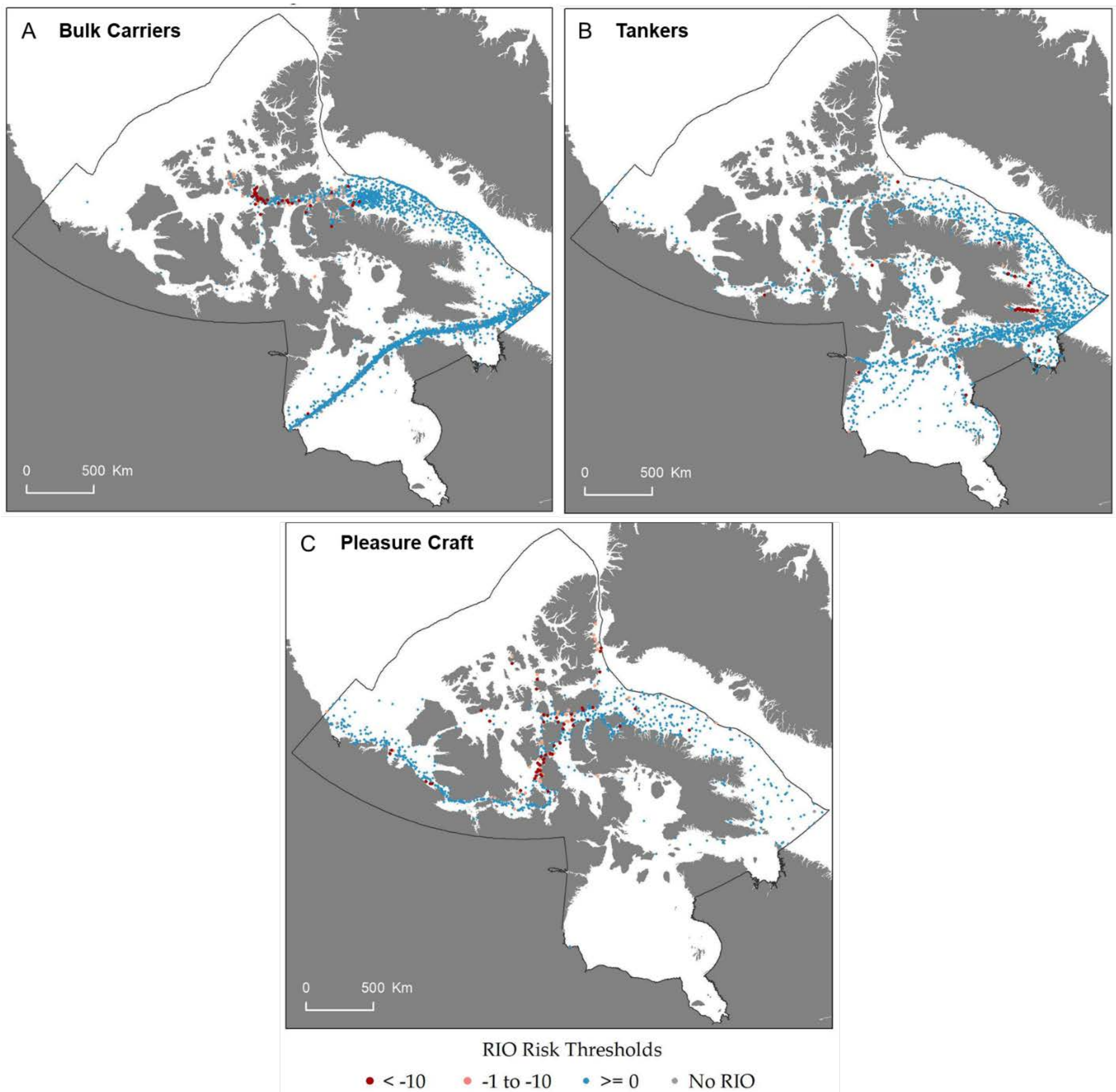

Figure 17: Spatial distribution of all ship position reports with RIO values from 1990-2019, for: (A) bulk carriers, (B) tankers, (C) pleasure craft.

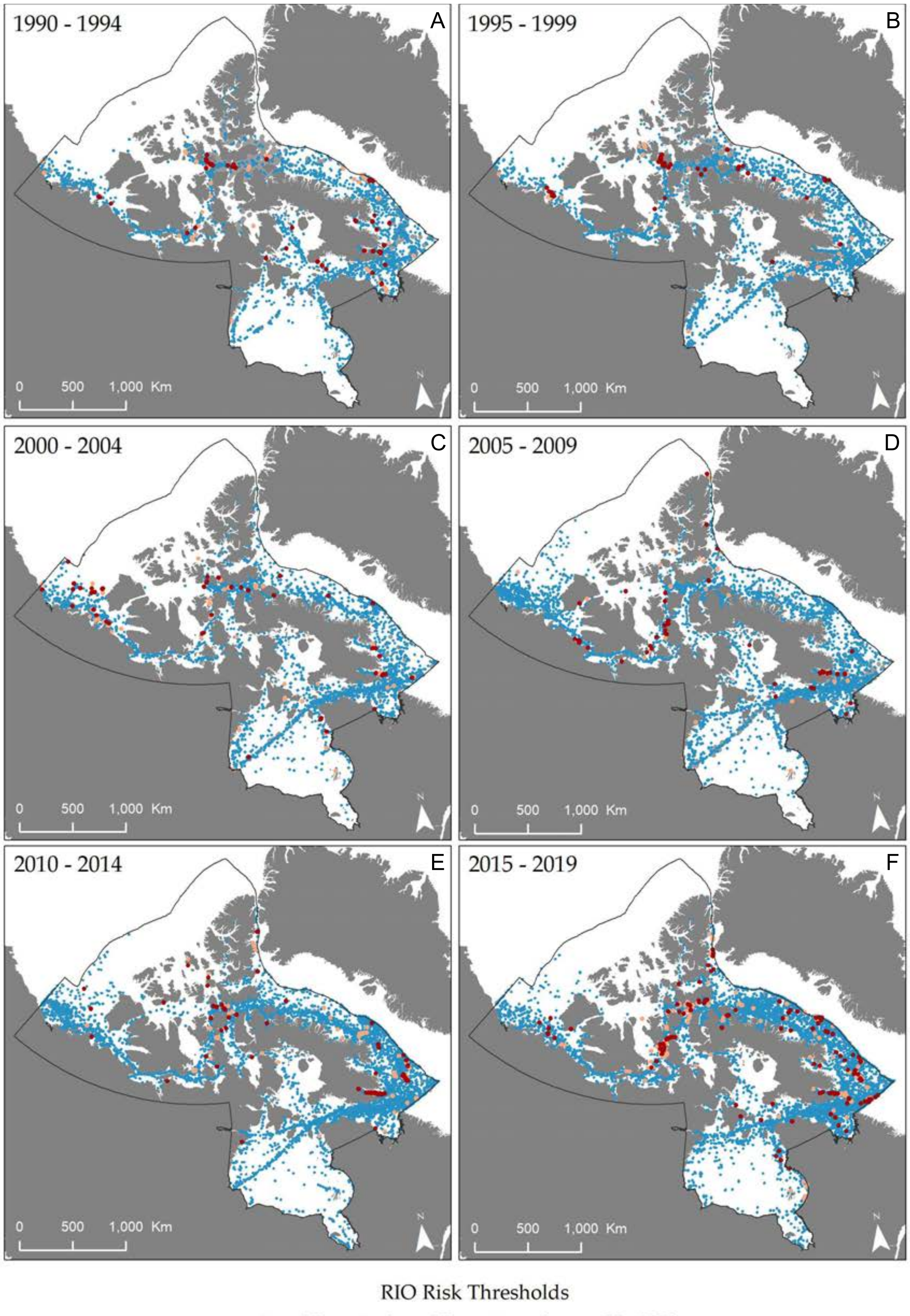

Figure 18: Spatial patterns for ship position reports with RIO values over 5-year periods between 1990 – 2019, for all ship types.

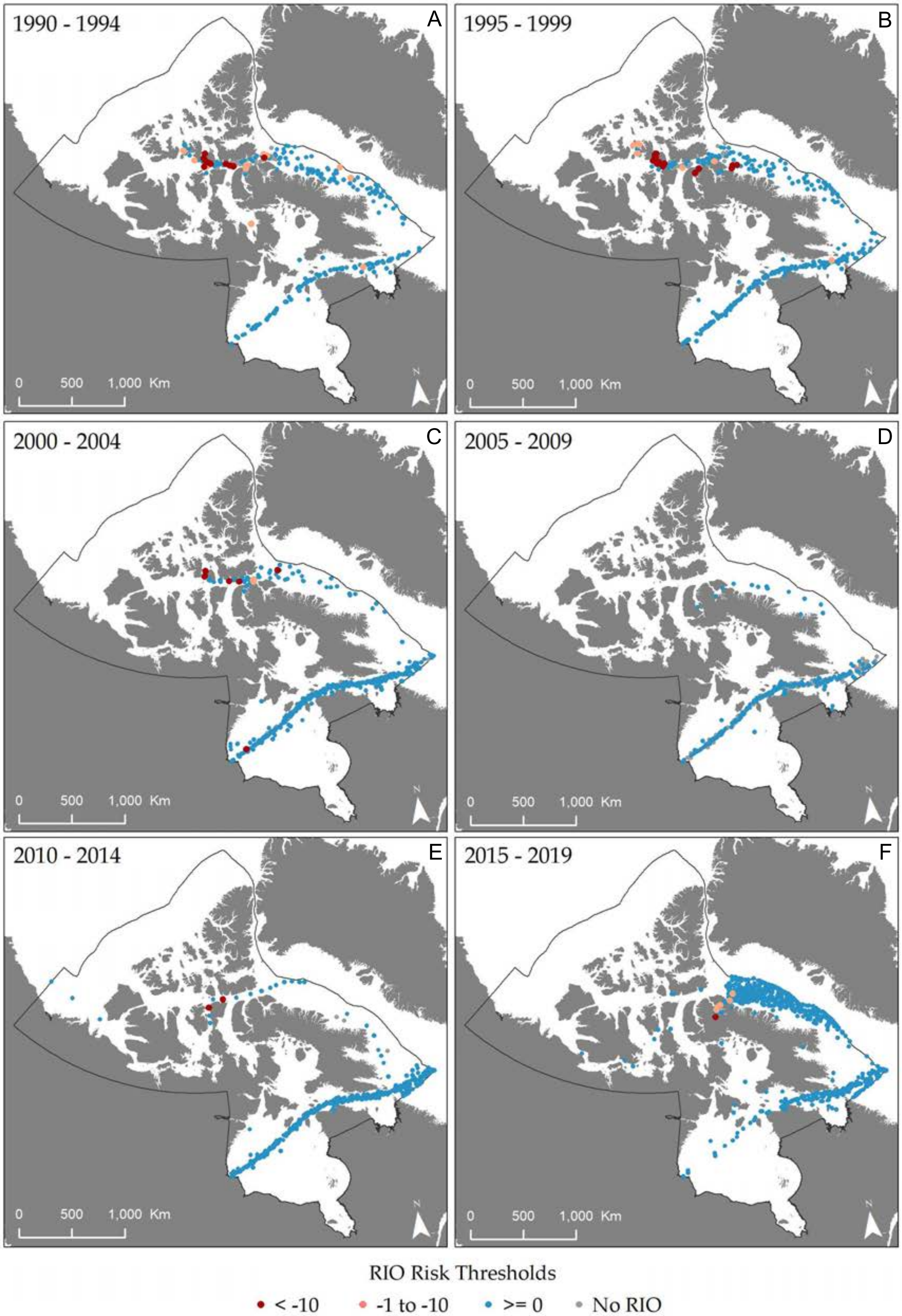

Figure 19: Spatial patterns for ship position reports with RIO values over 5-year periods between 1990 – 2019 for bulk carriers.

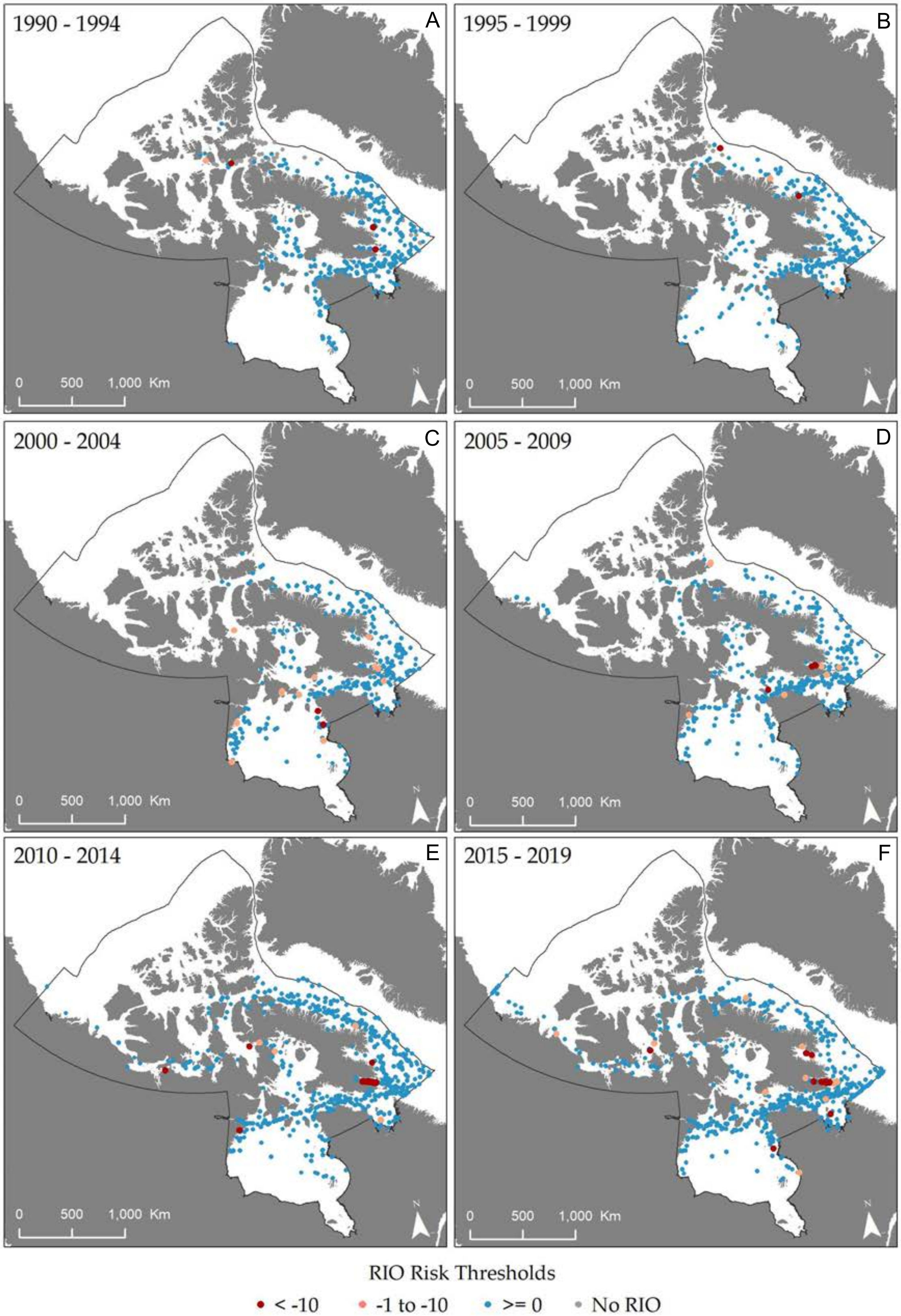

Figure 20: Spatial patterns for ship position reports with RIO values over 5-year periods between 1990 – 2019 for tankers.

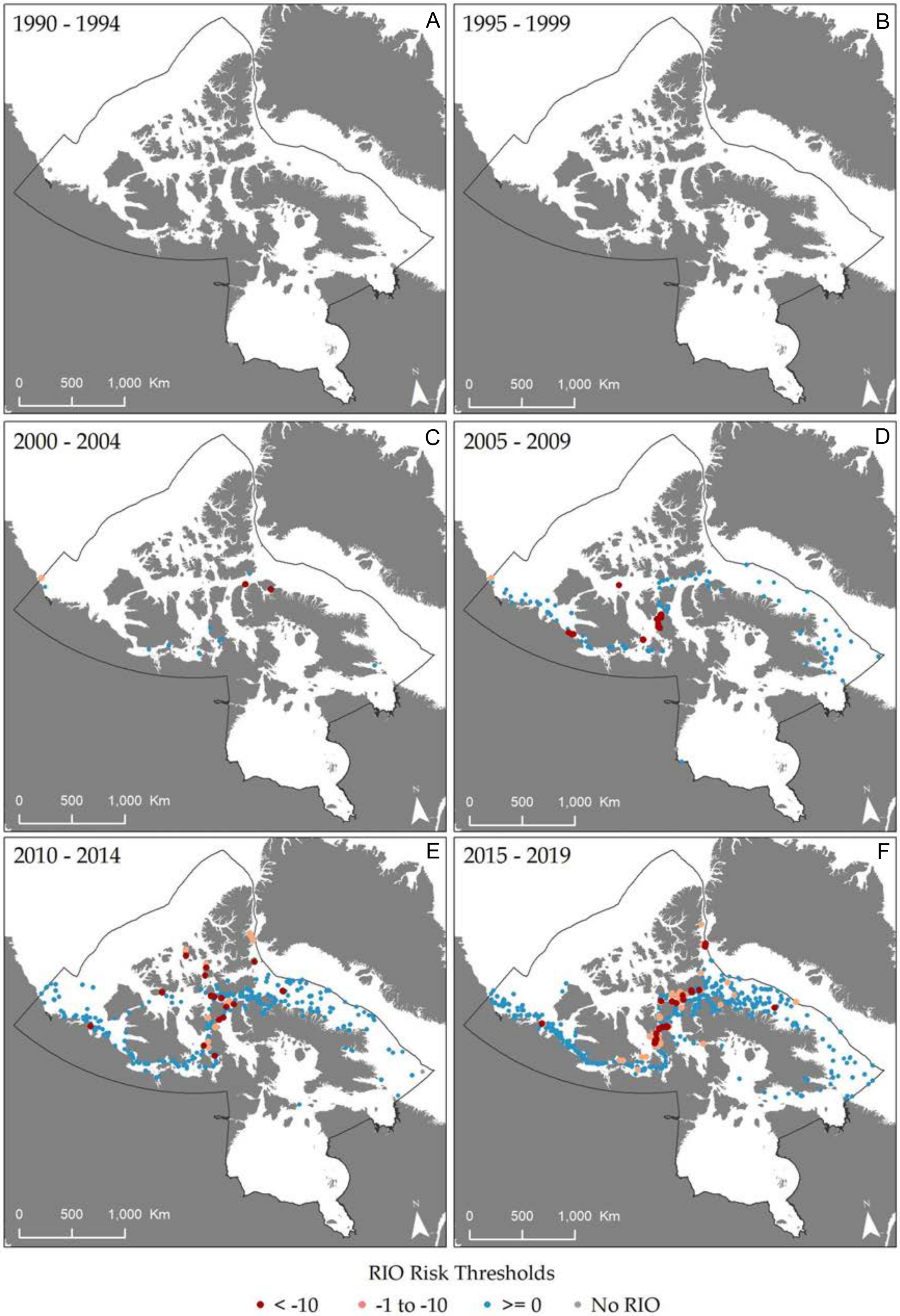

Figure 21: Spatial patterns for ship position reports with RIO values over 5-year periods between 1990 – 2019 for pleasure craft.

6.0 ANALYSIS OF THREE HIGHER RISK ZONES – FRANKLIN STRAIT, FROBISHER BAY, AND LANCASTER SOUND

In this section, we expand on details in the three geographical regions where a larger number of ship position reports occurred in areas of increased operational risk (i.e., negative RIO values), comprising Franklin Strait, Frobisher Bay, and Lancaster Sound (Figure 22). For Franklin Strait, there were many dispersed elevated and high risk events, including near Fort Ross through Bellot Strait (Figure 22A). In Frobisher Bay there were a substantial number of high risk ship position reports, clustered mainly on the south-central side of the Bay near Meta Incognita Peninsula, diminishing near Iqaluit (Figure 22B). Locations of elevated and high risk conditions were dispersed throughout Lancaster Sound (Figure 22C).

The three regions are dominated by distinct ship types, and changes in the number and proportion of these ship types over time (Figure 23A-C). Franklin Strait predominantly saw passenger ships, pleasure craft, and government vessels and icebreakers, likely due to pleasure craft using Bellot Strait as they travel through the NW Passage (Figure 23A). The number of pleasure craft increased substantially after 2005 for this region, comprising 35% of the ship position reports with RIO values between 2015-19. General cargo and passenger ships also increased later in the record (Figure 23A). For example, in 1990-94 there were two passenger ship position reports with RIO values in Franklin Strait, which increased to 33 position reports in 2015-19. The composition of ship types was different for Frobisher Bay, which had a limited number of pleasure craft (only four position reports in 2015-19), and numerous fishing vessels, which spiked to 49% of the total ship position reports in 2010-14 (Figure 23B). Lancaster Sound had predominantly government vessels and icebreakers, until the most recent time period when the number of pleasure craft greatly increased (Figure 23C). In 2015-19, 124 ship position reports with RIO values from pleasure craft occurred in Lancaster Sound (out of a total of just less than 300 ship position reports with RIO values), compared to only six in 1990-94. There was also a decline in position reports from bulk carriers in the early record, and an increase in passenger ships over time.

The three regions show different changes in the number of ship position reports with negative RIO values over time (Figure 24). Both elevated and high risk occurrences increased over time in Franklin Strait, with this region showing the largest number of ship position reports with elevated and high risk conditions between 2005 and 2019 (Figure 24A). In particular, high risk counts increased from 2 to 35 between 1995 and 2019 for this region. The trend was similar for Lancaster Sound, although values dropped in 2005-09 before increasing again, with a maximum of 19 high risk ship position reports between 2015-19 (Figure 24C). Frobisher Bay had the largest total number of ship position reports with RIO values overall (2239), but the smallest number of negative RIO values (total of 49 high risk and 33 elevated risk over the whole record), and this did not change dramatically over time (Figure 24B).

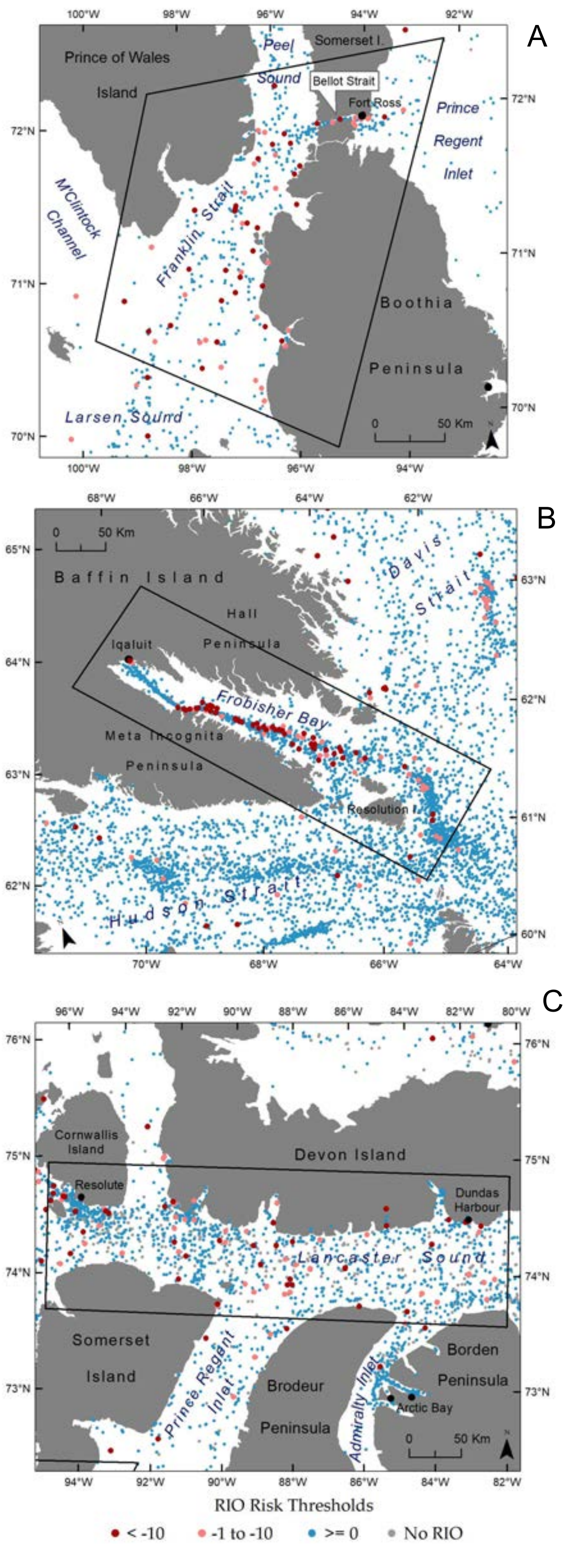

Figure 22: RIO risk thresholds for all ship position reports between 1990-2019 in: (A) Franklin Strait, (B) Frobisher Bay, (C) Lancaster Sound.

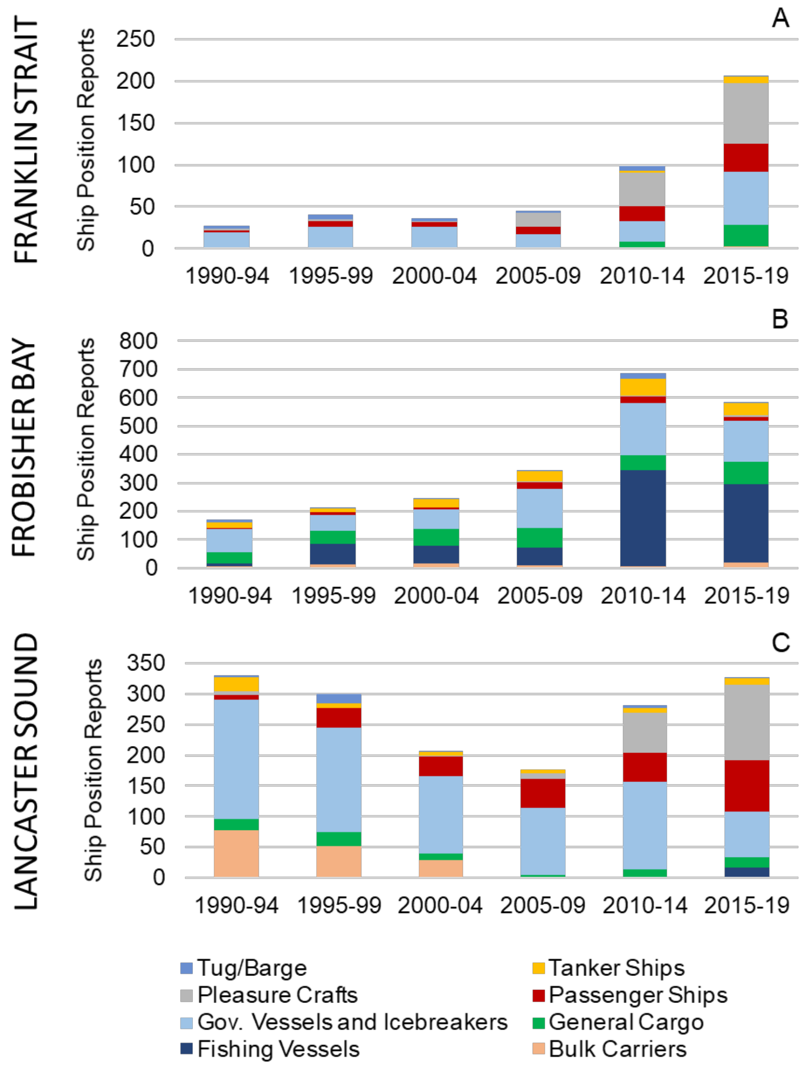

Figure 23: Total number of ship position reports with RIO values over 5-year periods between 1990 – 2019, for all ship types, for: (A) Franklin Strait, (B) Frobisher Bay, (C) Lancaster Sound.

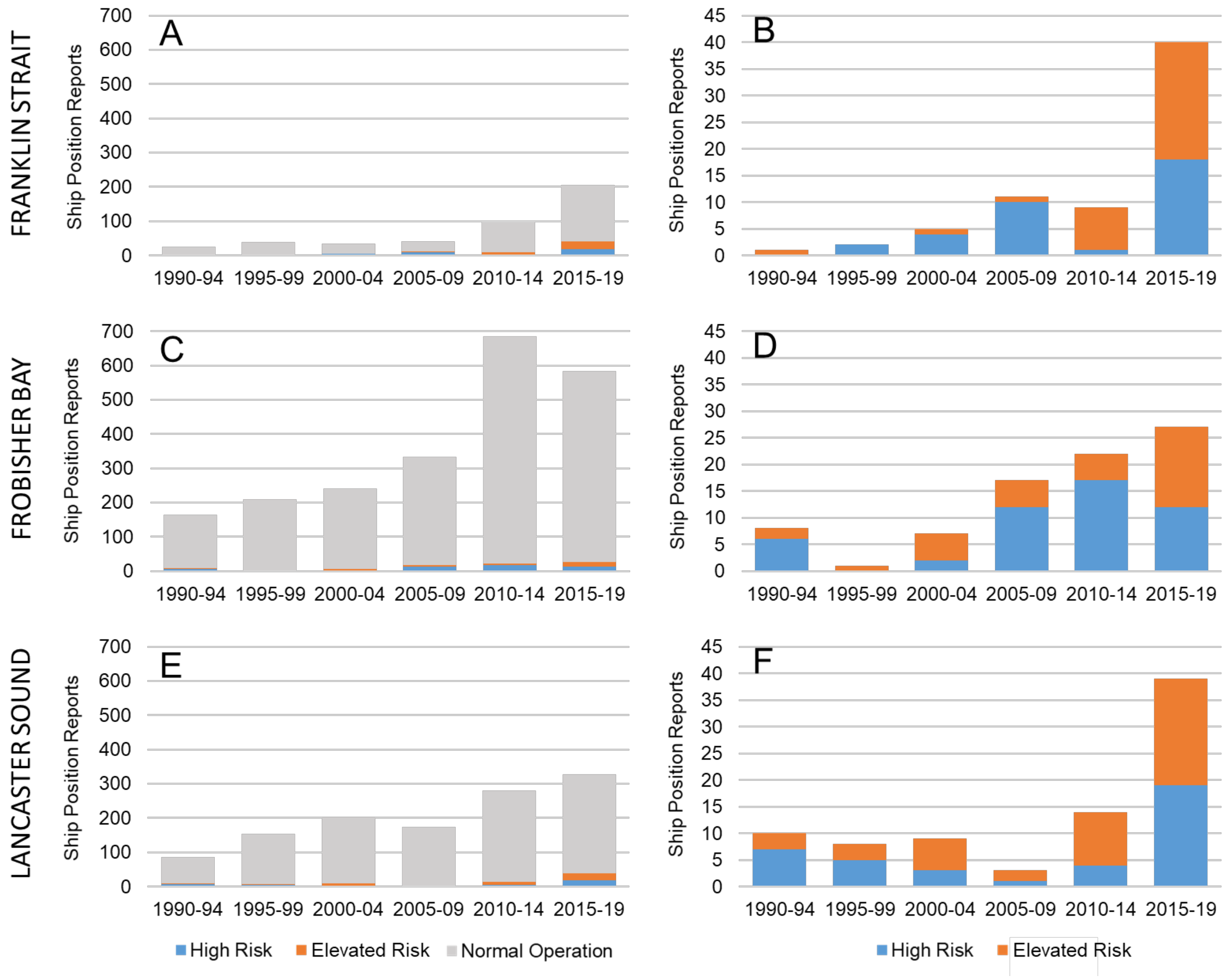

Figure 24: Total number of ship position reports with RIO values categorized by: (A, C, F) all risk thresholds, and (B, D, F) just high and elevated risk categories over 5-year periods between 1990 – 2019 for all ship types, for: (A and B) Franklin Strait, (C and D) Frobisher Bay, (E and F) Lancaster Sound.

To understand the causes of the variations in the number of ship position reports in the elevated risk categories highlighted above, it is useful to break down the data by individual ship type (Figure 25). This shows, for example, that the peak in high risk ship position reports in Franklin Strait in 2005-09 (Figure 24B) was due to four pleasure craft which travelled through that region over that period, which produced ten position reports out of the total of 45 position reports (~25%; Figure 25A). Similarly, for Lancaster Sound, the peak in high risk ship position reports in 1990-94 is due to bulk carriers (Figure 25E), and the spike in 2015-19 for both high and elevated risk categories are due to a 466% and 85% increase for pleasure craft after 2010-14 (Figure 25E and F). More information regarding changes in the number of ship position reports within each risk threshold, as well as trends showing the number of unique ships in the regions during each 5-year time interval, are available in Appendix F.

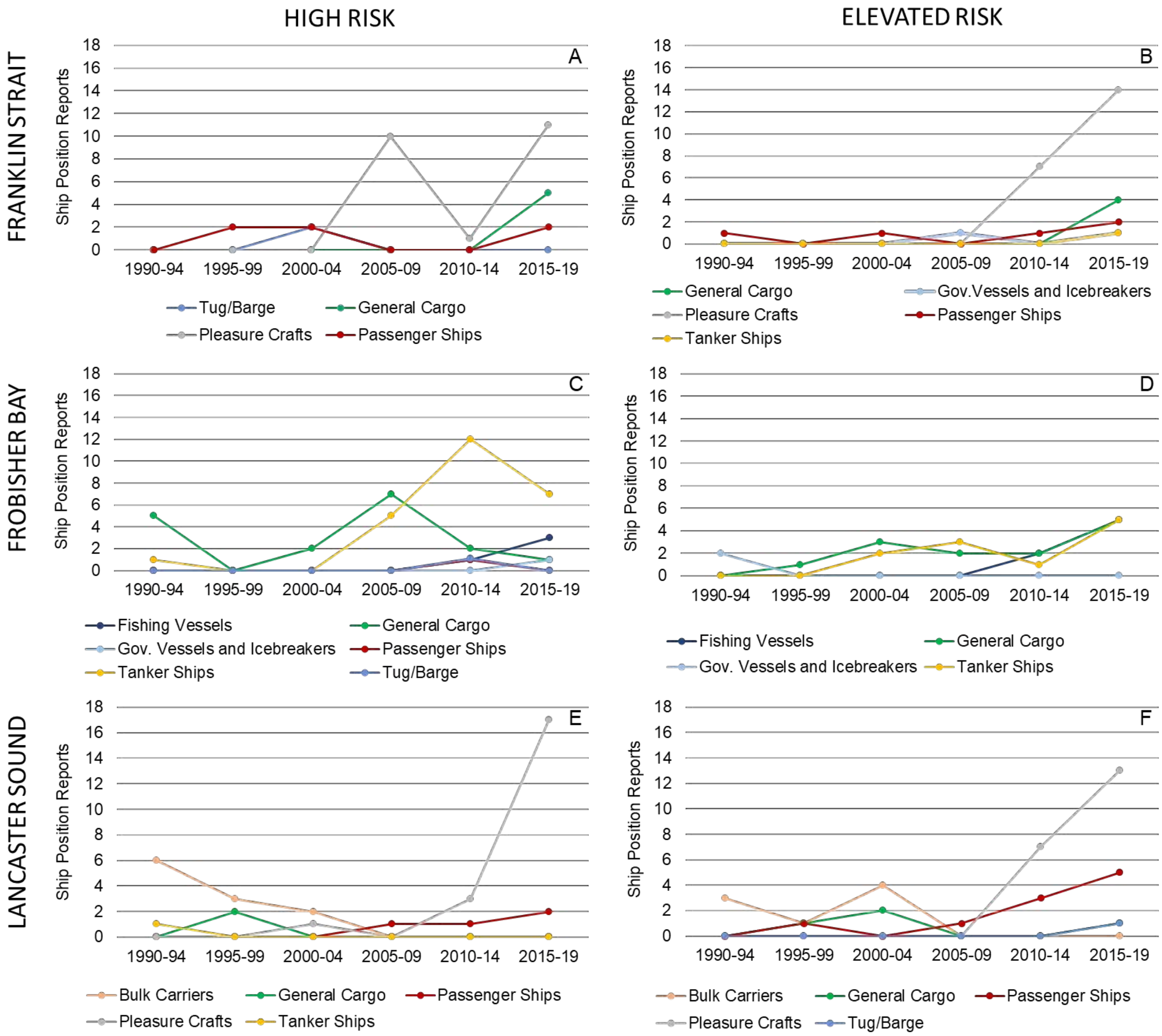

Figure 25: Number of ship position reports with RIO values by ship type in: (A, C, E) high risk (RIO < -10) areas, and (B, D, F) elevated risk (RIO < 0 to -10) areas over 5-year periods between 1990 – 2019 for Franklin Strait (A and B), Frobisher Bay (C and D) and Lancaster Sound (E and F).

7.0 CONCLUSION

Shipping in the Canadian Arctic is undergoing rapid and systematic changes. There has been a general increase in the number of unique ships operating in the NORDREG zone since 1990, with a particularly marked increase since 2007. This has included a large increase in the number of vessels that travelled with little to no ice strengthening, particularly pleasure craft. However, sea ice conditions are highly variable from one year to the next, and there are still significant operational risks to ships, especially those that are poorly ice strengthened. Our analysis of ship position reports with RIO values indicates that, between 1990-2019, ships regularly travelled through the NORDREG zone under conditions of increased risk (RIO < 0), with a total of 488 ship position reports in a high risk (RIO < -10) setting, and 438 in an elevated risk (RIO < 0 to -10) setting, compared to a total of 36,594 ship position reports in the normal category. The numbers in these risk categories need to be regarded as minimums, as we were only able to assign RIO values to approximately a third of the total number of ship position reports due to the requirement to have CIS charts issued between 1-3 days (1990-2007) or 0-2 days (2008-2019) before the chart issue date (cf. Section 2.0). Similarly, the number of track counts has also increased over the recorded period, from 118 tracks in 2006 to over 500 tracks in 2019.

In terms of percentages, the majority of ship position reports (>96% in all 5-year periods, 97.5% total over the period 1990-2019) are from ships located in normal operating conditions. However, it is important to note that there has been an increase in operational risk overall as the number of ship position reports in the high and elevated risk categories is increasing over time, particularly for specific ship types, most notably fishing vessels and pleasure craft. This is concerning as it is expected that growth in the number of ships operating in the Canadian Arctic will continue and that the type of vessels that are most often found to be experiencing high risk conditions are also the fastest growing maritime sector in the region – i.e. non ice strengthened pleasure craft. Further, the number of tracks in the high and elevated risk categories has increased substantially since 2005. Of particular importance is that low or non-ice strengthened vessels make up the largest proportion of ships now operating in the Canadian Arctic overall, and it is these vessels that also most often experience conditions in the high risk category, especially since 2004.

We identified three key areas where there is a higher proportion of ship position reports within higher risk categories: Franklin Strait, Frobisher Bay, and Lancaster Sound. In these regions, high risk events increased over time, particularly in Franklin Strait and Lancaster Sound. In each of the three regions, certain vessel types contributed more to the risk counts, specifically bulk carriers, tanker ships, and pleasure craft. The specific location of risk events has changed over time, as did the type of ship that contributed to these events, with notable increases in the percentage of pleasure craft for Franklin Strait and Lancaster Sound that travelled in conditions of both high and elevated risk.

Our results show that ships operated under conditions of increased operational risk throughout the Canadian Arctic between 1990-2019, with this pattern expected to continue in the future. This is a region where there is currently limited infrastructure and support services, including critical search and rescue services, which will compound any risks that exist for ship-ice interactions. It is clear that the combination of increased shipping traffic, with increased numbers of non-ice strengthened vessels, vessels travelling under increased risk conditions, increased mobility of sea ice, and the limited infrastructure and support services, will continue to create navigational challenges for this area.

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APPENDIX A - METHODOLOGY

Risk Index Values

The following table provides the Risk Index Values (RIVs) used for the calculation of the Risk Index Outcome (equation 1 in Section 2.0) for each egg code in each Canadian Ice Service ice chart (source: Table 1.3 in International Maritime Organization. 2016. Guidance on Methodologies for Assessing Operational Capabilities and Limitations in Ice. MSC.1/Circ.1519). A positive RIO value indicates an acceptable risk level where operations may proceed, while a negative RIO indicates increased risk, potentially to levels where it is not recommended that the vessel advances.

Ice Class	Ice-Free	New Ice	Grey Ice	Grey White Ice	Thin First Year ice 1st Stage	Thin First Year Ice 2nd Stage	Medium First Year Ice less than 1 m thick	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Light Multi Year Ice, less than 2.5 m thick	Heavy Multi Year Ice
PC1	3	3	3	3	2	2	2	2	2	2	1	1
PC2	3	3	3	3	2	2	2	2	2	1	1	0
PC3	3	3	3	3	2	2	2	2	2	1	0	-1
PC4	3	3	3	3	2	2	2	2	1	0	-1	-2
PC5	3	3	3	3	2	2	1	1	0	-1	-2	-2
PC6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
PC7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
IA Super	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8
Not Ice Strengthened	3	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-8

RIO Ship Position Reports: ArcGIS methodology

All ship position reports were obtained from the Marine Communications and Traffic Services (MCTS) as an Excel spreadsheet for each individual year between 1990-2019. The first step involved tidying and merging the data in the spreadsheets into one text file per year, to be edited further in ArcGIS. In ArcGIS, each shapefile was clipped to the NORDREG boundary and the non-spatial ship characteristics table was joined to the spatial dataset. Erroneous points were removed (e.g., ship position reports over land) and attributes corrected in cases where they were clearly incorrect (e.g., misspelling of ship names). The following steps (set out as instructions) were then taken to assign RIO values to the ship position reports where they overlay relevant ice charts.

In ArcGIS, for <u>each separate year (1990-2019)</u>, follow this sequence:

1. Ship point data
    a. Assign the week of the year from the ship position report date with the format yyyy-mm-dd (using w2 option, which is week start Monday). Reproject to Lambert Conformal Conic projection.
2. Polar code chart vector data (mainly produced by Frances Delaney)
    a. Assign the week of the year from the Date_carte attribute. (Note, ArcGIS calculates week numbers based on January 1st as being the first week of the year, so this means some have weeks +1 more than actual weeks of the year which start on the first Monday of the year). The same is true for the ship position report data and since both are converted using this consistent method the datasets are compatible.
3. Assign Polar Code RIO values to each ship position report point
    a. Extract identity of PC chart polygons for every ship position report point, for each year:
        i. Batch ‘Identity’ [*between 5 mins (1990) and 20 mins (2019) processing time per year of data*]
            1. Identity Features – All PC charts for one year (separate one per row)
            2. Input Features – The same ship position report point shapefile for all rows (e.g. 2000_lcc.shp)
            3. Output Feature Class – Different ship position report file names for every row (it doesn’t matter what the names are: automate filenames by giving the first one a name, then click ‘check values’ which will fill all others with names)
        ii. Batch ‘Select’ [*approx. 5-10 mins for 100 shapefiles*]

        1. Input Features - all ship position report point shapefiles with identity attributes (separate one per row)
        2. Output Feature Class – Different ship position report points file names for every row
        3. Select according to the following criteria:
            a. Ship position date (“DATE”) is either the same as, or up to two days before, the ice chart date (“DATE_CARTE”). This is because the DATE_CARTE is the Monday but uses images up to 2 days before. This is applicable for ice charts from 2008 onwards. From 1990-2007, the images used were between 1 and 3 days before the DATE_CARTE. [Note: years 1990-1996 may have included images from more than 3 days prior to the Date_carte (Date_carte is more random as well), but only those up to 3 days before were selected]. Also, 2-3 days is considered reasonable for ice movement, although this varies regionally].
            b. Select ship position report point data using following expression for 1990-2007: ("DATE" = "DATE_CARTE"-1) OR ("DATE" = "DATE_CARTE"-2) OR ("DATE" = "DATE_CARTE"-3)) AND "PShip_type" <> 'Land'
            c. Select ship position report point data using following expression for 2008-2019: ("DATE" = "DATE_CARTE") OR ("DATE" = "DATE_CARTE"-1) OR ("DATE" = "DATE_CARTE"-2)) AND "PShip_type" <> 'Land'
    b. For each year, combine all identity selected shapefiles to create one shapefile for the whole year that includes all ship position report points that meet the above criteria. [There is an issue with the ‘Append’ and ‘Merge’ tools when background geoprocessing is enabled, so make sure it is disenabled. Use Merge tool for all selected files for each separate year].
4. To remove identical ship position reports in overlapping ice chart regions
    a. The ice chart borders are not straightforward. The ice chart shapefiles are named according to three regions: a09, a10, a11 (which are the first part of all filenames for the PC RIO chart output produced by Frances Delaney). The regional limit for these filenames is not the same between all years. The attributes within the shapefiles include a ‘REGION’ attribute and these are defined as ‘HB’ (Hudson Bay), ‘WA’ (Western Arctic) and

'EA' (Eastern Arctic) for the years 2000-2019, which correspond to the a09, a10 and a11 boundaries respectively. The REGION attribute has different values for the years 1990-1998, which are 'BH', 'AO' and 'AE', corresponding to a09, a10 and a11 respectively. The year 1999 consists of a combination of these values. This is detailed in the section below about Ice Charts.

b. To remove duplicated ship position reports where regional ice charts overlap, the following sequence was followed:
    i. Run 'identity' tool on the ship position report point shapefile, first for the region a09 shapefile, followed by region a10.
    ii. From this identity shapefile, run the 'select' tool. Select using the following expression to remove duplicate records where they overlie different charts from the same week:
    iii. For years 2000 – 2019: ("REGION" = 'WA' AND "Region2" <> 0) OR ("REGION" = 'HB' AND "Region1" <> 0) OR ("REGION" = 'EA' AND "Region1" = 0 AND "Region2" = 0)
    iv. For years 1990 – 1998: ("REGION" = 'AO' AND "Region2" <> 0) OR ("REGION" = 'BH' AND "Region1" <> 0) OR ("REGION" = 'AE' AND "Region1" = 0 AND "Region2" = 0)
    v. Years 1990 – 1996 need editing following the selection procedure because neighbouring charts have different dates (although the same borders). Manually select tracks from region AE (a11) that were missing from the selected output and copy them into output file.
    vi. Year 1999 is a combination of borders so selected using both of the above criteria, then merged.

5. Final ship position report point shapefile attributes
    a. For each year, run 'Delete Field' to remove all unnecessary attributes. Merge all of the yearly shapefiles. The final merged ship position report point shapefile for 1990-2019 has all of the following attributes:

Field	Value
FID_2010	0
Sort_ID	0
VesselName	Terry Fox (CCGS)
Name_Mod	Terry_Fox_CCGS
Voyage_ID	2014_Terry_Fox_CCGS_3
Year	2014
Month	9
CALL_SIGN	CGTF
DATE	2014-09-29
Date_1	20140929
LATITUDE	73.37.6N
DD_Lat	73.618333
LONGITUDE	090.08W
DD_Long	-90.133333
LOC	
SUBLOC1	
SUBLOC2	Prince Regent Inlet
REMARKS	
NWPTransit	
Ship_name	Terry Fox (CCGS)
Latest_Per	2015-2019
Call_Sig_1	CGTF
IMO	8127799
MMSI	316122000
Flag	Canada
VesselType	CCG Icebreaker
AMSA_Class	Government Vessels and Icebreakers
Length	88
Breadth	17.82
Draught	7.99
Dimensions	88.00m X 17.82m
HP_Engines	21989
KW_Engines	16288
Engines	21,989 HP or 16,288 KW
GRT_Tonnag	4234
NRT_Tonnag	1955
DWT_Tonnag	
Tonnage	4,234 GRT or 1,955 NRT
MCTS_IceCl	Arctic Ice Class 4
IceClass	2
ShipPtIDv2	ID_027_2014_Terry_Fox_CCGS_3
New_2019	0
Week	40
REGION	EA
DATE_CARTE	2014-09-29
SOURCE	EGG
MOD	
EGG_ID	346
PNT_TYPE	120
CAC3	10
CAC4	5
TypeA	1
TypeB	0
TypeC	-1
TypeD	-1
TypeE	-6
Ship_type	TypeB
AIRSS_num	4
PC1	19
PC2	17
PC3	15
PC4	12
PC5	11
PC6	3
PC7	2
IA_Super	0
IA	-3
IB	-6
IC	-16
No_Stngth	-22
PShip_type	IA_Super
ChartWeek	40
Region1	0
Region2	0

6. Assign RIO values according to ship Ice Class
    a. Export the attribute table from ArcGIS as a .txt file and open in Excel.
    b. Create an 'RIO' field and assign the relevant RIO number according to the ship ice class. This must be a numeral, so convert all 'N/A' values to 1000. Where RIO values are 300, this is where the ice chart had no data. Where RIO values are 500, this is open water.
    c. Create three RIO Threshold fields, with numerals that define each risk threshold, as follows:
        i. High Risk (RIO < -10). Attribute numeral is -10
        ii. Elevated Risk (RIO -1 to -10). Attribute numeral is -1
        iii. Normal Op (RIO >= 0). Attribute numeral is 1
    d. Create a field that is the risk threshold obtained from the above attributes:
        i. Op Thresh: Attribute numerals are -10, -1, 0 (Null) and 1
        ii. Make further edits to the spreadsheet before exporting to join to the ship position report point shapefile, including creating the following fields:
            1. IceClassv2 (tidy the IceClass attribute by converting 'None' to 'No', and blank to 'N/A')
            2. AMSA_v2 (tidy the AMSA attribute by correcting pleasure craft and tug/barge where misspelt)

3. Create separate fields for each 5-year time period

e. Save these attributes into a .csv text file and join the table to the ship position report point shapefile based on FID values. This shapefile is then used for selecting all relevant data for each map, and the attributes are used for all further statistical analyses.

Canadian Ice Service Ice Charts

<u>Relevant details about CIS generation of ice charts:</u>

- Ice charts are currently created on Mondays, using imagery between the Saturday morning and Monday morning (images closest to Monday are prioritised). Radarsat-2 is the primary imagery used. Since 2014, the gaps are filled with Sentinel imagery. Charts are started on Mondays and released at 6pm on Wednesdays. Date_carte is the Monday.
- Radarsat-1 was launched end 1997 and used for ice charts from 1998 onwards. Before this, polar orbiting satellites with visible bands and poor resolution were used. Radarsat-1 was decommissioned in 2013.
- Both Radarsat-1 and Radarsat-2 have been used, resulting in full region-wide coverage since 2000.
- Radarsat-2 was launched end 2007 and used for ice charts from 2008 onwards. Satellite tracks have a 27 day cycle, when exact footprints are repeated. There is full coverage every 4 days.
- Prior to 2008, imagery from Friday to Sunday were used, and since then it has been Saturday to Monday imagery. Chart dates have been Mondays (during the shipping season) since 1998.

<u>Ice chart generation:</u>

- Manual digitisation is carried out at CIS using overlapping imagery. Image days/times for each chart vary regionally but these are not maintained within chart files. They are available on request from CIS. They will be within 2 days of the Date_Carte (or within 3 days prior to 2008).
- At present, charts are at 1:2 million scale on 8.5” x 11” paper size. Polygon minimum sizes are where a letter fits inside at 1:4 million scale (or 1,000 km^2 min poly size). In the past, minimum polygon sizes were greater and not digitised with the same level of precision.

<u>Ice Chart borders:</u>

- 1990 – 1996: the three region borders a09, a10, a11 are the same in each year
- 1997: a09 and a11 are same as 1990-1996; a10 is different
- 1998: same as 1990-1996

- 1999: a09 and a10 are the same as borders in Frances Delaney's dataset; a11 is different
- 2000: a09, a10 and a11 are the same as borders in Frances Delaney's dataset
- 2001 – 2019: a09 and a10 are the same as borders in Frances Delaney's dataset; a11 is same as 1999

<u>'REGION' attributes in ice chart data:</u>

- Years 1990 – 1998 have 'Region' field names: BH, AO and AE (equating to a09, a10 and a11).
- Years 2000 – 2019 have 'Region' field names: HB, WA and EA (equating to a09, a10 and a11).
- Year 1999 'Region' field names are a combination of the above, so first Select those using the 1990-1998 criteria, then the 2000-2019 criteria, then merge the two outputs.

<u>Ice charts – weeks of the year</u>

- 1990 – chart dates are inconsistent days of the week (anywhere between Monday and Sunday) throughout the year. The conversion of Date_carte to week of the year is correct. Charts are monthly between January and the end of May, then weekly. Very generalised vectors, but more detailed between June and August. The three regions (a09, a10 and a11) have differing chart dates.
- 1991 – same as 1990
- 1992 – same as 1990
- 1993 – same as 1990, but week conversion is +1 (start date is 04/01)
- 1994 – same as 1990, but week conversion is +1 (start date is 03/01)
- 1995 – same as 1990
- 1996 – same as 1990
- 1997 – same as 1990. The 3 regions have matching chart dates. Charts are detailed between May and December.
- 1998 – same as 1997. Charts are detailed year round. Chart dates are Mondays between 15th June and 23rd Nov.
- 1999 – same as 1998, but week conversion is +1 (start date is 04/01). Chart dates are Mondays between 14th June and 22nd Nov.
- 2000 – same as 1998, but week conversion is +1 (start date is 03/01). Chart dates are Mondays between 19th June and 27th Nov.
- 2001 – same as 1998. Chart dates are Mondays between 18th June and end Dec.
- 2002 – same as 1998. Chart dates are Mondays between 13th May and end Dec.

- 2003 – same as 1998. Chart dates are Mondays between 23rd June and end Dec.
- 2004 – same as 1998. Chart dates are Mondays between 7th June and end Dec.
- 2005 – same as 1998, but week conversion is +1 (start date is 03/01). Chart dates are Mondays between 13th June and end Dec.
- 2006 – same as 1998. Chart dates are Mondays between 15th May and end Dec.
- 2007 – same as 1998. Chart dates are Mondays year-round (1st Jan – end Dec). Bi-weekly 1st Jan – 26th March, then weekly.
- 2008 – same as 2007. Chart dates are Mondays year-round (31st Dec – end Dec). Bi-weekly 31st Dec – 24th March, then weekly.
- 2009 – same as 2007. Chart dates are Mondays year-round (29th Dec – end Dec). Bi-weekly 29th Dec – 30th March, then weekly.
- 2010 – same as 2007, but week conversion is +1 (start date is 04/01). Chart dates are Mondays year-round (4th Jan – end Dec). Bi-weekly 4th Jan – 29th March, then weekly.
- 2011 – same as 2007, but week conversion is +1 (start date is 03/01). Chart dates are Mondays year-round (3rd Jan – end Dec). Bi-weekly 3rd Jan – 28th March, then weekly.
- 2012 – same as 2007. Chart dates are Mondays year-round (2nd Jan – end Dec). Weekly, year-round.
- 2013 – same as 2012. Chart dates are Mondays year-round (31st Dec – end Dec). Weekly, year-round.
- 2014 – same as 2012. Chart dates are Mondays year-round (30th Dec – end Dec). Weekly, year-round.
- 2015 – same as 2012. Chart dates are Mondays year-round (29th Dec – end Dec). Weekly, year-round.
- 2016 – same as 2012, but week conversion is +1 (start date is 04/01). Chart dates are Mondays year-round (4th Jan – end Dec). Weekly, year-round.
- 2017 – same as 2012. Chart dates are Mondays year-round (2nd Jan – end Dec). Weekly, year-round.
- 2018 – same as 2012. Chart dates are Mondays year-round (1st Jan – end Dec). Weekly, year-round.
- 2019 – same as 2012. Chart dates are Mondays year-round (1st Jan – end Dec). Weekly, year-round.

APPENDIX B – DATA LIMITATIONS

Risk Threshold Data Limitations:

<u>Ship position report limitations</u>

All ship position reports were provided by MCTS for each individual year as Excel spreadsheets. The methodology section of the report and the Appendix outline how the data were edited to make ArcGIS shapefiles consisting of ship position reports with RIO values. Limitations of the dataset are as follows:

1. Only ship position reports that have a corresponding ice chart are included in our study. However, there does not seem to be any bias as to which reports are selected, and there are a large number of reports (a total of 37,520 RIO ship position reports from a total of 115,173 ship position reports), which are well distributed throughout the NORDREG region. From this we can be confident that the statistical analyses are robust, but it is important to remember that the quantification of ship position reports within each risk threshold is not absolute.
2. Ship position report timings: many ships reported their positions more than once per day (and there is no time recorded), but for this study we removed daily duplicates by choosing only the first recorded position of the day for consistency. In many cases there are several days in between recorded positions, but this should not have an impact on the results.
3. Ship position reports missing attributes: some RIO ship position reports are missing details on ship type and Ice Class. These are therefore not included in the statistical analysis, but the number is low (<1%).

<u>Ice chart limitations</u>

A summary of differences in ice chart data between years:

- 1990-1996: very generalised vectors, although more detailed between June and August. The three regions have differing chart dates, and they are on inconsistent days of the week. Monthly between January and May, then weekly.
- 1997: the three regions have matching chart dates. Detailed between May and December.
- 1998-2000: Charts are detailed (and improved, with launch of Radarsat-1 in 1997) year round. Chart dates are Mondays between June and Nov.
- 2001-2006: Chart dates are weekly on Mondays between June and end Dec, monthly rest of the year.
- 2007-2011: Chart date are Mondays year-round: bi-weekly until March, then weekly. Improved detail from 2008 onwards, with launch of Radarsat-2 in 2007.
- 2012-2018: Mondays year-round and weekly year round.

Precautions when using ice chart data alongside ship position reports:

1. For years 2008-2018, the ice charts are made from imagery up to 2 days before the chart date (images from Saturday morning to the Monday morning). For years 1990-2007, images between 1 and 3 days before the chart date were used. Also, years 1990-1996 may have included images throughout the whole week, but only 3 days prior were chosen. This leads to the issue that the ship position report date may be 2 or 3 days different to the image date and therefore the ship was not within the region for which the RIO was assigned. This cannot be avoided as the image dates are not recorded on the ice charts. However, the images closest to the chart date are always prioritised when ice charts are digitised, therefore we can have confidence that a difference of 2 or 3 days is less likely.
2. The three ice chart region boundaries differ throughout the 28 year period. This issue has been largely overcome by removing duplicated ship position reports in overlapping regions for individual years. For 1990-1996 this was more complicated as they have mixed boundaries and dates, but the correct ship position reports have been successfully extracted.
3. The number of charts differs between years (monthly/weekly) which results in varying number of selected ship position reports between years. Early years have fewer ship position reports with RIO values as there were fewer ice charts produced at this time. However, there are still a sufficient number of ship position reports in all years for reliable statistical analysis of change over time.
4. Accuracy (quality of satellite imagery) and precision (how generalised the vectors are) varies between years and improves over time. More recently, more detailed polygons means smaller areas are digitised. This must be noted, but these are not expected to have an impact on the risk threshold statistical results.

Example:

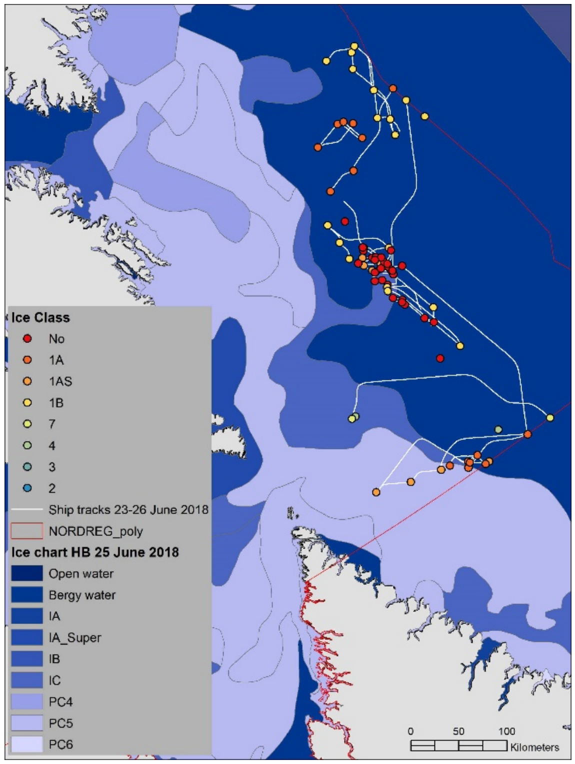


Figure B1: Ice chart (25 June 2018) with ship tracks and position reports (23-26 June 2018) overlaid. Some 1AS ship position reports cross an area accessible only for PC5 ships or stronger (southern area).

APPENDIX C - ADDITIONAL DATA FOR REPORT SECTION 3.0

Changes in Temporal Patterns of Ship Traffic in Arctic Canada (NORDREG ZONE)
The following graphs are for all NORDREG ship position report data between 1990-2019. Results show data broken down into number of ship position reports. Unique ship counts and track counts are in the main report.

1) Number of ship position reports

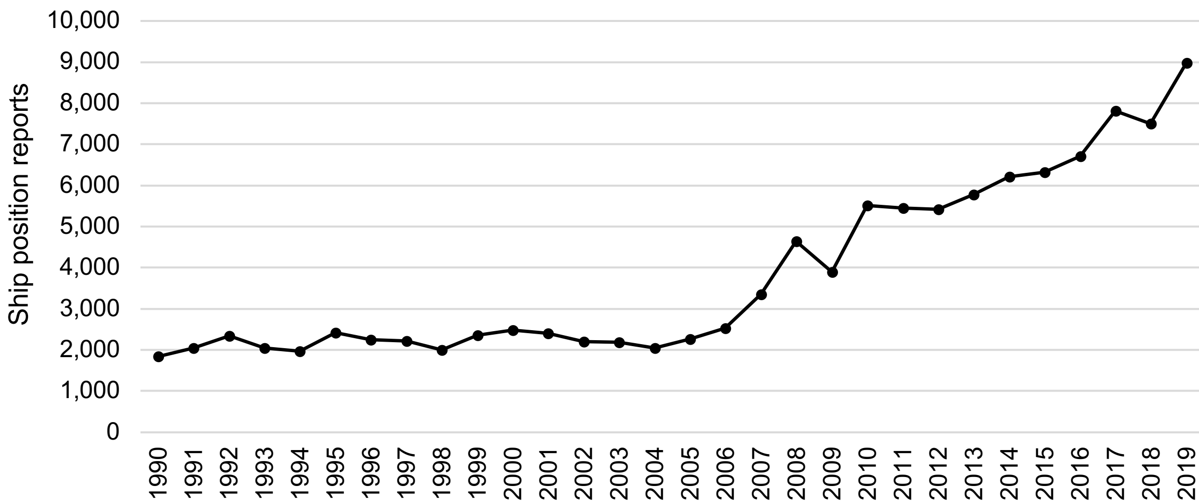


Figure C1: NORDREG Zone all ship position reports by year.

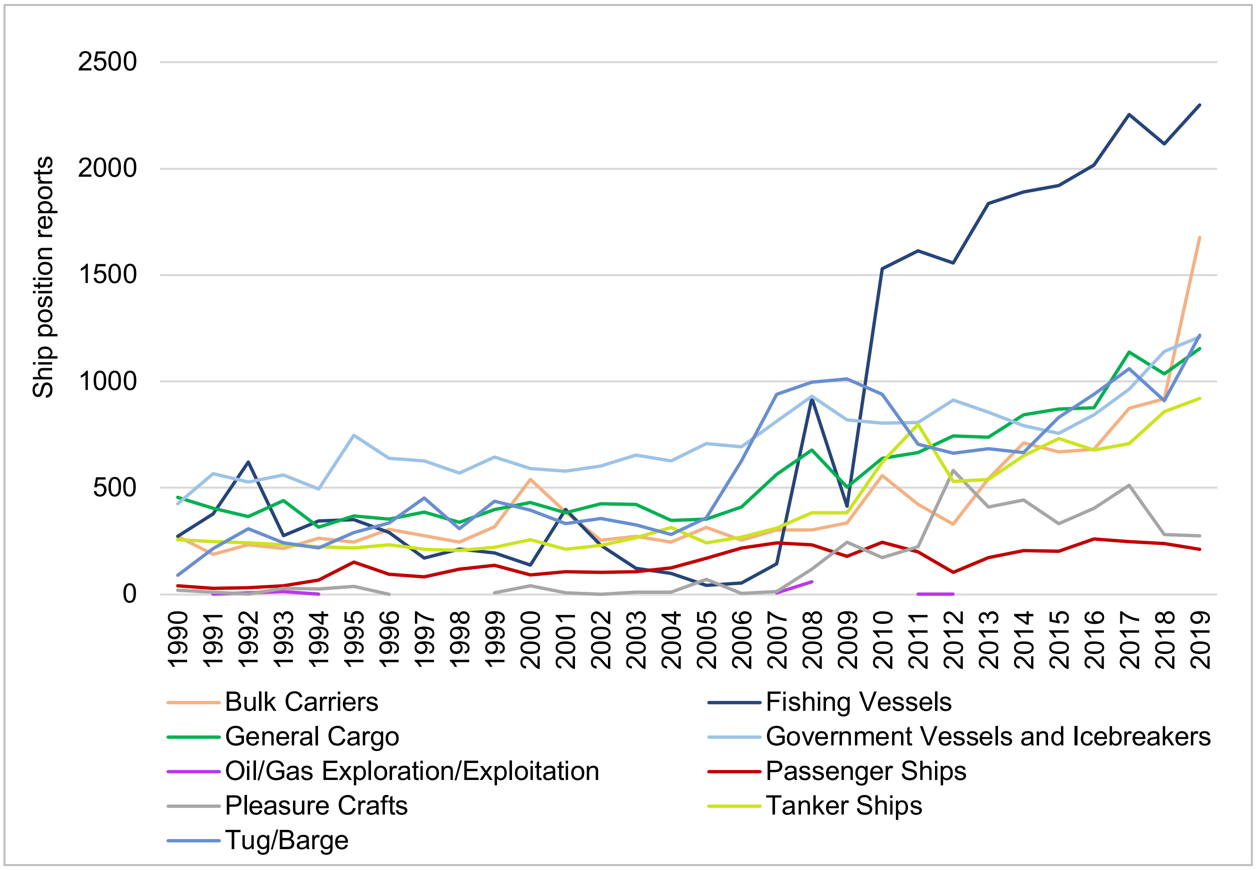


Figure C2: NORDREG Zone all ship position reports by year and ship type.

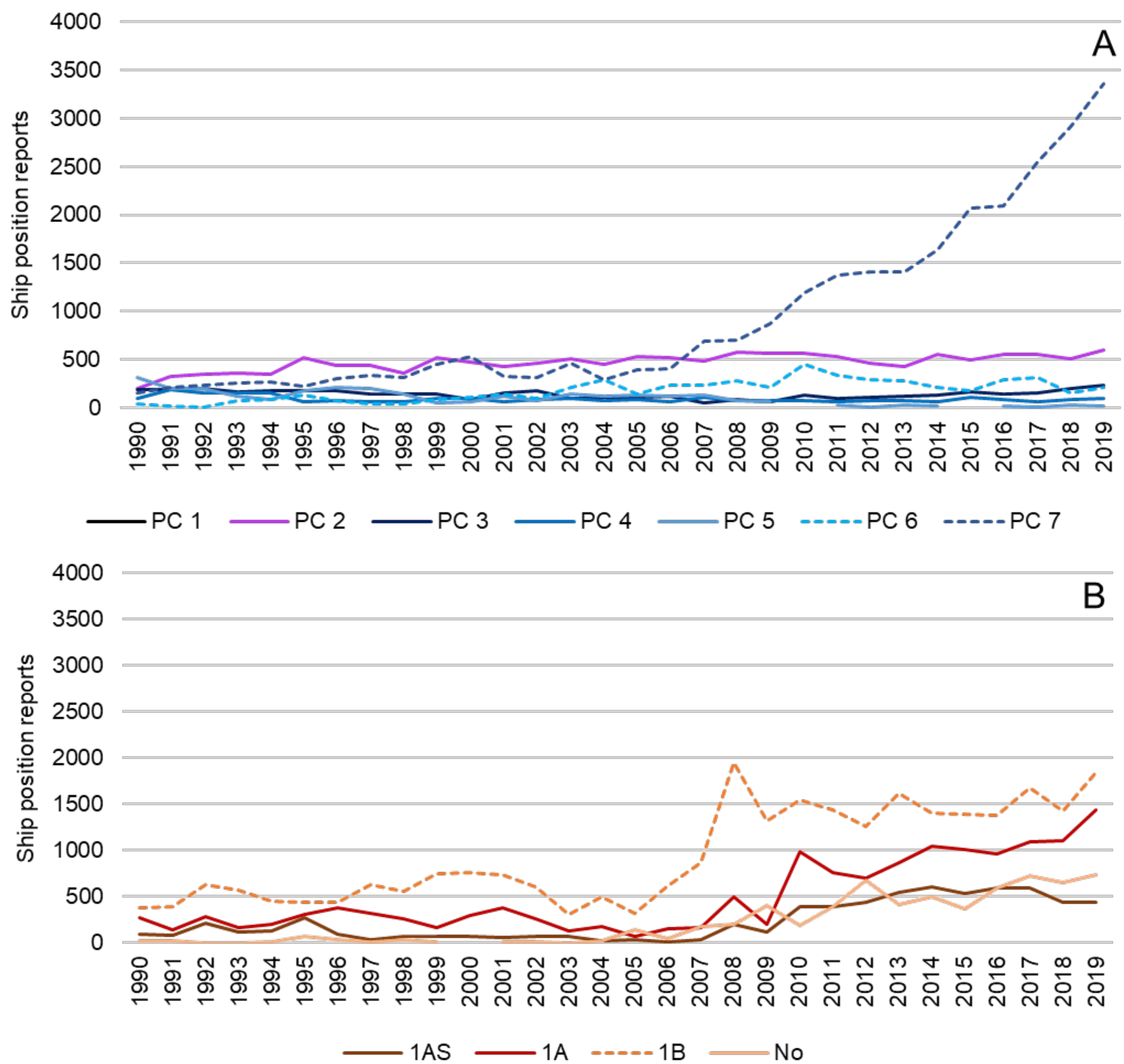


Figure C3: All ship position reports by year and Ice Class in: (A) Ship Category A and B, and (B) Category C.

APPENDIX D - ADDITIONAL DATA FOR REPORT SECTION 4.0

Temporal Analysis of Operational Risk Based on Ship-Strength and Ice Type (RIO)

Ship Position Reports results:
Graphs summarizing the number and percentages of RIO ship position reports within the elevated and high risk thresholds are in the main report. Below is a table showing the number of RIO ship position reports by ship type.

Table D1: Number of RIO ship position reports in each risk threshold by ship type for each 5-year period between 1990-2019.

	High Risk	Elevated Risk	Normal Operation	Total Count
Bulk Carriers	**88**	**35**	**4170**	**4293**
1990-94	21	14	380	415
1995-99	37	11	473	521
2000-04	27	4	621	652
2005-09			268	268
2010-14			667	667
2015-19	3	6	1761	1770
Fishing Vessels	**80**	**143**	**10246**	**10469**
1990-94	13	10	806	829
1995-99	6	4	514	524
2000-04		3	426	429
2005-09	1	1	662	664
2010-14	20	59	3463	3542
2015-19	40	66	4375	4481
General Cargo	**73**	**52**	**4704**	**4829**
1990-94	22	4	560	586
1995-99	10	4	524	538
2000-04	9	12	538	559
2005-09	9	3	686	698
2010-14	8	8	988	1004
2015-19	15	21	1408	1444
Government Vessels and Icebreakers	**29**	**17**	**7655**	**7701**
1990-94	3	4	855	862
1995-99	2	1	1003	1006
2000-04	4	4	996	1004

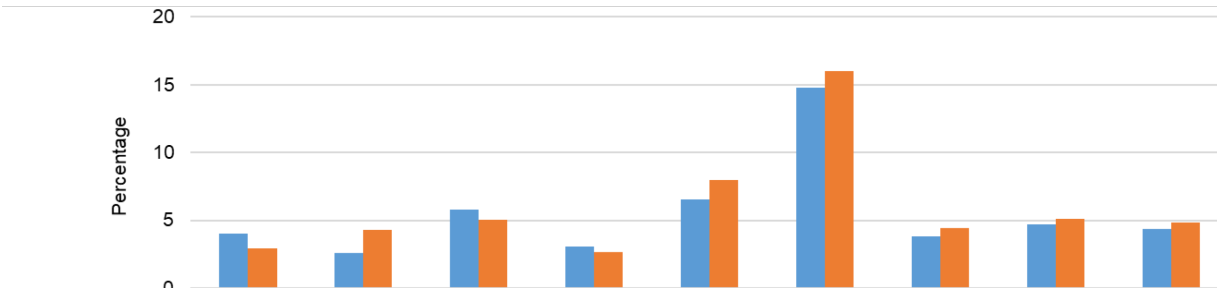
2005-09	4	2	1435	1441
2010-14	2	1	1588	1591
2015-19	14	5	1778	1797
Oil/Gas Exploration/Exploitation			**38**	**38**
1990-94			6	6
2005-09			28	28
2010-14			4	4
Passenger Ships	**27**	**33**	**1551**	**1611**
1990-94	1	3	62	66
1995-99	3	2	199	204
2000-04	4	4	183	191
2005-09	4	6	314	324
2010-14	3	6	361	370
2015-19	12	12	432	456
Pleasure Craft	**63**	**64**	**1134**	**1261**
1990-94				0
1995-99				0
2000-04	2		12	14
2005-09	14	1	116	131
2010-14	16	20	428	464
2015-19	31	43	578	652
Tanker Ships	**94**	**55**	**3346**	**3495**
1990-94	3	1	364	368
1995-99	1	3	340	344
2000-04	2	10	396	408
2005-09	6	8	512	526
2010-14	69	18	786	873
2015-19	13	15	948	976
Tug/Barge	**34**	**38**	**3748**	**3820**
1990-94	6	8	308	322
1995-99	5	10	443	458
2000-04	10	14	423	447
2005-09	8		877	885
2010-14	1	3	929	933
2015-19	4	3	768	775
Grand Total	**488**	**438**	**36594**	**37520**

Table D2: Percentage of RIO ship position reports in each risk threshold by ship type for each 5-year period between 1990-2019.

	High Risk	Elevated Risk	Normal Operation
Bulk Carriers	**2.05**	**0.82**	**97.13**
1990-94	5.06	3.37	91.57
1995-99	7.10	2.11	90.79
2000-04	4.14	0.61	95.25
2005-09	0.00	0.00	100.00
2010-14	0.00	0.00	100.00
2015-19	0.17	0.34	99.49
Fishing Vessels	**0.76**	**1.37**	**97.87**
1990-94	1.57	1.21	97.23
1995-99	1.15	0.76	98.09
2000-04	0.00	0.70	99.30
2005-09	0.15	0.15	99.70
2010-14	0.56	1.67	97.77
2015-19	0.89	1.47	97.63
General Cargo	**1.51**	**1.08**	**97.41**
1990-94	3.75	0.68	95.56
1995-99	1.86	0.74	97.40
2000-04	1.61	2.15	96.24
2005-09	1.29	0.43	98.28
2010-14	0.80	0.80	98.41
2015-19	1.04	1.45	97.51
Government Vessels and Icebreakers	**0.38**	**0.22**	**99.40**
1990-94	0.35	0.46	99.19
1995-99	0.20	0.10	99.70
2000-04	0.40	0.40	99.20
2005-09	0.28	0.14	99.58
2010-14	0.13	0.06	99.81
2015-19	0.78	0.28	98.94
Oil/Gas Exploration/Exploitation	**0.00**	**0.00**	**100.00**
1990-94	0.00	0.00	100.00
2005-09	0.00	0.00	100.00

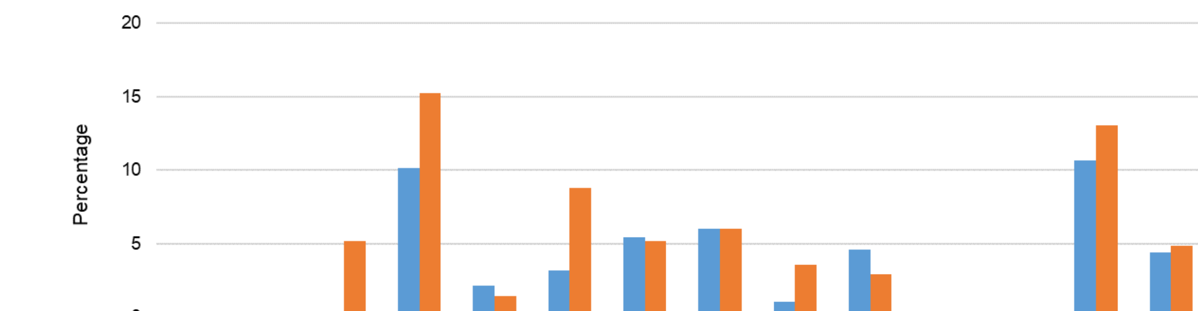
2010-14	0.00	0.00	100.00
Passenger Ships	**1.68**	**2.05**	**96.28**
1990-94	1.52	4.55	93.94
1995-99	1.47	0.98	97.55
2000-04	2.09	2.09	95.81
2005-09	1.23	1.85	96.91
2010-14	0.81	1.62	97.57
2015-19	2.63	2.63	94.74
Pleasure Craft	**5.00**	**5.08**	**89.93**
1990-94			
1995-99			
2000-04	14.29	0.00	85.71
2005-09	10.69	0.76	88.55
2010-14	3.45	4.31	92.24
2015-19	4.75	6.60	88.65
Tanker Ships	**2.69**	**1.57**	**95.74**
1990-94	0.82	0.27	98.91
1995-99	0.29	0.87	98.84
2000-04	0.49	2.45	97.06
2005-09	1.14	1.52	97.34
2010-14	7.90	2.06	90.03
2015-19	1.33	1.54	97.13
Tug/Barge	**0.89**	**0.99**	**98.12**
1990-94	1.86	2.48	95.65
1995-99	1.09	2.18	96.72
2000-04	2.24	3.13	94.63
2005-09	0.90	0.00	99.10
2010-14	0.11	0.32	99.57
2015-19	0.52	0.39	99.10

<u>Ship track</u> results: tracks that have at least one record within a risk threshold (each track is defined as when the ship enters and leaves the NORDREG Zone).



	Bulk Carriers	Fishing Vessels	General Cargo	Government Vessels and Icebreakers	Passenger Ships	Pleasure Crafts	Tanker Ships	Tug/Barge	Grand Total
% High Risk	4.04	2.56	5.77	3.05	6.51	14.75	3.80	4.71	4.37
% Elevated Risk	2.93	4.31	5.02	2.67	7.99	15.98	4.44	5.10	4.82
Total Voyages	989	1717	797	525	338	244	631	510	5769

Figure D1: Percentage of RIO ship tracks with at least one record within a high or elevated risk threshold across the whole time period (1990-2019), categorized by ship type.



	1	2	3	4	5	6	7	1A	1AS	1B	IS	N/A	No	Grand Total
% High Risk	0.00	0.00	0.00	10.17	2.11	3.13	5.44	6.01	1.04	4.61	0.00	0.00	10.64	4.37
% Elevated Risk	0.00	0.00	5.19	15.25	1.41	8.78	5.15	6.01	3.55	2.93	0.00	0.00	13.07	4.82
Total voyages	1	266	270	59	142	319	1398	848	479	1432	22	204	329	5769

Figure D2: Percentage of RIO ship tracks with at least one record within a high or elevated risk threshold across the whole time period (1990-2019), categorized by Ice Class.

Number of tracks that have at least one record occurring within a high or elevated risk threshold:

Table D3: Number of tracks with records in each risk threshold

	High Risk	Elevated Risk	Normal Operation	Total Count
1990-94	32	33	503	568
1995-99	33	27	537	597
2000-04	38	33	496	567
2005-09	26	20	641	687
2010-14	40	58	1,419	1,517
2015-19	83	107	1,903	2,093
Grand Total	252	278	5,499	6,029

Percentage of tracks that have at least one record occurring within a high or elevated risk threshold:

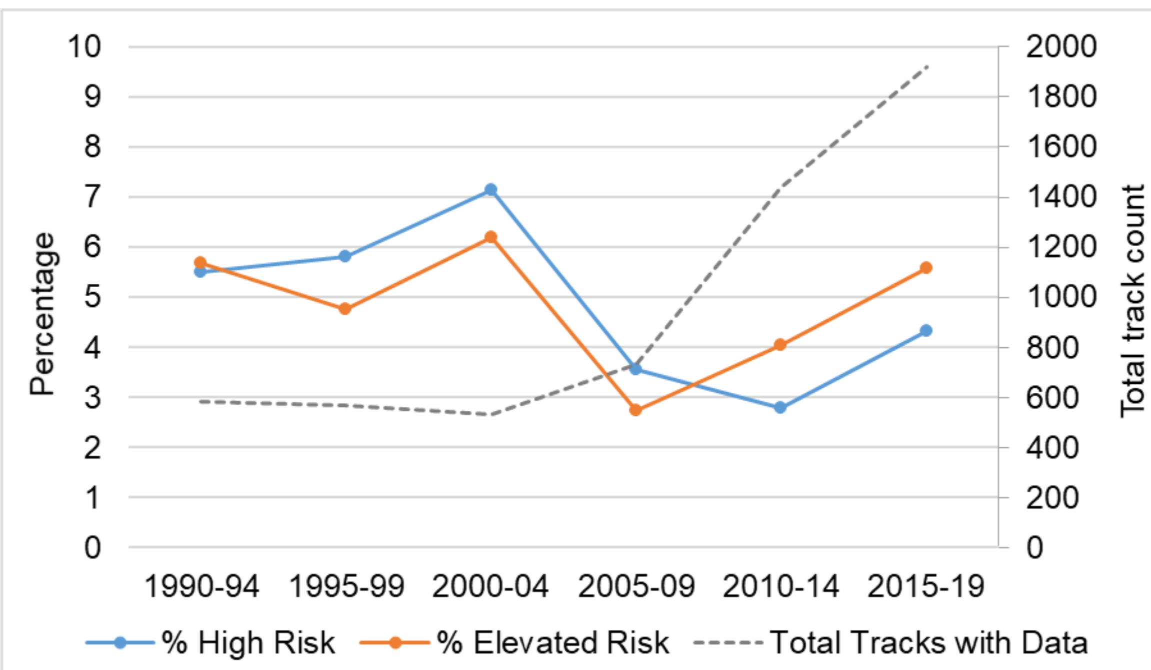


Figure D3: Percentage of tracks with records in each risk threshold.

Table D4: Percentage of tracks with records in each risk threshold.

	High Risk	Elevated Risk	Normal Operation
1990-94	5.50	5.67	86.43
1995-99	5.81	4.75	94.54
2000-04	7.14	6.20	93.23
2005-09	3.55	2.73	87.57
2010-14	2.79	4.04	98.82
2015-19	4.33	5.58	99.17
Grand Total	4.37	4.82	95.32

Percentage of tracks that have at least one record occurring within a high or elevated risk threshold, by ship type:

Table D5: Number of tracks in each risk threshold by ship type for each 5-year period between 1990-2019.

	High Risk	Elevated Risk	Normal Operation	Total Count
Bulk Carriers	40	29	907	976
1990-94	8	13	101	122
1995-99	17	8	109	134
2000-04	14	2	115	131
2005-09			65	65
2010-14			132	132
2015-19	1	6	385	392
Fishing Vessels	44	74	1638	1756
1990-94	4	5	105	114
1995-99	3	4	103	110
2000-04		1	60	61
2005-09	1	1	131	133
2010-14	11	27	557	595
2015-19	25	36	682	743
General Cargo	46	40	783	869
1990-94	13	4	95	112
1995-99	6	3	98	107
2000-04	7	9	87	103
2005-09	5	2	105	112
2010-14	3	7	171	181
2015-19	12	15	227	254
Government Vessels and Icebreakers	16	14	509	539
1990-94	1	3	53	57
1995-99	1	1	47	49
2000-04	3	3	56	62
2005-09	2	2	79	83
2010-14	2	1	129	132
2015-19	7	4	145	156
Oil/Gas Exploration/Exploitation			6	6

1990-94			2	2
2005-09			2	2
2010-14			2	2
Passenger Ships	22	27	321	370
1990-94	1	1	13	15
1995-99	2	2	37	41
2000-04	3	4	42	49
2005-09	3	6	63	72
2010-14	3	6	64	73
2015-19	10	8	102	120
Pleasure Craft	36	39	216	291
1990-94				0
1995-99				0
2000-04	1		1	2
2005-09	6	1	18	25
2010-14	13	11	92	116
2015-19	16	27	105	148
Tanker Ships	24	28	615	667
1990-94	3	1	90	94
1995-99	1	1	82	84
2000-04	1	6	89	96
2005-09	4	7	96	107
2010-14	7	5	133	145
2015-19	8	8	125	141
Tug/Barge	24	26	503	553
1990-94	2	6	44	52
1995-99	3	8	61	72
2000-04	9	8	46	63
2005-09	5		81	86
2010-14	1	1	139	141
2015-19	4	3	132	139
Grand Total	**252**	**277**	**5492**	**6021**

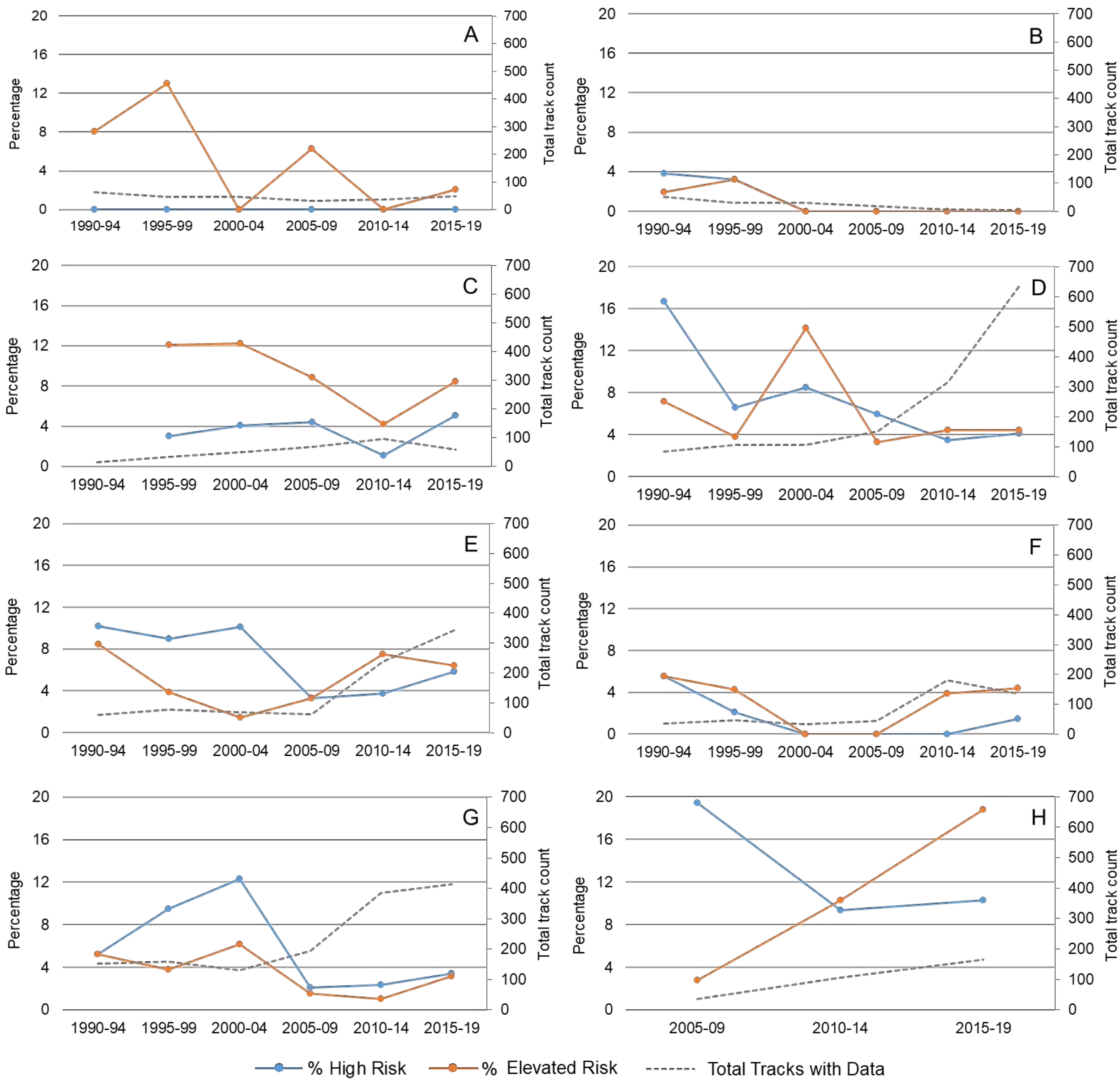


Figure D4: Percentage of tracks in each risk threshold for each ice class: (A) PC3, (B) PC5, (C) PC6, (D) PC7, (E) 1A, (F) 1AS, (G) 1B, and (H) no ice strengthening.

APPENDIX E – ADDITIONAL DATA FOR REPORT SECTION 5.0

Geographic/Spatial Analysis of Operational Risk Based on Ship-Strength and Ice Type for Ship Position Reports with RIO Values

These are the maps of ship position reports for all ship types not included within the main report, comprising general cargo, government vessels and icebreakers, fishing vessels, passenger ships, and tugs/barges.

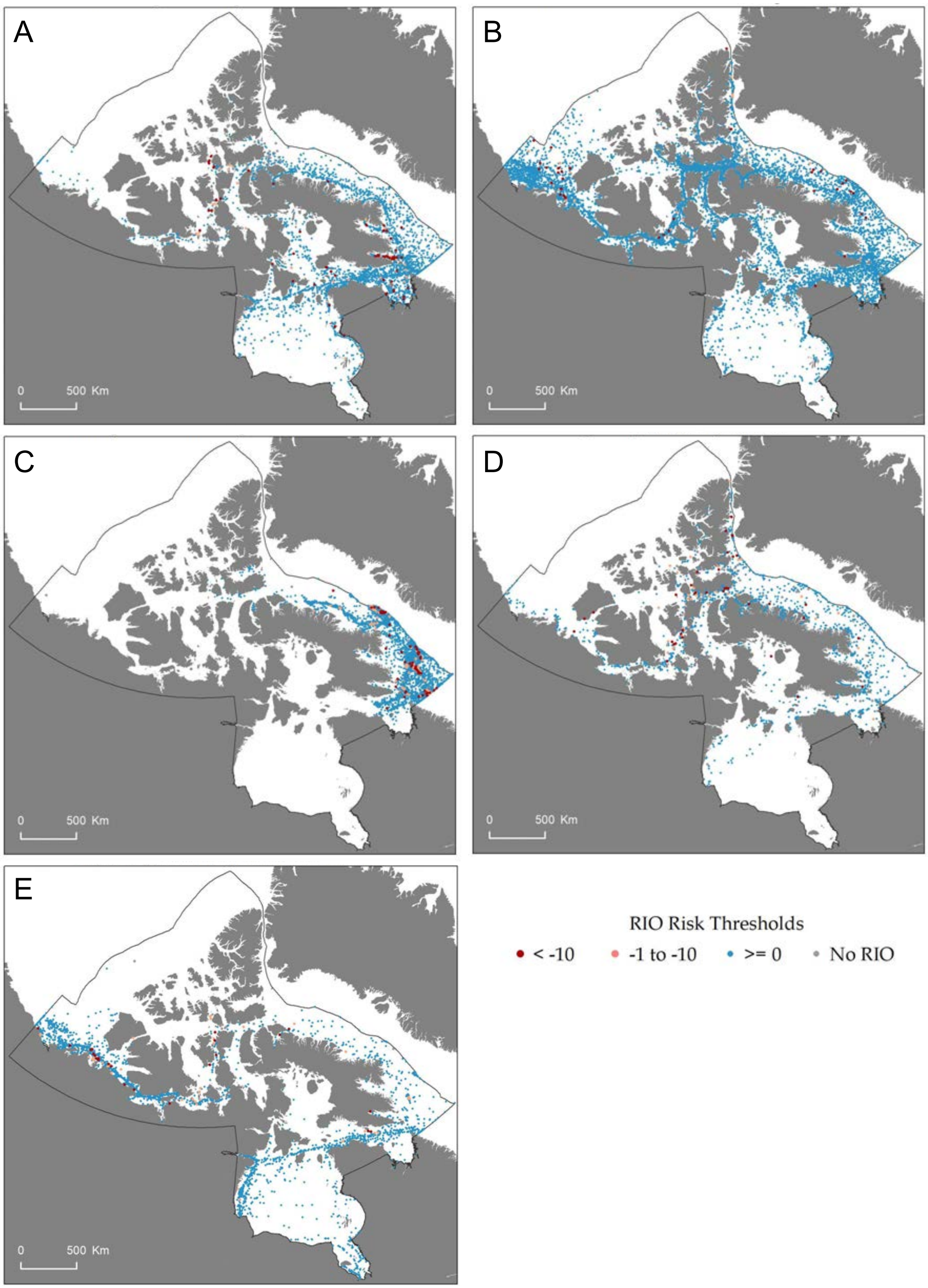


Figure E1: Spatial patterns of ship position reports with RIO values for each ship type: (A) general cargo, (B) government vessels and icebreakers, (C) fishing vessels, (D) passenger ships, and (E) tugs/barges.

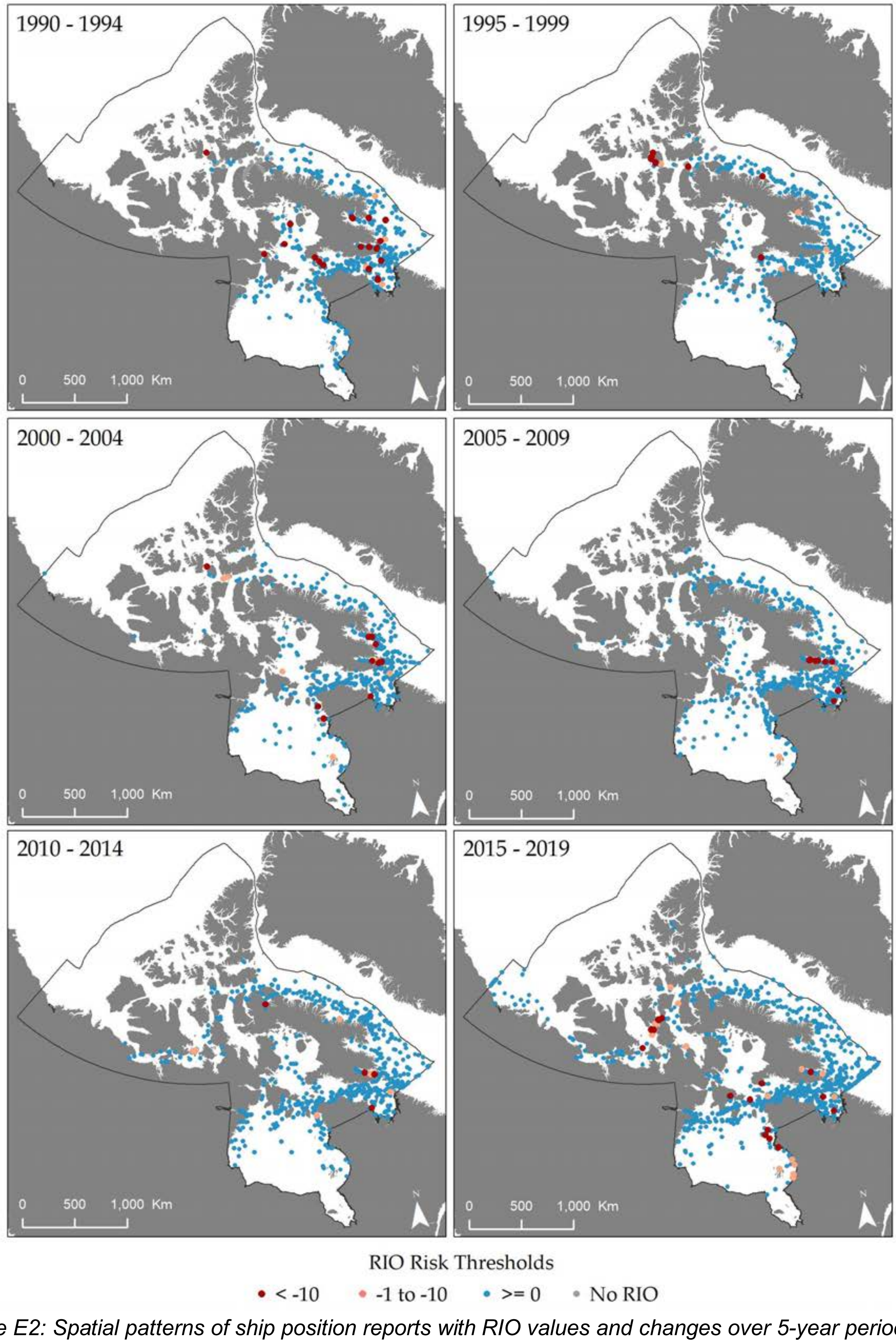


Figure E2: Spatial patterns of ship position reports with RIO values and changes over 5-year periods for general cargo ships.

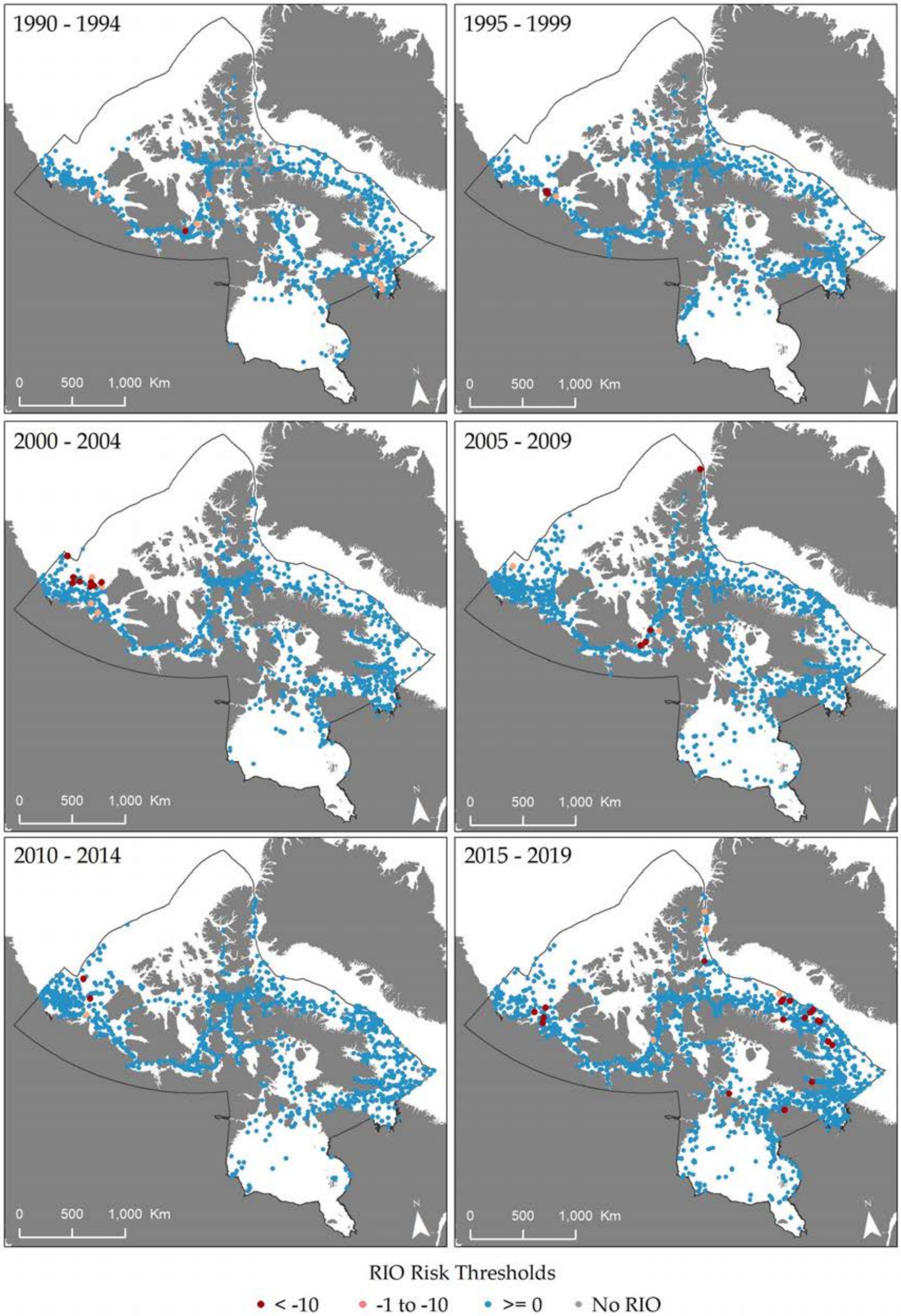


Figure E3: Spatial patterns of ship position reports with RIO values and changes over 5-year periods for government vessels and icebreakers.

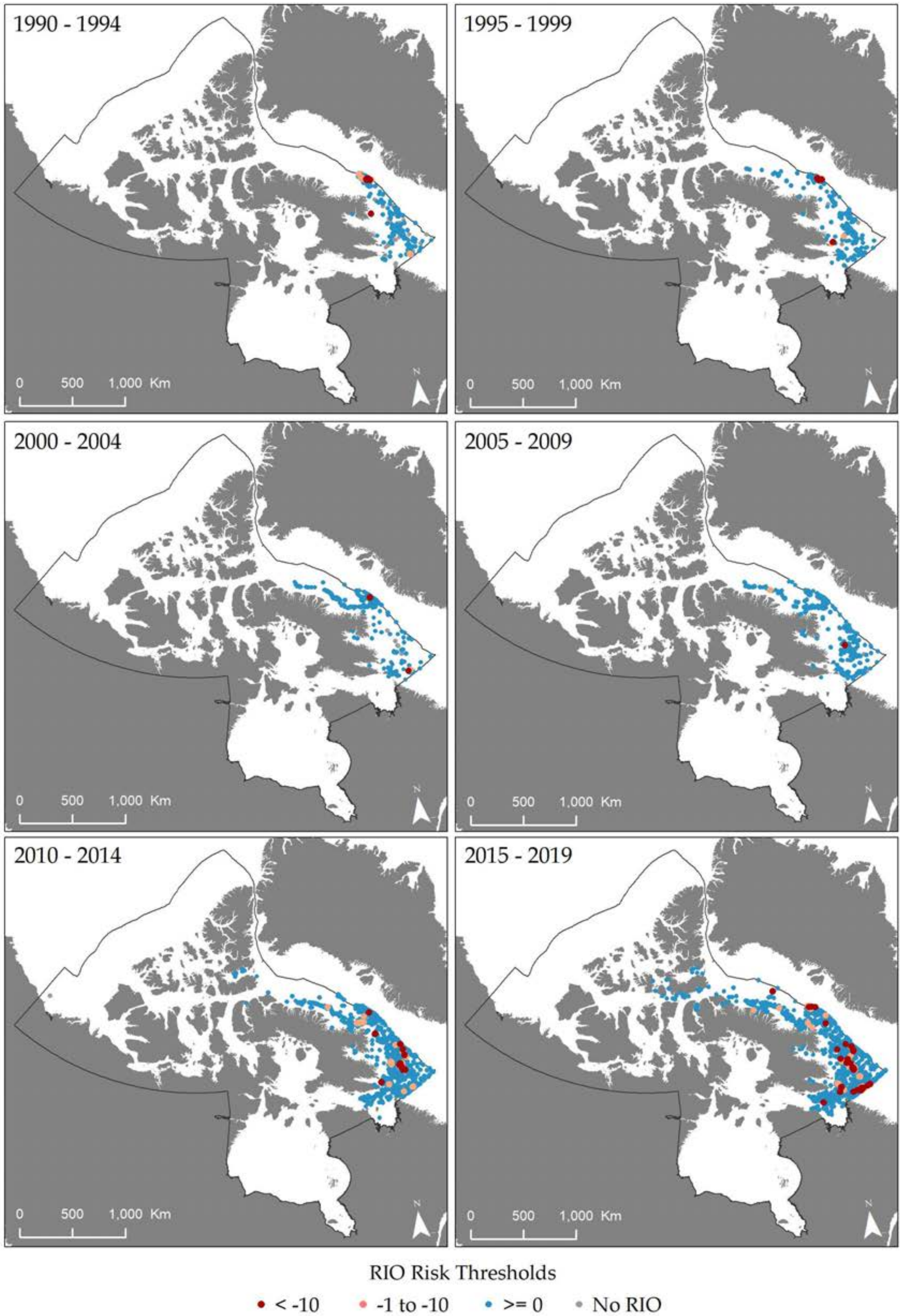


Figure E4: Spatial patterns of ship position reports with RIO values and changes over 5-year periods for fishing vessels.

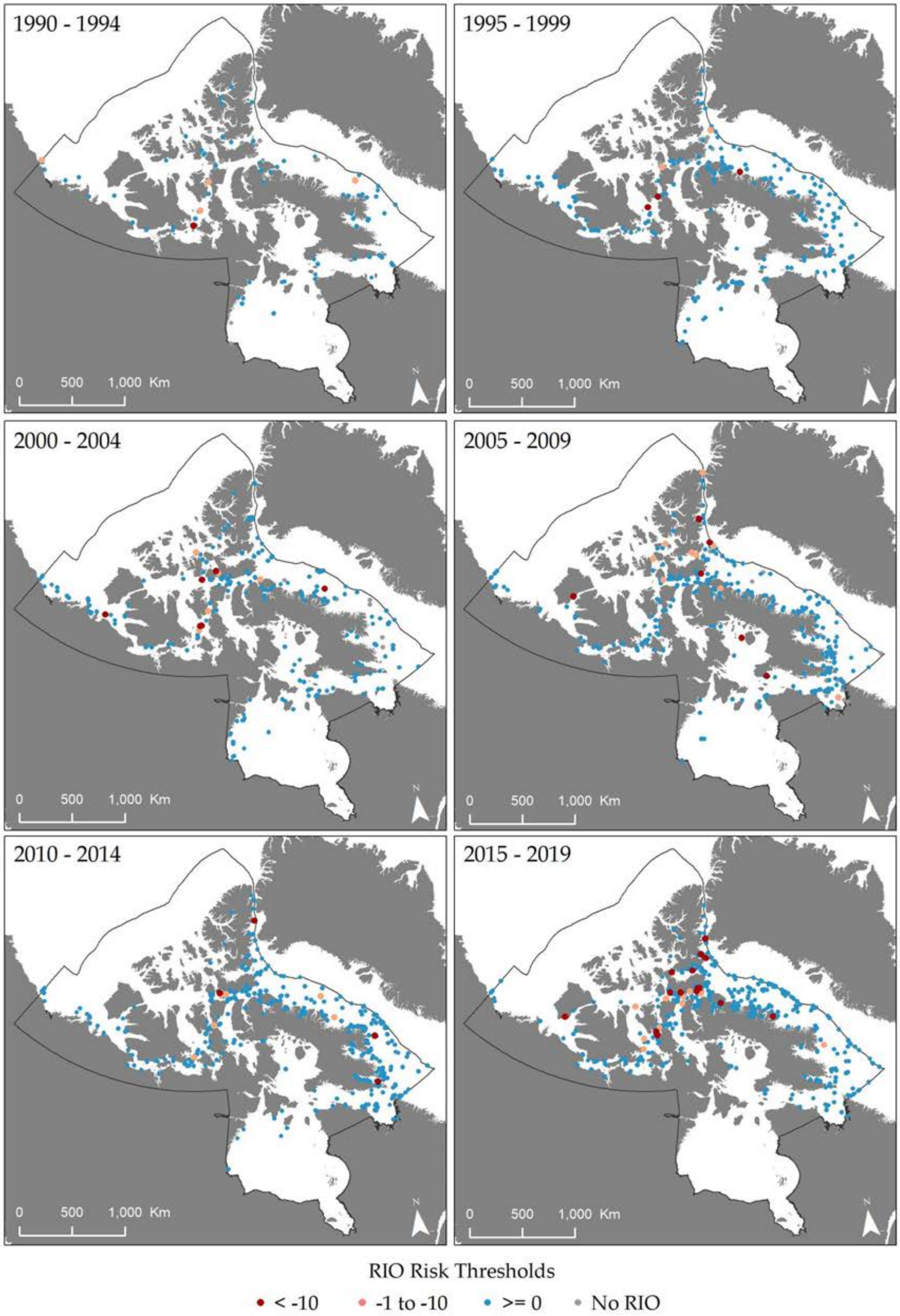


Figure E5: Spatial patterns of ship position reports with RIO values and changes over 5-year periods for passenger ships.

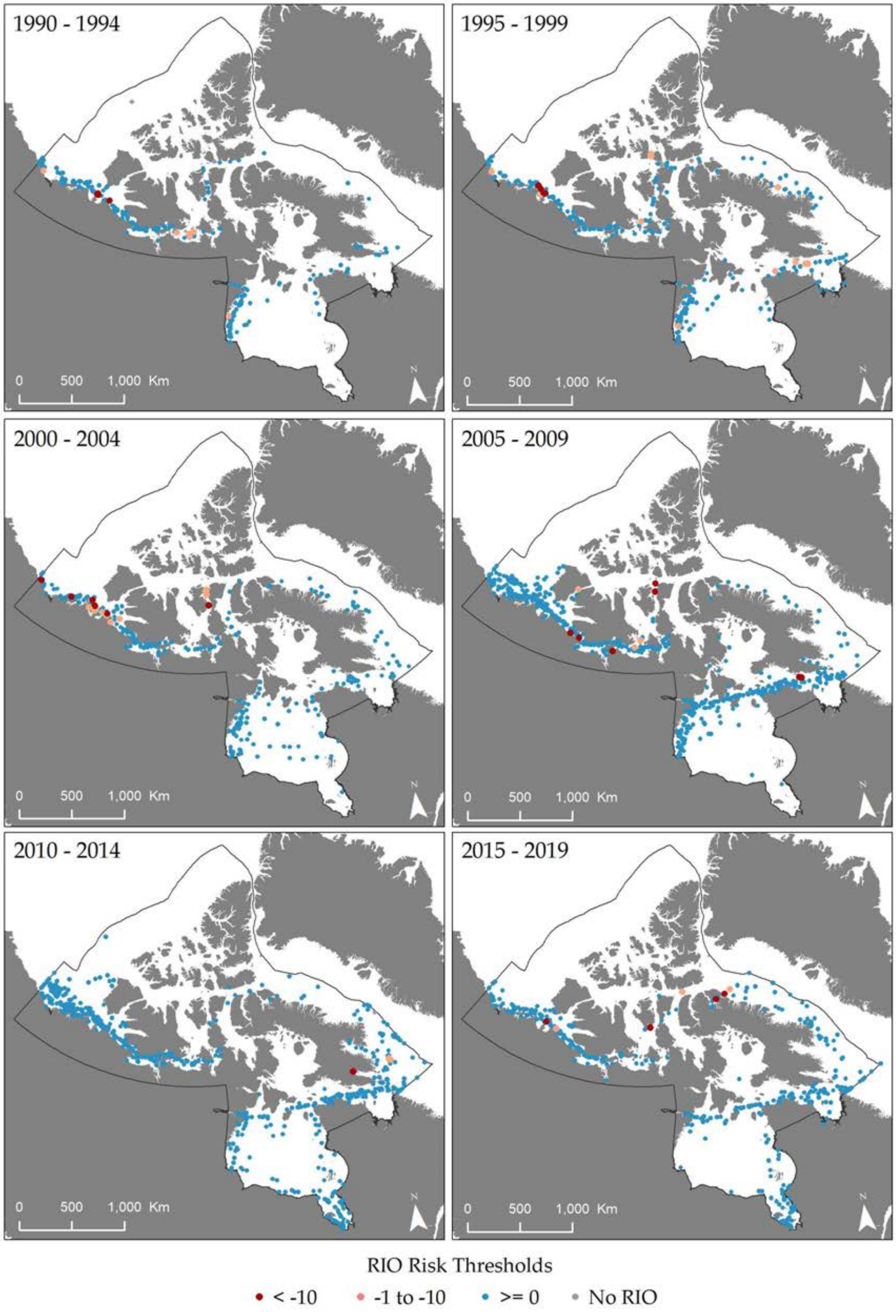


Figure E6: Spatial patterns of ship position reports with RIO values and changes over 5-year periods for tugs/barges.

APPENDIX F – ADDITIONAL DATA FOR REPORT SECTION 6.0

Analysis of Three Higher Risk Zones – Franklin Strait, Frobisher Bay, and Lancaster Sound

In the main report, the graphs for the three higher risk zones show the number of ship position reports by ship type within each risk threshold. The following graphs show the ship position reports by ship type within each risk threshold as a percentage of records of the same ship type. These are only shown when the number of ship position reports by ship type is 10 or more.

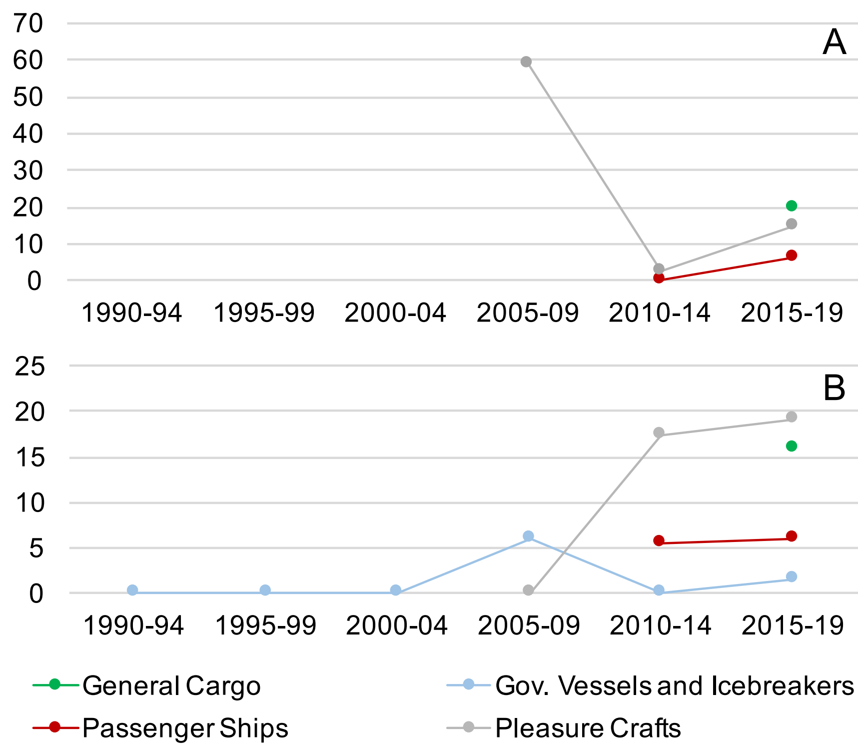


Figure F1: Percentage of ship position reports by ship type for: (A) high risk conditions, and (B) elevated risk conditions, in Franklin Strait.

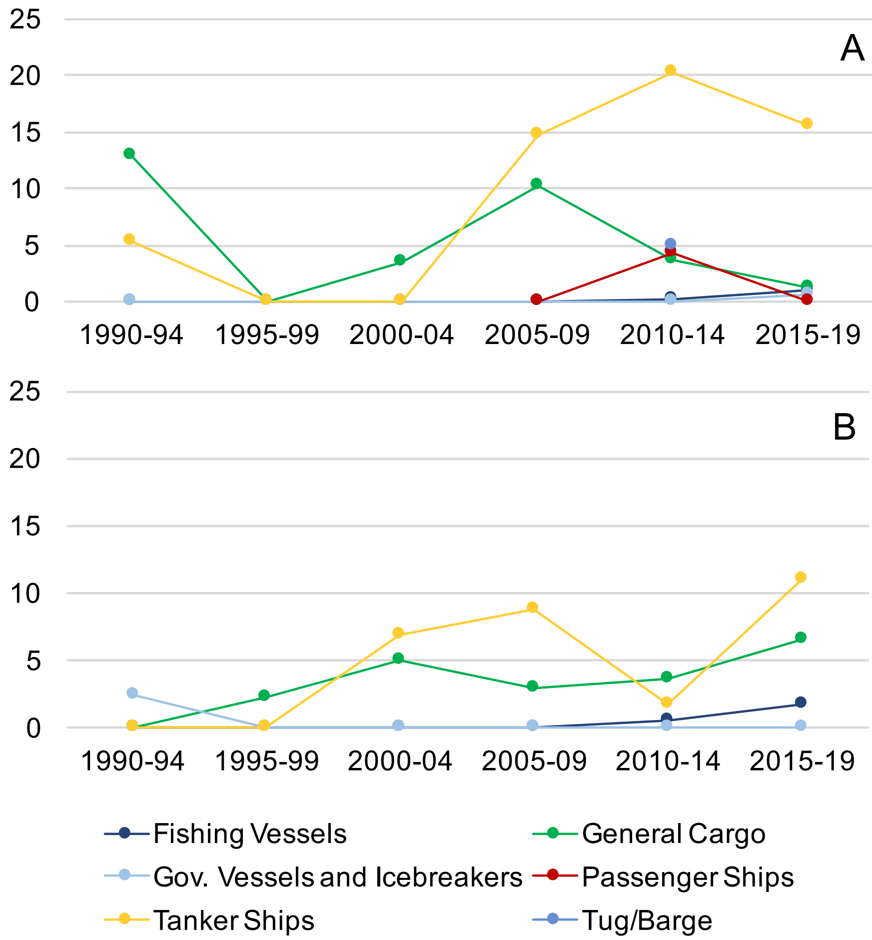


Figure F2: Percentage of ship position reports by ship type for: (A) high risk conditions, and (B) elevated risk conditions, in Frobisher Bay.

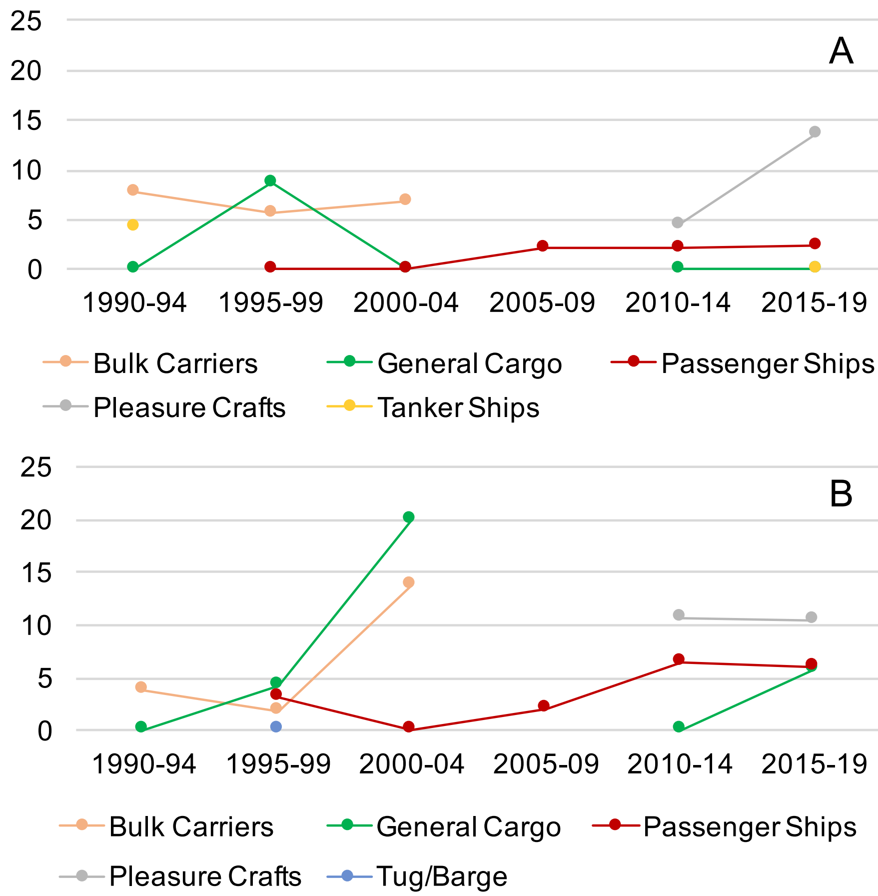


Figure F3: Percentage of ship position reports by ship type for: (A) high risk conditions, and (B) elevated risk conditions, in Lancaster Sound.

Unique Ships

All results in Section 6 of the report, and results above, are for ship position reports (i.e. all point data). Below we provide details for unique ships, in terms of counts and percentages, within each 5-year time interval within elevated and high risk thresholds, and tables that show which specific ships took the greatest number of risks. The unique ship results and lists of individual ships that contribute to these results are in an Excel spreadsheet (available upon request).

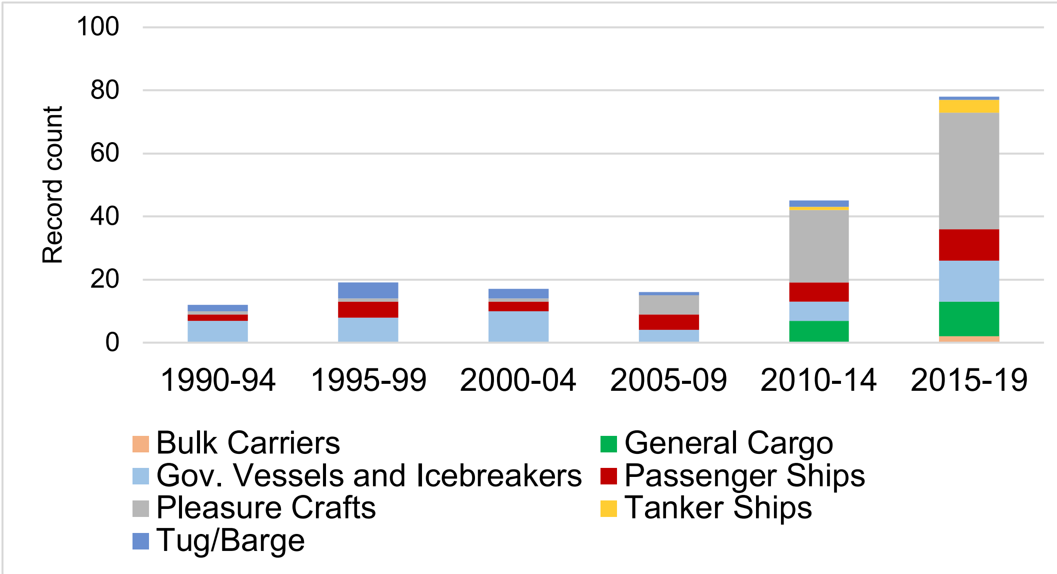


Figure F4: All unique ship counts by ship type in Franklin Strait.

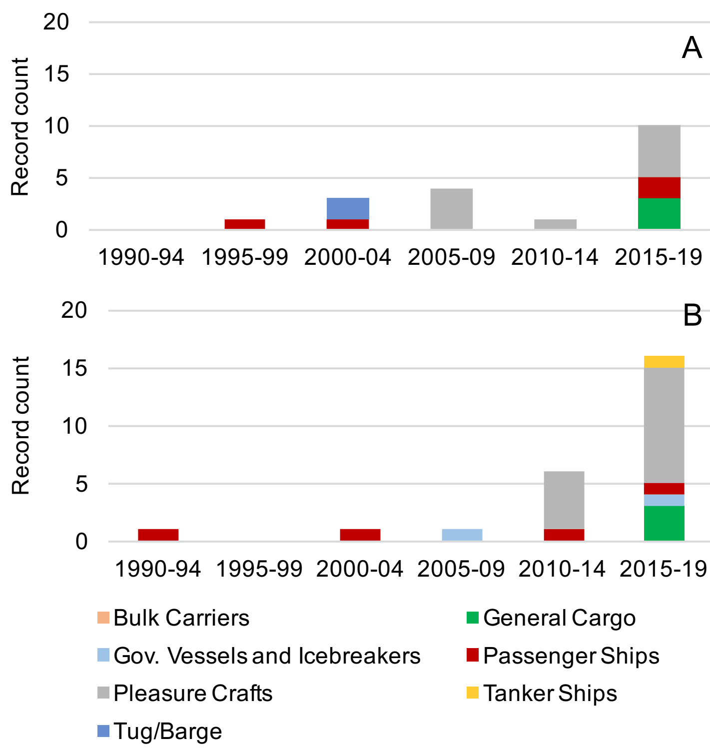


Figure F5: Unique ship counts for each ship type for: (A) high risk conditions, and (B) and elevated risk conditions, in Franklin Strait.

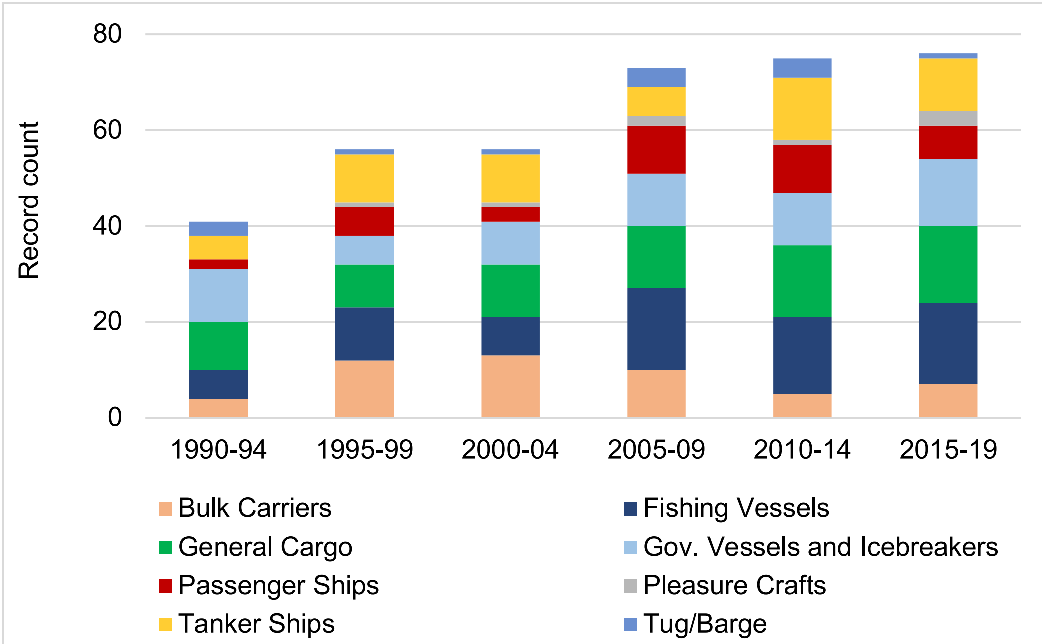


Figure F6: All unique ship counts by ship type in Frobisher Bay.

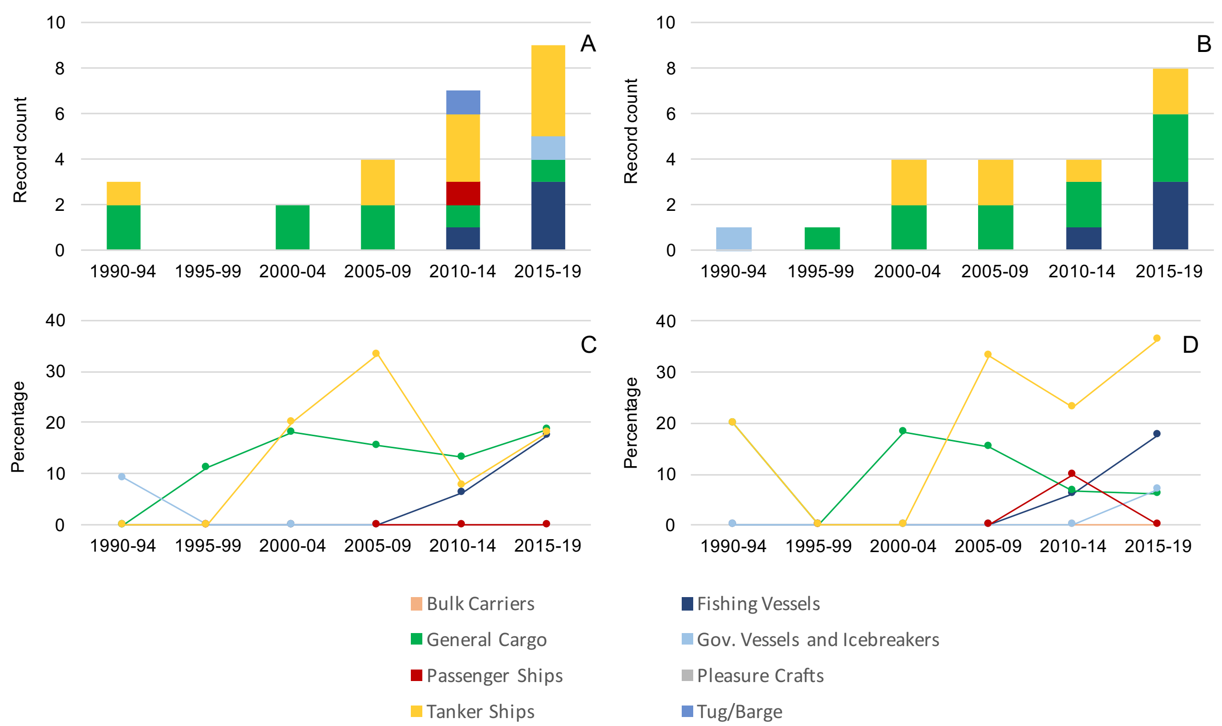


Figure F7: Unique ships counts in Frobisher Bay, by ship types, within: (A) high risk, and (B) elevated risk areas, as well as the percentage of all unique ships by ship type (where count > 4) for: (C) high risk, and (D) elevated risk areas.

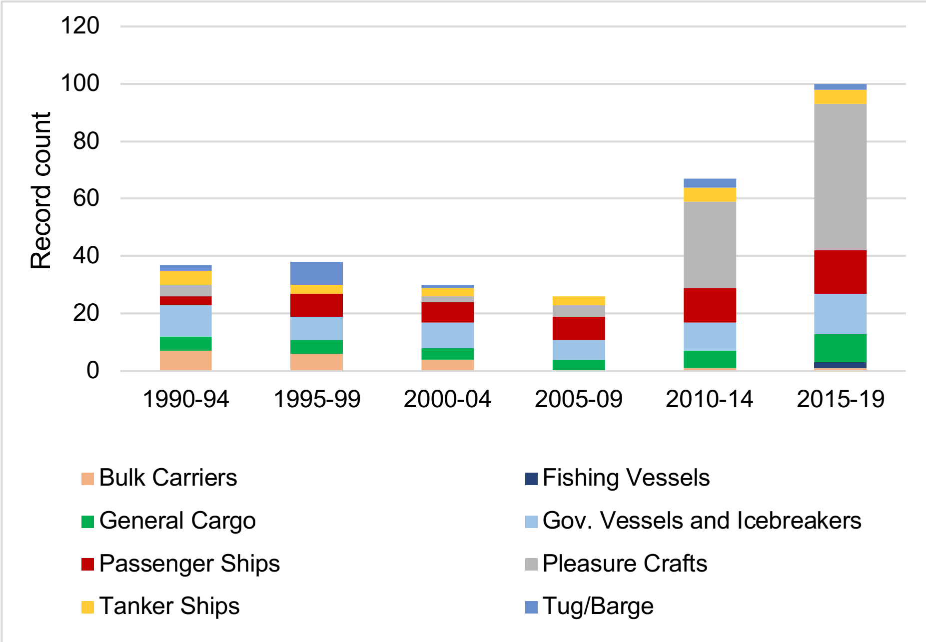


Figure F8: All unique ship counts by ship type in Lancaster Sound.

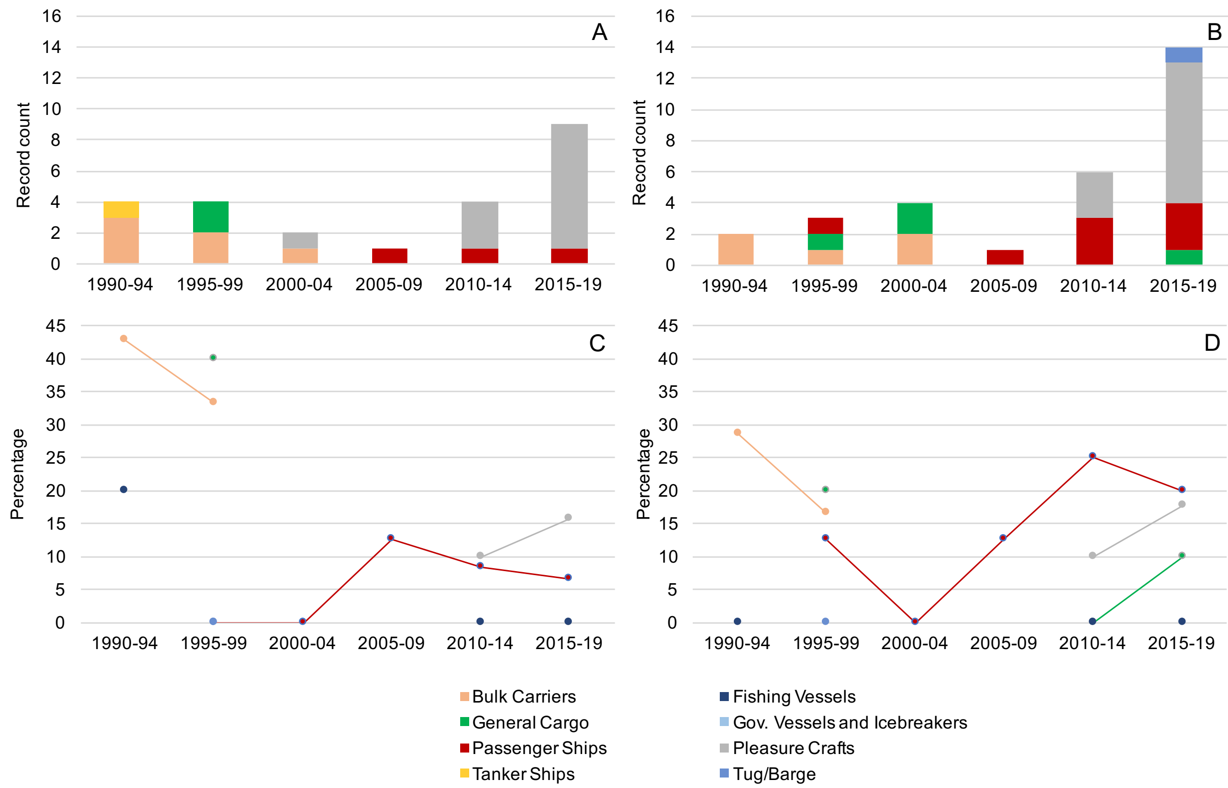


Figure F9: Unique ships counts in Lancaster Sound, by ship types, within: (A) high risk, and (B) elevated risk areas, as well as the percentage of all unique ships by ship type (where count > 4) for: (C) high risk, and (D) elevated risk areas.