Analysis of ship traffic and ship accidents in the Canadian and global Arctic

Adrian Nicoll

A thesis submitted to the

University of Ottawa

in partial fulfillment of the requirements for the degree of

Master of Science in Geography

Department of Geography

Faculty of Arts

University of Ottawa

Supervisors:

Dr. Jackie Dawson and Dr. Jérôme Marty

Thesis Committee:

Dr. Luke Copland and Dr. Michael Sawada

Table of Contents

List of Figures

List of Tables

Abstract

In the Canadian Arctic, ship traffic has been increasing at the same time as sea ice has been declining over the past decade-plus. The decrease in sea ice has been associated with trends in warm weather and atmospheric conditions in the summer seasons, which are expected to continue. Thus, it is anticipated that ship traffic will also continue to grow, as areas in the Arctic, including the Northwest Passage (NWP) and Northern Sea Route (NSR) experience less and less sea ice. The appeal of the opening of these major Arctic shipping routes, is that these routes are shorter in distance for commercial ships on international voyages in comparison to traditional routes that travel through the Panama and Suez Canals. Assuming safe and smooth sailing a shorter route can be beneficial monetarily for commercial shipping companies and as a result for other economic sectors reliant on the efficient shipment of goods. However, a major concern associated with the anticipated increase in Arctic ship traffic is the potential for an increase in the number and severity of maritime navigational related accidents. Thus, the overall aim of this thesis is to quantify recent historic links between ship traffic, sea ice, ship accidents, and accident rates within the Canadian Arctic as well as the global Arctic. There are three specific objectives including to:

1. Conduct a comparative statistical analysis between two ship traffic databases (NORDREG and AIS) within the Canadian Arctic to evaluate datasets strengths and weaknesses;

2. Use the best available data (see objective 1) to examine the statistical associations and trends for ship traffic, ship accidents, accident rates, and sea-ice extent within the Canadian Arctic during the shipping-season from 1990 to 2019; and

3. Derive and compare recent ship traffic accident rates to determine if statistical trends from 2012 to 2019 exist for ships across the global Arctic.

Results of the study show that both NORDREG and AIS data is useful in understanding shipping traffic trends in Arctic Canada over time and that each dataset is effective depending on the temporal period of interest (*Objective 1*). NORDREG data is most effective for identifying ship positioning before 2012 (+106,811 more nm sailed per matched unique vessels and +9 overall unique vessels from NORDREG) and from 2012 onwards AIS is more accurate, highlighted by the year of 2018 (+84,149 more nm sailed and +169 unique vessels from AIS).

Using available data sources from 1990 to 2019, it was revealed that although commercial and non-commercial ship traffic is increasing across in Arctic Canada, the total number of accidents and overall accident rate for commercial vessels has declined, whereas they have increased for non-commercial ships (*Objective 2*). There are significant positive trends in overall ship traffic for all ship types (+9,275 nm yr^{-1}), commercial ships (+5,011 nm yr^{-1}) and non-commercial ships (+4,658 nm yr^{-1}). Whereas there have been significant negative trends in ship accidents for commercial ships (-0.06 accidents yr^{-1}), ship accident rates, for all ship types (-6.31E-07 accidents/nm yr^{-1}). Sea ice extent at the monthly level during the shipping season has been significantly decreasing (-3,193 km^2 mo^{-1}). Results also indicate that there are significant negative correlations between monthly ship traffic and sea ice extent, for all ship types (-0.50), commercial ships (-0.49), and non-commercial ships (-0.48).

At the global scale, ship traffic is increasing while ship accident rates are decreasing (*Objective 3*). For the global Arctic there are positive statistically significant trends for all ship traffic (+2.655 million nm yr^{-1}), commercial ships (+1.598 million nm yr^{-1}), and non-commercial ships (+1.446 million nm yr^{-1}); where there are statistically significant annual decreases in ship accident rates for all ships (-3.64E-07 ship accidents/nm yr^{-1}), commercial ships (-9.39E-07 ship accidents/nm yr^{-1}), and non-commercial ships (-1.19E-07 ship accidents/nm yr^{-1}). At the country level, ship traffic associate to Russia, Norway, and Iceland contributes the most to global increase for both commercial and non-commercial ships. Norway has the largest statistically significant negative trend for all ship and commercial ship accident rates.

Future research should focus around expanding on the analytical approach taken for objective 3, as more years of AIS data become available, as currently, the focus is on a shorter time-period (2012 to 2019). Given that incident rates are low globally, for high impacts (i.e., large spills), working with a long time series allows for considering more incidents. It would also be beneficial to perform an analysis that determines if there are statistical associations between yearly accident rates and sea ice extent in the global Arctic, as well as for each country within the Arctic. This information can help to answer questions around ship safety in the global Arctic, specifically:

(a) Has the shipping become safer (e.g., less accidents per distance sailed) for the global Arctic and the countries within the Arctic?

(b) Are there statistical associations between sea ice extent and accident rates within the global Arctic and the countries within the Arctic?

(c) Are there countries associated with a higher incident rate compared to others? This information would help target measures to specific country ships that may be less safe for navigation.

Acknowledgements

From adult high school to graduate school, it has been an interesting journey! I would like to say a very warm thank you to my supportive immediate (Mark, Maria, and Julia) and extended family, friends, and loved ones (Nicole) that have helped me through this journey. A big thanks to Drs. Jackie Dawson and Jérôme Marty for their continued support, mentoring, and patience with me during my graduate studies. I would also like to thank my workplace (Transport Canada) for being fully supportive of my goal of pursuing my graduate degree while working full-time.

Chapter 1: Introduction

1.1 Problem statement

Sea ice has been declining in the Arctic over the past decade (Onarheim et al., 2018) as a result of both natural and anthropogenic processes (Ding et al., 2017), including warming trends and unique atmospheric conditions from the summer season (Outten et al., 2011; Frey et al., 2015; Ding et al., 2017; Onarheim et al., 2018). It has been estimated that, sometime around the mid to late century, the Arctic will be consistently and reliably ice-free in the summertime (Laliberté et al., 2016). In large part as a consequence of declining sea ice but also increased demand for natural resources, significant increases in ship traffic have been observed in recent years within the global Arctic (Huntington et al., 2015; Eguiliz et al., 2016; Eriksen et al., 2018), and including the Canadian Arctic (Pizzolato et al., 2014; Pizzolato et al., 2016; Chénier et al., 2017; Dawson et al., 2018; Halliday et al., 2018; Gunnarsson, 2021; Olsen et al., 2020; Stocker et al., 2020; Kochanowicz et al., 2021; Copland et al., 2021). Within the Canadian Arctic, ship traffic over the past decade has increased by approximately 75%, and the total distance travelled by ships in the region has nearly tripled (Johnston et al., 2017; Dawson et al., 2018).

It is expected that ship traffic will continue to increase as sea ice declines in the future (Smith & Stephenson, 2013; Melia et al., 2016), and it remains unclear the extent to which ship traffic in key trade corridors, such as Canada's Northwest Passage (NWP) and Russia's Northern Sea Route (NSR) will see increases in activity. These long sought-after Arctic Sea routes are desirable as they are much shorter in distance compared to regular routes through the Panama and Suez Canals that link Europe and East Asia (Stephenson et al., 2014; Aksenov et al., 2015). Previous research has indeed statistically correlated a decline in sea ice with increases in historic ship traffic, including stronger correlations in more recent years compared to the past (Pizzolato et al., 2014; Pizzolato et al., 2016). However, the extent to which overall ship traffic will increase in Canada's Arctic, and within the Northwest Passage, because of climate and other social changes remain disputed.

One of the main concerns associated with the expected increase in ship traffic, regardless of the extent or the relative increase in accessibility related to sea ice change, is the increased potential for accidents and incidents, leading to potentially important environmental and social impacts. Concerns are often associated with commercial vessels and risks such as possible oil spills from refined products and fuel oil (Marty et al., 2016) and maritime navigational-related accidents, such as ship-ship and ship-ice collisions (Stevenson et al., 2019). Comparing the Canadian Arctic to other maritime regions across Canada, it becomes clear that it has the highest accident rate per ship movement among commercial vessels (e.g., tankers, containerships, bulk carriers) at approximately ten accidents per 1,000 movements. Comparatively, the St. Lawrence region, where sea ice is also present for a part of the shipping season and where there is substantially more activity overall, has the second-highest accident rate per ship movement at approximately seven accidents per 1,000 movements (Council of Canadian Academies, 2016) (also see Marty et al., 2014).

There is an increasing need to understand better the historical commercial and non-commercial shipping patterns in the long and short-terms within the Arctic, as shipping in this region is currently and will be in the future, a foundation to connect the global economy (Brigham, 2011; Brigham, 2017). The decrease and change in sea ice within the Arctic are opening new shipping routes with the anticipation of more commercial (e.g., route-bound vessels such as cargo, container, dry bulk, tankers) and non-commercial (e.g., non-route bound ships such as government, passenger, pleasure vessel, tugs) shipping activity moving through these areas (Smith & Stephenson, 2013; Melia et al., 2016). An increase in ship traffic due to the decrease in sea ice could lead to more ship accidents and incidents and corresponding oil spills, as ship traffic is generally one of the main drivers of ship accidents and incidents (Mou et al., 2010; Silveira et al., 2013; Zhang et al., 2021). The increase in ship accidents and incidents can, in turn, can lead to the potential for pollution to occur in highly sensitive ecological areas (Stevenson et al., 2019; Dawson et al., 2020) where shipping safety management (e.g., infrastructure, response times) are also not established as other parts of the world and have shortcomings (Jensen, 2008; Knol & Arbo, 2014; Marchenko et al., 2018). To ensure that the analyses being conducted to quantify the links between ship traffic, sea ice, and ship accidents are vigorous, the best available data sources must be identified and used; otherwise, incorrect assumptions and problematic outputs are not truly representative of the conditions could be presented

1.2. Research aim and objectives

The overall aim of this thesis is to quantify recent historical links between ship traffic, sea ice, ship accidents, and accident rates within the Canadian Arctic as well as the global Arctic (North of the 60th parallel). To achieve this aim, three research objectives were established:

1. Conduct a comparative analysis between two ship traffic databases (NORDREG and AIS) within the Canadian Arctic to evaluate datasets strengths and weaknesses;

Objective 1 is presented in *Chapter 2*. The aim is to perform a comparative analysis between the NORDREG and AIS-derived datasets between 2011 to 2018 within the Canadian Arctic to understand the differences/similarities between the datasets. Ultimately, the research will help inform analysts and decision-makers on the differences between the two sources prior and provide a foundation for performing analyses/studies underlying policy decisions. It also justifies/rationale the ship traffic data sources used in *Chapter 2*. This manuscript is prepared for submission and is titled: *Examining the utility of non-spatial NORDREG data to model spatial shipping patterns in the Canadian Arctic (2011 to 2018)*. The co-authors of this manuscript are Drs. Jackie Dawson, Jérôme Marty, Luke Copland, and Michael Sawada.

2. Use the best available data (see objective 1) from 1990 to 2019 to examine the statistical associations and trends for ship traffic, ship accidents, accident rates and sea-ice extent within the Canadian Arctic during the shipping-season; and

Objective 2 is presented in *Chapter 3.* The study examines the statistical associations and trends for ship traffic, ship accidents, accident rates, and sea-ice extent within the Canadian Arctic during the shipping season (July to October) from 1990 to 2019. Studies have quantified the link between sea ice and ship traffic within the Canadian Arctic (Pizzolato et al., 2014; Pizzolato et al., 2016). This study builds on those before it by incorporating new and more recent data and attempting to quantify the link between ship accident rates and sea-ice extent, which has not been quantified within the Canadian Arctic. This manuscript is prepared for submission and is titled: *Evaluating the changing level of shipping accidents between commercial and non-commercial vessels operating in the Canadian Arctic during the open water season from 1990-2019*. The co-authors of this manuscript are Drs. Jackie Dawson, Jérôme Marty, Luke Copland, and Michael Sawada.

3. Derive and compare recent ship traffic accident rates to determine if statistical trends exist for ships across the global Arctic from 2012 to 2019.

Objective 3 is presented in *Chapter 4.* The objective of this study was to derive and compare ship traffic accident rates and determine any statistical trends exits for said rates in all ships, commercial ships, and non-commercial ships from 2012 to 2019 N60 and all-encompassing EEZs. This is the first study to use AIS combined with LRFP accident data to derive and assess trends for accidents rates N60. This manuscript is prepared for submission and is titled: *Shipping traffic accident trends across the global Arctic (60th parallel) (2012-19).* The co-authors on this manuscript are Drs. Jackie Dawson, Jérôme Marty, Luke Copland, and Michael Sawada.

1.3 Study areas

The main study area covered in this thesis research is the Arctic marine areas supporting maritime shipping activities. Specific focus areas include the Canadian Arctic’s Northern Canada Vessel Traffic Services Zone (NORDREG zone) maritime region including the Northwest Passage (NWP) and Arctic Bridge (AB) (Chapters 2 and 3) and all waters North of the 60th parallel (N60), including ten Exclusive Economic

Zones (EEZ) and three popular shipping corridors, including the NWP, AB, and Northern Sea Route (NSR) (Chapter 4) (Figure 1.1).

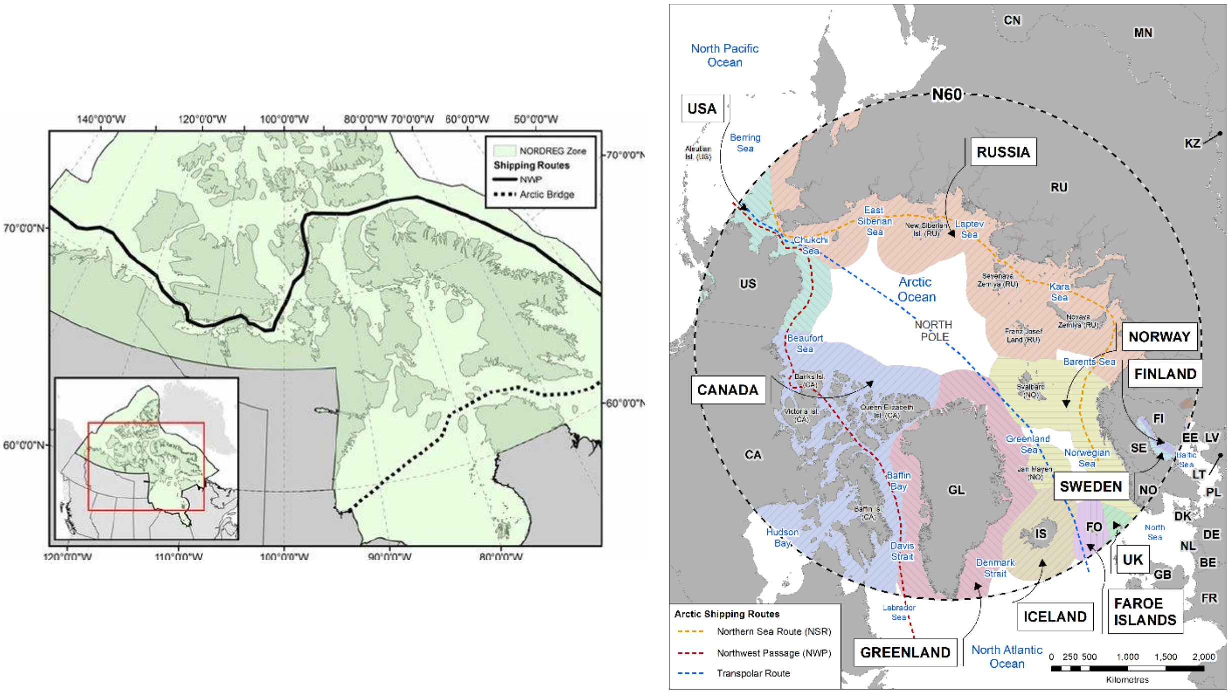


Figure 1.1: (Left map) NORDREG zone used for Chapters 2 and 3. (Pizzolato et al., 2014). (Right map) Study area used in Chapter 4.

1.4 Background and context

1.4.1 Arctic ship traffic

The increase in Arctic shipping observed for the last decades has been related to a decrease in sea ice leading to more frequent and longer ice-free areas (Pizzolato et al., 2016). The region is expected to be seasonally ice-free by the end of the 21st century (Laliberté et al., 2016). Arctic shipping generally comprises around 9% of the global shipping traffic and occupies between 57 to 80% of ice-free waters in the Arctic (Eguiliz et al., 2016). In general, Automatic Identification System (AIS) data show that more ships have been observed transiting through the Arctic (IPCC, 2022), including smaller ships since 2010 (Eriksen et al., 2018), indicating an overall increase in traffic AIS related ships.

As ship traffic rises across the Arctic and in regions of Canada where ice is prevalent and increasingly variable, safety measures that exist in other navigable waterways will need to be considered for implementation. For example, a way to regulate busy shipping routes is to implement Traffic Separation Schemes (TSS), which act as “highways” for maritime traffic and help to prevent maritime accidents (i.e., one of many safety measures). One TSS in the Arctic was recently (2018) approved by the International Maritime Organization (IMO) for the Bering Sea. However, even though there are relatively busy and dangerous routes in the Canadian Arctic, no IMO-approved TSS is located there, although they exist in other parts of Canada, such as the Gulf of St. Lawrence. Although there are no TSS’ within the Canadian Arctic, there are low-impact shipping corridors that aim to enhance the safety of maritime navigation (Dawson et al., 2020). These corridors have been adopted voluntarily (i.e., without IMO approval), and they were identified based on historical ship traffic patterns and volume, areas where maritime accidents are expected to occur, and culturally/ecologically/biologically sensitive areas.

Two of the most transited shipping routes in the Arctic are the Northwest Passage (NWP) in Canadian waters and the Northern Sea Route (NSR) in Russian waters, where traffic is generally concentrated from July to October during the ice-free season (Eguiliz et al., 2016). The NSR has been more frequented by ships travelling between Europe and East Asian ports than in the last two decades (Stephenson et al., 2014; Aksenov et al., 2015). The NSR route is approximately 6,000 nautical miles (nm) shorter than routes around the Cape of Good Hope (South Africa) and 2,700 nm shorter than routes around the Suez Canal (Aksenov et al., 2015). The NWP has also seen a large increase in ship traffic over the last decades. However, the recent increase in traffic has comprised mostly of pleasure crafts, while commercial ships are not transiting frequently in this area (Lassere et al., 2015). In general, communities around the NWP have seen large increases in ship traffic from the 1990s (1990-2000) to more recent years (2011-15) (Dawson et al., 2018).

Work has also been completed to create a more extensive database from 1990 to 2015 within the Canadian Arctic as an alternative to AIS-related information. This alternative database has been used in multiple studies (Pizzolato et al., 2014; Pizzolato et al., 2016; Dawson et al., 2018). Within the Canadian Arctic, an increase in overall unique ships was reported, from approximately 80 in 1990 to over 130 in 2015, where most of the spatial ship traffic increase from 1990 to 2015 occurred around the Beaufort Sea, NWP, and Eastern portions of the Canadian Arctic (Pizzolato et al., 2016). Within the Canadian Arctic, studies have linked the increase in ship traffic to the decrease of multi-year ice, one of the most significant correlations identified for August (Pizzolato et al., 2014). This indicates that the increase in ship traffic in August (over the years) is correlated with the decrease in sea ice.

The main datasets used to create the database for the studies were Canadian Coast Guard (CCG) Northern Canada Ship Traffic Services (NORDREG) data as the ship information, along with information on sea ice from weekly regional ice charts derived from the Canadian Ice Service Digital Archive (CISDA), bathymetry, and distance from the land were used with a spatial least-cost path (LCP) algorithm to estimate specific ship routes. Pizzolato et al. (2016) ran an error/sensitivity analysis with 25 random samples of the LCP-derived ship routes with S-AIS data (as the ground truth points) and found an error rate of approximately 8.5km. The benefit of this database is that it dates back much further than AIS can, allowing for the detection of longer-term trends in ship traffic within the Canadian Arctic. The limitation of this dataset is that tracks are modelled and are less spatially accurate than AIS.

Other factors at play are and will continue to increase ship traffic within the Canadian Arctic, which can be attributed to commodity prices, global economic trends (Lassere et al., 2015; AMAP 2018), last chance tourism (Lemelin et al., 2010; Dawson et al., 2014), and resource extraction projects (e.g., Baffinland Mary River Iron Ore Mine) with increases in bulk carrier traffic.

1.4.2 Arctic ship accidents

As shipping traffic and the overall number of ships increase in the Arctic due to changes in environmental conditions (i.e., decrease in sea ice, increase in temperature), it is expected there could also be increases/higher probability of ship accidents and pollution events (Hartsig et al., 2012; Marchenko et al., 2018). Ships will start to navigate in waters that are not charted/serviced as sea ice decreases, as currently, the Canadian Arctic has a limited infrastructure. For example, there are gaps in Electronic Navigation Charts (ENC) (that provide invaluable information for ship operators) for portions of the Canadian Arctic, including the Hudson Bay, Foxe Basin, Northern portions of the Beaufort Sea, and Northern Baffin Bay. The Canadian Arctic is also poorly serviced in terms of emergency response capacity. An example is that there are no oil spill response organizations North of the 60th parallel (whereas the rest of the country, south of the 60th parallel, has response organizations in place in case of ship-source oil spills).

Concerning waterways, it has been found that most reported commercial ship-related accidents in Northern Canada were around Harbor Areas or Lakes/Bays. It was found that about half of all maritime accidents from 1993 to 2011 (out of 65 accidents/incidents analyzed) North of the 66th parallel was recorded in the high seas (i.e., open water) by the Marine Accident Investigation Branch (Kum et al., 2015). While most of the accident types were accidents relating to a person (e.g., injury or death), most ships involved in the accidents were cruise ships and fishing ships. They found that design inadequacy and heavy weather were the root causes of technical-related accidents.

The Canadian Council of Academies (2016) assessed commercial marine shipping accidents in Canadian waters using data from the Transportation Safety Board (TSB) on accidents and incidents from 2004 to 2015 from liquid and solid cargo ships (e.g., bulk carriers, containerships, chemical tankers, crude oil tankers), which are generally indicative of the larger sized ships.

Shipping accidents involving sold/liquid cargo ships are declining. Generally, most accidents/incidents were historically located in St. Lawrence, while the least number of accidents/incidents were in Northern Canada. However, it was found that the highest accident rate per ship movement was in Northern Canada, followed by St. Lawrence – which indicates that ships are getting into more issues in Northern Canada and St. Lawrence than anywhere else in Canadian waters.

1.4.3 Environmental conditions affecting navigation

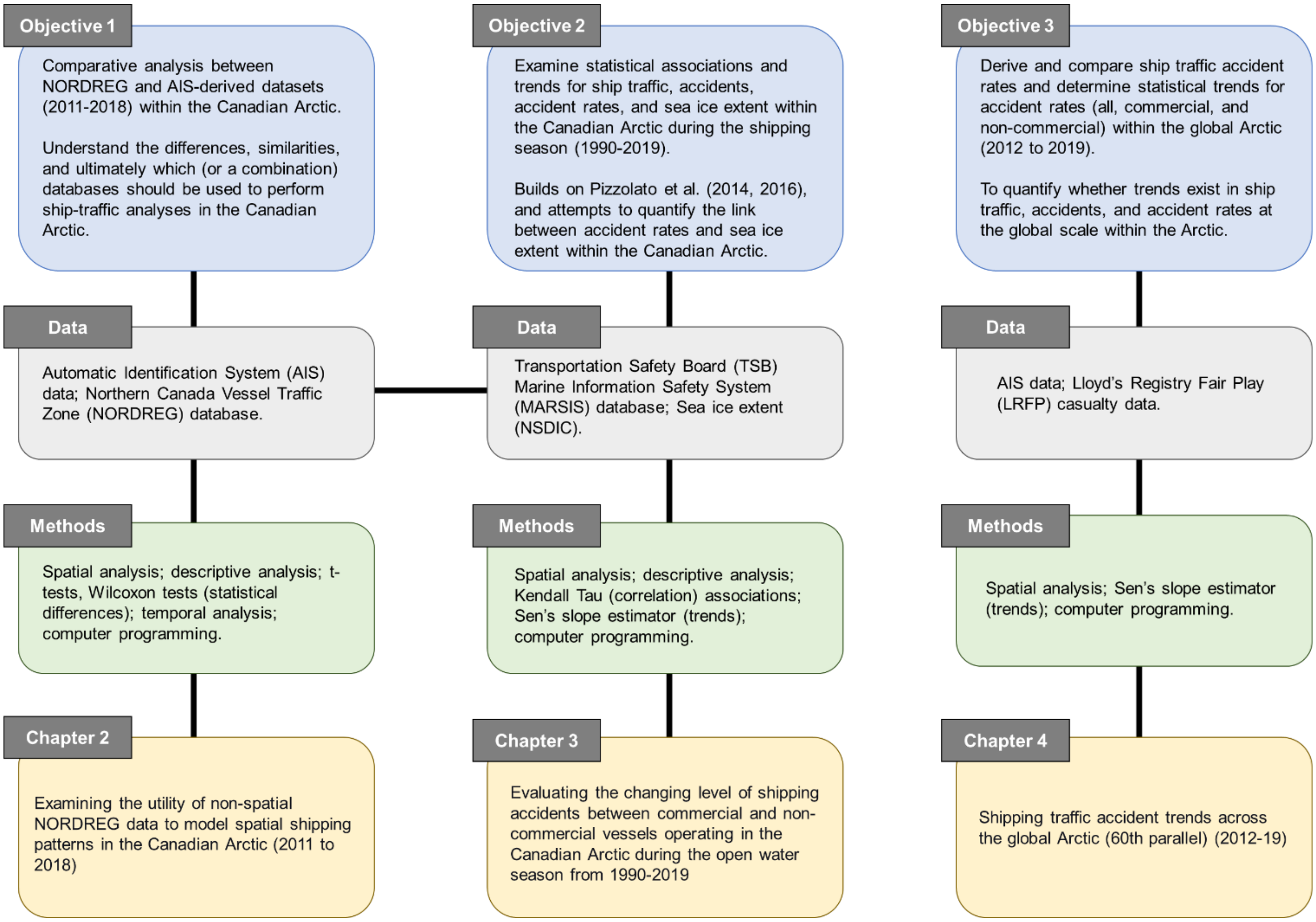
In the Arctic, during the sea ice minimum (September), areas with the fastest sea ice decline from 1979 to 2014 include the Beaufort Sea (where the NWP passes through), Chukchi, and East Siberian Seas (Ding et al., 2017). The identified areas had an average of >10% per decade decrease in sea ice; the decrease is influenced by atmospheric circulation. As sea ice in September decreases in these areas, other environmental conditions, including temperature, humidity, and downward longwave radiation (also influenced by atmospheric circulation) for summertime (June, July, and August), are increasing. The maximum sea-ice extent in the Arctic generally occurs during March (Maksym, 2019).

Onarheim et al. (2018) looked at the long-term (1950-2013) and recent (1979-2016) regional variations in sea ice concentration in the Northern Hemisphere for different seasons by using sea ice extremes (March being the sea ice maximum and September being the sea ice minimum). The study used the NSIDC-0051 data to examine the recent sea ice variability and trends in the Northern Hemisphere. Their findings indicated that the annual, monthly mean sea ice extent has decreased by 2.0 x 10-6 km^2, and the month with the largest decrease from 1979 to 2016 was September (sea ice minimum), with a decrease of 45%. There was only a 9% decrease in March (sea ice maximum). However, regional differences in sea ice decrease varied vastly by region. The study found that four regions (the Barents Sea, the Sea of Okhotsk, the Greenland Sea, and the Baffin Bay/Gulf of St. Lawrence) contributed 81% to the interannual variance of sea ice extent in March.

As previously described, there are strong linkages between increased summertime temperatures and decreased sea ice in September in the Arctic from 1979 to 2014 (Ding et al., 2017). Arctic air temperature has increased over the last decades (IPCC, 2021) and exceeded Northern Hemisphere averages substantially by a factor of 2 (Overland et al., 2016). Increasing temperatures can be associated with geopotential height, leading to changes in wind patterns (Overland et al., 2016).

1.5 Organization of the thesis

This thesis is presented in article-based *format and* includes three scientific papers that directly respond to outlined thesis research objectives (see section 1.2), as well as this introductory chapter, and a final concluding chapter. The first scientific paper, (*Chapter 2 – objective 1*) is the first study to provide a fulsome comparative analysis between two ship databases commonly used in the Canadian Arctic and is used iteratively in this study, and can be relied upon by others, to support the choice and use of certain datasets under certain circumstances *to* enhance analysis validity. The second scientific paper (*Chapter 3 – objective 2*) uses findings from Chapter 2 and builds upon research conducted by Pizzolato et al. (2014) in the Canadian Arctic by incorporating new and updated data sources (e.g., AIS, more recent years of sea ice data, ship accident data) and by considering long-term statistical trends and correlations associated with ship accident rates in the Canadian Arctic. The final scientific paper (*Chapter 4* – objective 3) is the first study to use AIS data with Lloyd’s Register FairPlay (LRFP) accident data to derive and assess annual short-term statistical trends for accident rates North of the 60th (N60) parallel and encompassing the EEZs for polar nations globally. Chapter 5 concludes the thesis, discussing the summary of key results, relevant contributions (methodological, policy, and scientific), the limitations associated with each scientific paper, and potential future work.



Objective 1

Comparative analysis between NORDREG and AIS-derived datasets (2011-2018) within the Canadian Arctic.

Understand the differences, similarities, and ultimately which (or a combination) databases should be used to perform ship-traffic analyses in the Canadian Arctic.

Data

Automatic Identification System (AIS) data; Northern Canada Vessel Traffic Zone (NORDREG) database.

Methods

Spatial analysis; descriptive analysis; t-tests, Wilcoxon tests (statistical differences); temporal analysis; computer programming.

Chapter 2

Examining the utility of non-spatial NORDREG data to model spatial shipping patterns in the Canadian Arctic (2011 to 2018)

Objective 2

Examine statistical associations and trends for ship traffic, accidents, accident rates, and sea ice extent within the Canadian Arctic during the shipping season (1990-2019).

Builds on Pizzolato et al. (2014, 2016), and attempts to quantify the link between accident rates and sea ice extent within the Canadian Arctic.

Data

Transportation Safety Board (TSB) Marine Information Safety System (MARSIS) database; Sea ice extent (NSDIC).

Methods

Spatial analysis; descriptive analysis; Kendall Tau (correlation) associations; Sen's slope estimator (trends); computer programming.

Chapter 3

Evaluating the changing level of shipping accidents between commercial and non-commercial vessels operating in the Canadian Arctic during the open water season from 1990-2019

Objective 3

Derive and compare ship traffic accident rates and determine statistical trends for accident rates (all, commercial, and non-commercial) within the global Arctic (2012 to 2019).

To quantify whether trends exist in ship traffic, accidents, and accident rates at the global scale within the Arctic.

Data

AIS data; Lloyd's Registry Fair Play (LRFP) casualty data.

Methods

Spatial analysis; Sen's slope estimator (trends); computer programming.

Chapter 4

Shipping traffic accident trends across the global Arctic (60th parallel) (2012-19)

Figure 2.2: The thesis' conceptual framework. This framework provides an overview to the flow and connections of all the chapters, including the three analytical chapters (Chapters 2 to 4).

1.6 References cited in chapter 1

Aksenov, Y., Popova, E. E., Yool, A., Nurser, A. J. G., Williams, T. D., Bertino, L., & Bergh, J. (2017). On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice. Marine Policy, 75, 300–317. https://doi.org/10.1016/j.marpol.2015.12.027

AMAP. (2018). Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xvi + 354pp

Brigham, L. (2011). Marine protection in the Arctic cannot wait. Nature, 478(7368), 157-

157. doi: 10.1038/478157a

Brigham, L. (2017). The changing maritime arctic and new marine operations. In R. Beckman, T. Henriksen, K. Kraabel, E. Molenaar, & J. Roach (Eds.), Governance of Arctic shipping - balancing rights and interests of Arctic states and user states (pp. 3–23). Leiden: Brill Nijhoff

Chénier, R., Abado, L., Sabourin, O., & Tardif, L. (2017). Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. Transactions in GIS, 21 (6), 1085–1097

Copland, L., Dawson, J., Tivy, A., Delaney, F., Cook, A., and Creed, I. (2021). Changes in shipping navigability in the Canadian Arctic between 1972 and 2016. Facets 6, 1069–1087. doi: 10.1139/facets-2020-0096

Council of Canadian Academies. (2016). Commercial marine shipping accidents: understanding the risks in Canada : workshop report. Available at https://clearseas.org/wp-content/uploads/2016/04/CofCA_16-111_Clear-Seas_Book_e_web.pdf. Accessed March 2019.

Dawson, J., Johnston, M. E., & Stewart, E. J. (2014). Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. Ocean & Coastal Management, 89, 88–99. https://doi.org/10.1016/j.ocecoaman.2013.12.005

Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., & Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015 + Supplementary Appendix 1: Figs. S1–S7 (See Article Tools). ARCTIC, 71(1), 15. https://doi.org/10.14430/arctic4698

Dawson, J., Carter, N., van Luijk, N., Parker, C., Weber, M., & Cook, A. et al. (2020). Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. Environmental Science & Policy, 105, 19-36. doi: 10.1016/j.envsci.2019.11.013

Ding, Q., Schweiger, A., L'Heureux, M., Battisti, D. S., Po-Chedley, S., Johnson, N. C., … Steig, E. J. (2017). Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. Nature Climate Change, 7(4), 289–295. https://doi.org/10.1038/nclimate3241

Eguíluz, V. M., Fernández-Gracia, J., Irigoien, X., & Duarte, C. M. (2016). A quantitative assessment of Arctic shipping in 2010–2014. Scientific Reports, 6(1). https://doi.org/10.1038/srep30682

Eriksen, T., & Olsen, Ø. (2018). Vessel Tracking Using Automatic Identification System Data in the Arctic. In L. P. Hildebrand, L. W. Brigham, & T. M. Johansson (Eds.), Sustainable Shipping in a Changing Arctic (Vol. 7, pp. 115–136). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-78425-0_7

Frey, K. E., Moore, G. W. K., Cooper, L. W., & Grebmeier, J. M. (2015). Divergent patterns of recent sea ice cover across the Bering, Chukchi, and Beaufort seas of the Pacific Arctic Region. Progress in Oceanography, 136, 32–49. https://doi.org/10.1016/j.pocean.2015.05.009

Gross, M. (2018). Arctic shipping threatens wildlife. Current Biology, 28(15), R803-R805. doi: 10.1016/j.cub.2018.07.053

Gunnarsson, B. (2021) Recent ship traffic and developing shipping trends on the Northern Sea Route—Policy implications for future arctic shipping. Mar. Policy, 124, 104369.

Hartsig, A., I. Frederickson, C. Yeung, and S. Senner "Arctic Bottleneck: Protecting the Bering Strait Region from Increased Vessel Traffic." Ocean & Coastal LJ 18 (2012): 35–

88.

Huntington, H. P., Daniel, R., Hartsig, A., Harun, K., Heiman, M., Meehan, R., … Stetson, G. (2015). Vessels, risks, and rules: Planning for safe shipping in Bering Strait. Marine Policy, 51, 119–127. https://doi.org/10.1016/j.marpol.2014.07.027

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

IPCC. (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.). Cambridge University Press. In Press.

Jensen, Ø. (2008). Arctic shipping guidelines: towards a legal regime for navigation safety and environmental protection?. Polar Record, 44(2), 107-114. doi: 10.1017/s0032247407007127

Johnston, M., Dawson, J., De Souza, E., & Stewart, E. (2017). Management challenges for the fastest growing marine shipping sector in Arctic Canada: Pleasure crafts. Polar Record, 53(1), 67-78. https://doi:10.1017/S0032247416000565
Knol, M., & Arbo, P. (2014). Oil spill response in the Arctic: Norwegian experiences and future perspectives. Marine Policy, 50, 171-177. doi: 10.1016/j.marpol.2014.06.003

Kochanowicz, Z., Dawson, J., Halliday, W. D., Sawada, M., Copland, L., Carter, N. A., Nicoll, A., Ferguson, S. H., Heide-Jørgensen, M. P., Marcoux, M., Watt, C., &; Yurkowski, D. J. (2021). Using western science and Inuit knowledge to model ship-source noise exposure for cetaceans (marine mammals) in Tallurutiup Imanga (lancaster sound), Nunavut, Canada. Marine Policy, 130, 104557. https://doi.org/10.1016/j.marpol.2021.104557

Kum, S., and B. Sahin. 2015. “A Root Cause Analysis for Arctic Marine Accidents from 1993 to 2011.” Safety Science 74: 206–220. doi:10.1016/j.ssci.2014.12.010.

Laliberté, F., Howell, S. E. L., & Kushner, P. J. (2016). Regional variability of a projected sea ice-free Arctic during the summer months: REGIONAL SUMMER SEA ICE PROJECTIONS. Geophysical Research Letters, 43(1), 256–263. https://doi.org/10.1002/2015GL066855

Lasserre, F., & Alexeeva, O. (2015). Analysis of Maritime Transit Trends in the Arctic Passages. In International Law and Politics of the Arctic Ocean. Leiden, The Netherlands: Brill | Nijhoff. doi: https://doi.org/10.1163/9789004284593_010

Lemelin, H., Dawson, J., Stewart, E. J., Maher, P., & Lueck, M. (2010). Last-chance tourism: The boom, doom, and gloom of visiting vanishing destinations. Current Issues in Tourism, 13(5), 477-493.

Maksym, T. (2019). Arctic and Antarctic Sea Ice Change: Contrasts, Commonalities, and Causes. Annual Review of Marine Science, 11(1), 187-213. https://doi:10.1146/annurev-marine-010816-060610

Marchenko, N.A.; Andreassen, N.; Borch, O.J.; Kuznetsova, S.Y.; Ingimundarson, V.; Jakobsen, U. Arctic shipping and risks: emergency categories and response capacities. Int. J. Mar. Navig. Saf. Sea Transp. 2018, 12, 107–114

Marty, J., & Potter, S. (2014). Risk Assessment for Marine Spills in Canadian Waters, Phase 1: Oil Spills South of the 60th Parallel. WSP Canada.

Marty, J., A. Nicoll, S. Potter, M. Wallace, and C. Lumière. (2016). Evaluation of the Risk of Oil Spills in Canadian Arctic Waters. Proceedings of the Thirty-ninth AMOP Technical Seminar, Environment and Climate Change Canada. Ottawa, ON. 1035-1046.

Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st century trans-Arctic shipping routes: Trans-Arctic shipping in the 21st Century. Geophysical Research Letters, 43(18), 9720–9728. https://doi.org/10.1002/2016GL069315

Mou, J., Tak, C., & Ligteringen, H. (2010). Study on collision avoidance in busy waterways by using AIS data. Ocean Engineering, 37(5-6), 483-490. doi: 10.1016/j.oceaneng.2010.01.012

Olsen, J., Hovelsrud, G. K. & Kaltenborn, B. P. Increasing Shipping in the Arctic and Local Communities' Engagement: A Case from Longyearbyen on Svalbard. In Arctic Marine Sustainability (eds Pongrácz, E. et al.) 305–331 (Springer, Berlin, 2020).

Onarheim, I. H., Eldevik, T., Smedsrud, L. H., & Stroeve, J. C. (2018). Seasonal and Regional Manifestation of Arctic Sea Ice Loss. Journal of Climate, 31(12), 4917–4932. https://doi.org/10.1175/JCLI-D-17-0427.1

Outten, S. D., & Esau, I. (2012). A link between Arctic sea ice and recent cooling trends over Eurasia. Climatic Change, 110(3–4), 1069–1075. https://doi.org/10.1007/s10584-011-0334-z

Overland, J. E., Dethloff, K., Francis, J. A., Hall, R. J., Hanna, E., Kim, S.-J., Screen, J. A., Shepherd, T. G. and Vihma, T. (2016). Nonlinear response of mid-latitude weather to the changing Arctic. Nature Climate Change, 6 (11). pp. 992-999. ISSN 1758-678X doi: https://doi.org/10.1038/nclimate3121

Pizzolato, L., Howell, S. E. L., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic: SEA ICE AND SHIPPING, CANADIAN ARCTIC. Geophysical Research Letters, 43(23), 12,146-12,154. https://doi.org/10.1002/2016GL071489

Pizzolato, L., Howell, S. E. L., Derksen, C., Dawson, J., & Copland, L. (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Climatic Change, 123(2), 161–173. https://doi.org/10.1007/s10584-013-1038-3

Silveira, P., Teixeira, A., & Soares, C. (2013). Use of AIS Data to Characterise Marine Traffic Patterns and Ship Collision Risk off the Coast of Portugal. Journal Of Navigation, 66(6), 879-898. doi: 10.1017/s0373463313000519

Smith, L. C., & Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sciences, 110(13), E1191–E1195. https://doi.org/10.1073/pnas.1214212110

Stephenson, S. R., Brigham, L. W., & Smith, L. C. (2014). Marine accessibility along Russia's Northern Sea Route. Polar Geography, 37(2), 111–133. https://doi.org/10.1080/1088937X.2013.845859

Stevenson, T. C., Davies, J., Huntington, H. P., & Sheard, W. (2019). An examination of trans-Arctic vessel routing in the Central Arctic Ocean. Marine Policy, 100, 83–89. https://doi.org/10.1016/j.marpol.2018.11.031

Stocker, A. N., Renner, A. H. H., & Knol-Kauffman, M. (2020). Sea ice variability and maritime activity around Svalbard in the period 2012–2019. Scientific Reports, 10(1), 17043. https://doi.org/10.1038/s41598-020-74064-2

Zhang, Y., Sun, X., Chen, J., & Cheng, C. (2021). Spatial patterns and characteristics of global maritime accidents. Reliability Engineering & System Safety, 206, 107310. doi: 10.1016/j.ress.2020.107310

Chapter 2: Examining the utility of non-spatial NORDREG data to model spatial shipping patterns in the Canadian Arctic (2011 to 2018)

Adrian Nicoll[12], Jackie Dawson[1], Jérôme Marty[34], Luke Copland[1], and Michael Sawada[1]

[1] Department of Geography, Environment, and Geomatics, University of Ottawa, Canada
[2] Transport Canada
[3] Council of Canadian Academies
[4] International Association for Great Lakes Research

Planed for submission to: *Transport Geography*

Author's declaration: *I am the first author on this scientific paper, performed all the data analyses, and contributed significantly to the methodology design and writing of the final manuscripts. This scientific paper was designed, written, and revised in partnership with Drs. Jackie Dawson, Jérôme Marty, Luke Copland, and Michael Sawada.*

2.1 Abstract

There has been a large increase in ship traffic within the Canadian Arctic over the past decades as ship navigability has increased concurrent with changes in climate and economic trends. In the Canadian Arctic, several data sources are available for understanding ship traffic patterns in the region. Two main sources have typically been used for scientific analysis in this region in order to understand historic temporal and spatial traffic patterns these include; 1) Northern Canada Vessel Traffic Zone (NORDREG) managed by the Canadian Coast Guard and 2) satellite-based Automatic Identification System (AIS) that is managed by different private sector companies. Anecdotally, there seems to be varying advantages and disadvantage of each of these datasets, yet to date there has been no comprehensive comparative analysis to determine the utility of the data for use in scientific initiatives and for decision-making. To address this methodological knowledge gap, a detailed analytical and statistical comparison of NORDREG data and AIS data was completed using spatial and comparative time-series analyses. Findings of the comparative and statistical data analysis revealed that NORDREG in comparison to AIS captures more unique ships (9 more unique ships) and is more accurate in distance sailed metric for all ships contained within both databases (106,811 more nm sailed) in 2011. From 2012 onwards, AIS captures more unique ships and is more accurate in distance sailed metrics for ships contained within both databases, highlighted by 2018 (169 more unique ships; 84,149 more nm sailed).

Keywords: *Ship traffic; Canadian Arctic; AIS; NORDREG; Comparative data analysis*

2.2 Introduction

Over the past two decades, an increase in ship traffic has been observed within the Canadian Arctic (Pizzolato et al., 2014; Pizzolato et al., 2016; Chénier et al., 2017; Dawson et al., 2018; Halliday et al., 2018; Kochanowicz et al., 2021). Increased activity has been linked to several economic trends, including growing demand for adventure and expedition tourism experiences (Dawson et al., 2009; Stewart et al., 2009; Stewart et al., 2010; Lasserre & Têtu, 2013; Stewart et al., 2013; Bystrowska, 2019; Palma et al., 2019; Steiner et al., 2021), commercial and non-commercial fishing opportunities (Huntington, 2009; Christiansen et al., 2013; Shephard et al., 2016; Galappaththi et al., 2019; Tai et al., 2019), exploration and operation of natural resource mines (i.e., oil, gas, precious metals) (Hasle et al., 2009; Keil, 2013; Haley et al., 2011; Harsem et al., 2011; Têtu et al., 2015; Claes & Moe, 2018; Tolvanen et al., 2019), community re-supply needs and demographic trends (Brooks et al., 2012; Giguère et al., 2017; Carter et al., 2018; Carter et al., 2020; Islam et al., 2020), and a global desire for Arctic trade (Bennett et al., 2020; Zeng et al., 2020). The changing environmental and geopolitical landscape of the Arctic, which includes a warming rate of 3-4 times the global average (Miller et al., 2010; Bintanja et al., 2013), disputed sovereignty of the Northwest Passage (Huebert, 2001; Lalonde & Lasserre, 2013; Lu et al., 2013), and instability in Russia (i.e., the largest Arctic nation) has increased the importance and need to have reliable and robust data and understanding of shipping traffic trends that can then be used to answer a wide range of scientific, strategic, and political questions. For example, ship traffic data has and can be used to support marine protected areas development (Shelmerdine, 2015), model underwater noise impacts (Halliday et al., 2017; Halliday et al., 2021), interactions with marine mammals (Guzman et al., 2012; Martin et al., 2022) evaluate potential economic and development opportunities (Cheng et al., 2018), to understand navigation risks related to climate change (Löptien et al., 2014; Copland et al., 2021; Dawson et al., 2022), ship-to-ship and ship-to-object interactions (Van Iperen, 2015; Zhang et al., 2015; Altan & Otay, 2018; Schultz & Bourne, 2019), traffic management and waterway design (Mou et al., 2010), and risks from navigation such as ship accidents and oil spills (Eide et al., 2007; Akhtar et al., 2011; Marty et al., 2016; Bye et al., 2018).

Studies that have included analysis of shipping traffic trends in Arctic Canada rely on several different data sets, such as Long-Range Identification and Tracking (LRIT), Northern Canada Vessel Traffic Zone (NORDREG), Automatic Identification System (AIS), Vessel Monitoring Systems (VMS); as well as analytic providers such as MarineTraffic.com, Lloyds, and IHS-Markit. The two most used sources of ship traffic data to quantify historic shipping activities and patterns in Arctic Canada are the Northern Canada Vessel Traffic Zone (NORDREG) and Automatic Identification System (AIS) data. Based on anecdotal observations, there are some differences in the two data sets over different periods. However, a comparative analysis has never been completed to understand the varying utility of these two main sources of ship traffic data. Thus, this study aimed to address this gap to understand better which data sources may provide the highest level of accuracy for use in historical, current, and future ship traffic analyses within the Canadian Arctic.

To compare the two readily available sources of derived ship traffic data within the Canadian Arctic (NORDREG and satellite-based AIS) for the purpose of better understanding the differences or similarities between the two, in this study we: 1) conducted a descriptive analysis of ship traffic derived from NORDREG and Satellite-based AIS in the Canadian Arctic, and 2) identify and compare (statistically) the unique ships that are shared from NORDREG and Satellite-based AIS in the Canadian Arctic from 2011 to 2018 .

2.3 Study methods

2.3.1 Data sources and background

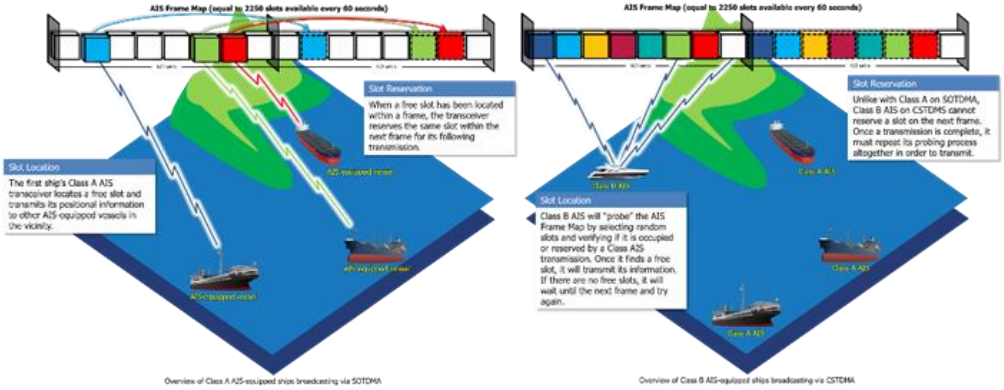
There are several sources of ship traffic data that can be consulted to understand traffic patterns in Arctic Canada. In recent studies for the region, the two main sources of data that is most typically used include Canadian Coast Guard derived data, called NORDREG (2.3.1.1) and Automatic Identification System data that is derived through several private sector companies including extactEarth (now Spire) (2.3.1.2).

2.3.1.1 NORDREG

The Northern Canada Vessel Traffic Zone (i.e., NORDREG zone) is managed by the Canadian Coast Guard's (CCG) Marine Communications and Traffic Services (MCTS) Centre, which is in Iqaluit, Nunavut. The NORDEG zone captures all marine waters within the Canadian Arctic (including Hudson Bay). Vessels must report a daily position report to the MCTS Centre, which would then be captured within the NORDREG database. Vessels that must report to NORDREG are (1) vessels of 300 Gross Tonnes (GT); (2) vessels engaged in towing or pushing another vessel if the combined gross tonnage of the vessel and the vessel being towed or pushed is 500 GT or more; and (3) vessels that are carrying as cargo a pollutant or dangerous goods, or that are engaged in towing or pushing a vessel that is carrying as cargo a pollutant or dangerous good. Pizzolato et al. 2014 and 2016 provide a detailed description of this data source and more information on these data can be found there.

2.3.1.2 Automatic Identification System (AIS)

Automatic Identification System (AIS) is an automated tracking system that is fitted onboard certain vessels (i.e., AIS transponder). AIS broadcasts information relating to the movement of the vessel and the vessel itself while operating in the Very High Frequency (VHF) maritime radio band, generally using Self-Organizing Time Division Multiple Access (SOTDMA) and Carrier-Sense Time division Multiple Access (CSTDMA) technologies to broadcast frequently (figure 2.1).



Slot Location

The first ship's Class A AIS transceiver locates a free slot and transmits its positional information to other AIS-equipped vessels in the vicinity.

Slot Reservation

When a free slot has been located within a frame, the transceiver reserves the same slot within the next frame for its following transmission.

Overview of Class A AIS-equipped ships broadcasting via SOTDMA

Slot Location

Class B AIS will "probe" the AIS Frame Map by selecting random slots and verifying if it is occupied or reserved by a Class AIS transmission. Once it finds a free slot, it will transmit its information. If there are no free slots, it will wait until the next frame and try again.

Slot Reservation

Unlike with Class A on SOTDMA, Class B AIS on CSTDMS cannot reserve a slot on the next frame. Once a transmission is complete, it must repeat its probing process altogether in order to transmit.

Overview of Class B AIS-equipped ships broadcasting via CSTDMA

Figure 2.1: Schematic view from the Canadian Coast Guard on SOTDMA (left figure, generally used by Class A vessels) and CSTDMA (right figure, generally used by Class B vessels) (from E-Nav-CCG, 2019).

AIS was originally intended as a navigation safety tool (collision avoidance) for ship-to-ship communication. The broadcasted messages sent out by an AIS transponder can be collected by terrestrial and satellite receivers (figure 2.2). 27 AIS message types can be exchanged through the AIS system, vessels generally providing dynamic (e.g., GPS position, speed, course) and static information (e.g., vessel name, vessel size, destination) about a vessel. The transponders send out dynamic information at a much more frequent rate than static information.

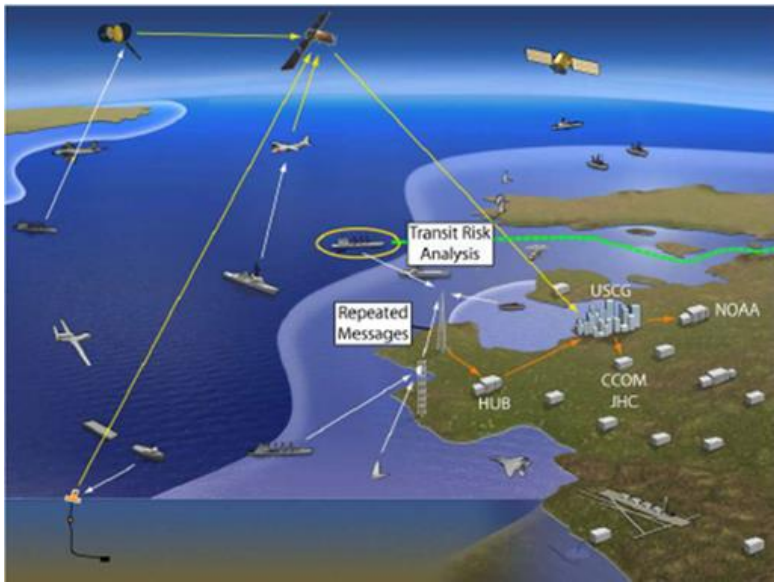


Figure 2.2: Schematic view from the United States Coast Guard of how AIS messages are transmitted and received from vessel to vessel/satellite or terrestrial receiver (from Calder et al., 2009).

Internationally, (1) all vessels that are greater than 300 GT and engaged in an international voyage, or (2) cargo vessels with GT of greater than 500 not engaged in an international voyage, or (3) all passenger ships, regardless of size are required to carry Class A[1] AIS transponders on board, per regulation 19 of the International Convention for the Safety of Life at Sea (SOLAS) Chapter V, as of December 31, 2004.

---

[1] Class A AIS transponders are mandatory on all ships of over 300GT on international voyages since December 31, 2004 (as per SOLAS). A Class AIS transponder broadcasts positional messages every 2 to 10 seconds while underway, and every 3 minutes while at anchor. Messages are sent at a power level of 12.5 watts, and are picked up by satellite receivers well, due to the strong power levels.

Class B[2] transponders are voluntary and are generally equipped aboard smaller vessels (e.g., pleasure vessels, small fishing vessels). Class A transponders can emit dynamic information every 2 to 10 seconds while underway, whereas Class B transponders can emit dynamic information every 30 to 180 seconds.

One of the main differences between the two transponders is that Class A transponders, in comparison to Class B transponders, broadcast messages at a more frequent rate along with a stronger signal power (12.5 watts compared to 1-2 watts), making it easier for satellite and terrestrial receivers to pick-up Class A messages than Class B messages. Although Class B transponders are voluntary, they are becoming more common to be voluntarily fitted onboard vessels (i.e., Class B transponders have become more affordable). This is especially true in the Arctic, where it has been reported that there has been an increase from approximately 100 recorded in 2010 to approximately 500 recorded vessels in 2014 using Class B transponders (Eriksen et al., 2018).

In Canada, AIS carriage requirements are regulated by Transport Canada (TC) as per the federal Navigation Safety Regulations (paragraph 65); as of June 15, 2019[3].

1. Every vessel of 150GT or more that is carrying more than 12 passengers and engaged on an international voyage shall be fitted with an Automatic Identification System (AIS) Class A.

2. Every vessel, other than a fishing vessel, of 300GT or more that is engaged on an international voyage shall be fitted with an AIS Class A.

---

[2] Class B AIS transponders are meant for smaller vessels, and generally are used voluntarily. Class B positional messages are sent at lower power levels (2 watts) in comparison to Class A, therefore they have a more difficult time reaching satellites due to the low power (terrestrial receivers are often much closer in proximity to the vessels than satellites).

[3] They have changed since June 2019, but the current regulation is not relevant to this study.

3. Every vessel, other than a fishing vessel, of 500GT or more that is not engaged on an international voyage shall be fitted with an AIS Class A.

4. Every vessel, other than a vessel subject to subsections (1) to (3), that is engaged on a voyage other than a sheltered waters voyage shall be fitted with an AIS Class A that meets the standards specified at item 15 of Schedule 1 or an AIS Class B if:

    a) the vessel is certified to carry more than 12 passengers; or
    b) the vessel is eight metres or more in length and is carrying passengers.

There are some limitations with AIS messages in general; for example, it is not mandatory for all vessels to carry AIS on them, so many smaller vessels (i.e., small recreational vessels) are usually not captured. There are also many threats relating to the security of AIS messages; there have been reported cases and potential for spoofing (e.g., ship positions, aids to navigation, ship-collision, search & rescue, and weather forecasting), hijacking and availability disruption (Balduzzi et al., 2014). There have been reports of fishing vessels practicing spoofing their positions to fish illegally and ensure their locations are not detected (Natale et al., 2015; Ray et al., 2015).

Generally, AIS information is recorded by terrestrial (i.e., land-based) and satellite-based AIS receivers. There are a couple of main differences between the two:

1) Spatial coverage

- A network of terrestrial receivers can generally only receive AIS messages from approximately (on average, it depends on other factors) 40-50 nautical miles from where a terrestrial receiver is placed.

- A constellation of satellites can receive AIS messages globally; the constellation of satellites follows a Low Earth orbit (LEO).

2) Temporal resolution

- Latency and revisit time from positionally related satellite AIS messages can vary greatly, based on the satellite's position and how fast and frequent it revisits the same location (Carson, 2012); this causes positional messages to potentially come in at inconsistent rates.

- This is especially true in regions like the Arctic (Winther et al., 2014), where the revisit time is generally longer than in other parts of the world.

- Theoretically, terrestrial AIS would not have any issues with temporal resolution – they should receive messages as frequently as every 2 seconds.

- The limitations are generally spatial (as mentioned above). Other limitations like weather and related atmospheric conditions can affect the overall resolution (including temporal) because AIS is line of sight and depends on where the receiver is placed.

3) Receiver strength

- Terrestrial receivers often receive lower power level messages (i.e., Class B messages) much more frequently and easier than satellite receivers due to their proximity (i.e., lower power level messages have a much more difficult time reaching satellites, and therefore Class B messages have the potential of not being recorded by satellites).

The satellite-based AIS (S-AIS) used in this study potentially contains terrestrial-based AIS messages depending on exactEarth’s land-based constellation.

2.3.2 Data preparation and analysis approach

In order to complete the descriptive and comparative analysis of ship traffic derived from NORDREG as compared to that derived from Satellite-based AIS in the Canadian Arctic, we utilized tracklines (i.e., ship movement) created by Pizzolato et al. (2016) and since modified by Cook et al. (2021) that were established from CCG NORDREG non-spatial data sources. The ship tracklines were constructed based on daily position reports to the Canadian Coast Guard (CCG) from prescribed ships within the Northern Canada Vessel Traffic Services Zone (NORDREG) along with weekly sea ice data from the Canadian Ice Service Digital Archive (CISDA) from 1990 to 2018 using a Least Cost Path (LCP) approach. Reporting is not mandatory for all ships, but a 98% reported compliance rate (Pizzolato et al., 2016). Static ship information (e.g., ship type, name, size) was readily available in the dataset. Although derived data from NORDREG for the years 1990 to 2018 were available, to ensure consistency and comparability only the years of 2011 to 2018 from the derived NORDREG dataset were included in the analysis used throughout this chapter.

Eight years (2011-2018) of decoded S-AIS data provided by exactEarth Ltd. Obtained through a data license with MEOPAR were used. We used Class A (1, 2, and 3), Class B (18) and long-range (27) positional AIS messages (i.e., dynamic). The positional AIS messages were converted into spatial points stored in a geodatabase by year and month. The points, based on their attributes (position and time), were converted into tracks to visualize vessel movements over space and time. This was done to construct tracklines similar to those created by Pizzolato et al. (2016) for the NORDREG dataset. A trackline was generated between subsequent positional AIS transmissions as long as the next AIS transmission was within a distance of 50 miles (80 kilometres) and 300 minutes (5 hours) for each Maritime Mobile Service Identity (MMSI). If the next AIS transmission exceeds at least one of the thresholds (distance or time), then the current trackline would be ended, and a new unique trackline for the ship is generated from this point. This was done to create independent vessel movements for each year/month of point data. The large thresholds are used because there can be large gaps in the distance/time subsequent dynamic messages are received, which, as previously mentioned, is true in regions like the Arctic (Winther et al., 2014). The tracklines were then combined with static ship information based on MMSI from online marine intelligence database sources (MarineTraffic.com, MyShipTracking.com, and Industry Canada). The tracklines are queried to only include valid ship MMSIs (e.g., MMSIs with valid country codes are between 201000000 to 775999999).

Prior to performing the analyses on the two sources of ship traffic information, the vessel types from NORDREG and S-AIS (via marine intelligence databases) datasets were reclassified into nine general vessel types (cargo, dry bulk, ferry/Ro-Ro/passenger, fishing, government/research, other/special ships, pleasure vessels, tankers, and tugs/barge) that were used throughout the analyses (table 2.1).

Table 2.1: General ship type classification used throughout the study, with example ship types from NORDREG and Marine Intelligence databases used to supplement the AIS data.

General ship type	Example NORDREG ship types	Example AIS ship types
Cargo	General cargo, heavy load vessel	Cargo, container ship, general cargo, heavy load carrier, reefer.
Dry bulk	Bulk carrier, grain ship	Bulk carrier
Ferry/Ro-Ro/passenger	Passenger ship	Passenger, ro-ro/passenger ship
Fishing	Fishing vessel	Factory trawler, fishing vessel, trawler
Government/research	Icebreaker, fisheries patrol/research, navy ship, oceanographic research, research	Icebreaker, fishery patrol/research, military ops, pilot ship, search and rescue
Others/special ships	Drill rig, drill ship	Diving support vessel, drill ship
Pleasure vessels	Adventurer, pleasure craft	Cruiser, pleasure craft, sailing vessel, sloop, yacht

Tankers	Tanker	Chemical carrier, chemical tanker, crude oil tanker, oil/chemical tanker
Tugs/barge	Self-powered barge, tug	Anchor handling vessel, port tender, tug

The first analysis compared seven unique vessels from different years in September (generally, the month with the highest ship traffic in Canadian Arctic). They were chosen to illustrate the spatial and numerical differences between the derived tracklines (i.e., vessel movements) and vessel positions using a Geographic Information System (GIS). The seven unique vessels chosen for this comparison included:

- Maria Desgagnés (tanker) – September 2011;
- Sir Wilfred Laurier (government/research) – September 2012;
- Mitiq (cargo) – September 2013;
- Amundsen (government/research) – September 2014;
- Travestern (tanker) – September 2015;
- Kiviuq I (fishing) – September 2016; and
- NS Energy (dry bulk) – September 2017.

The second analysis is where unique ships shared between the derived NORDREG and S-AIS were identified, based on the ship name, month, and year. Then for the shared data, a statistical comparison of the distance sailed, and distance sailed per unique ship was performed to understand whether NORDREG would over or under predict the true distance sailed per unique ship. We test for the statistical differences between the mean distance sailed per unique ship (by type), using a t-test or Wilcoxon text (alpha of 0.05), depending on the normality of the data.

2.4 Results

2.4.1 Comparison of descriptive and spatial characteristics

2.4.1.1 Maria Desgagnés (tanker) – September 2011

In the NORDREG database, there were 25 recorded positions for the *Maria Desgagnés (tanker)*, whereas there were 442 S-AIS positions (+1,668% more positions recorded from S-AIS). The S-AIS trackline broke multiple times due to the time and distance threshold (i.e., larger temporal gap of 300 minutes or distance gap of 50 miles between consecutive AIS positions), causing inaccurate/incorrect vessel movements from the S-AIS this vessel for this month. Distance sailed from the NORDREG dataset was 2,246 nm sailed, and 1,474 nm sailed from the S-AIS dataset (-34% less distance sailed from the S-AIS dataset).

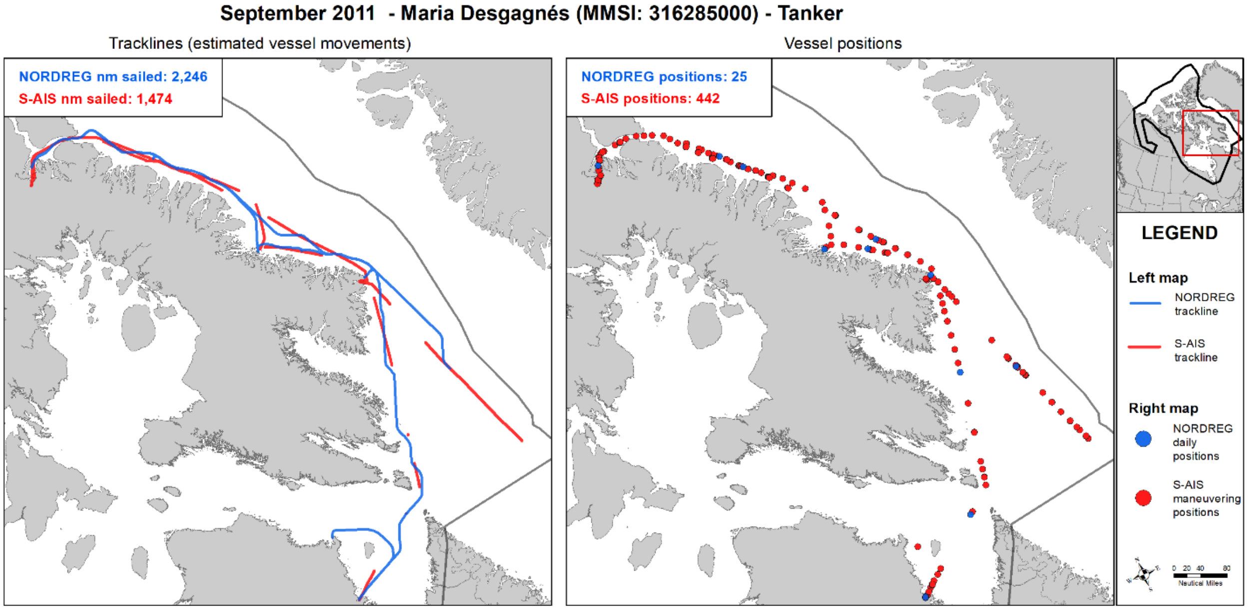


Figure 2.3: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the Maria Desgagnés (tanker) from September 2011.

2.4.1.2 Sir Wilfred Laurier (government/research) – September 2012

In the NORDREG database, there were 45 recorded positions, and in the S-AIS, there were 3,016 recorded positions (+6,602% more recorded from S-AIS). Distance sailed from the NORDREG dataset was 1,495 nm sailed, and 1,821 nm sailed from the S-AIS dataset (+22% more distance sailed from the S-AIS dataset). When spatially comparing the two trackline datasets, it is apparent that the NORDREG dataset deviates from the true vessel movement path at certain locations. For example, we see that the

NORDREG tracklines go south of a few islands (Nanukton Island and Jenny Lind Island) and do not transit to King William Island's northern edge, where the S-AIS dataset seems to travel to and from the northern portion of King William Island.

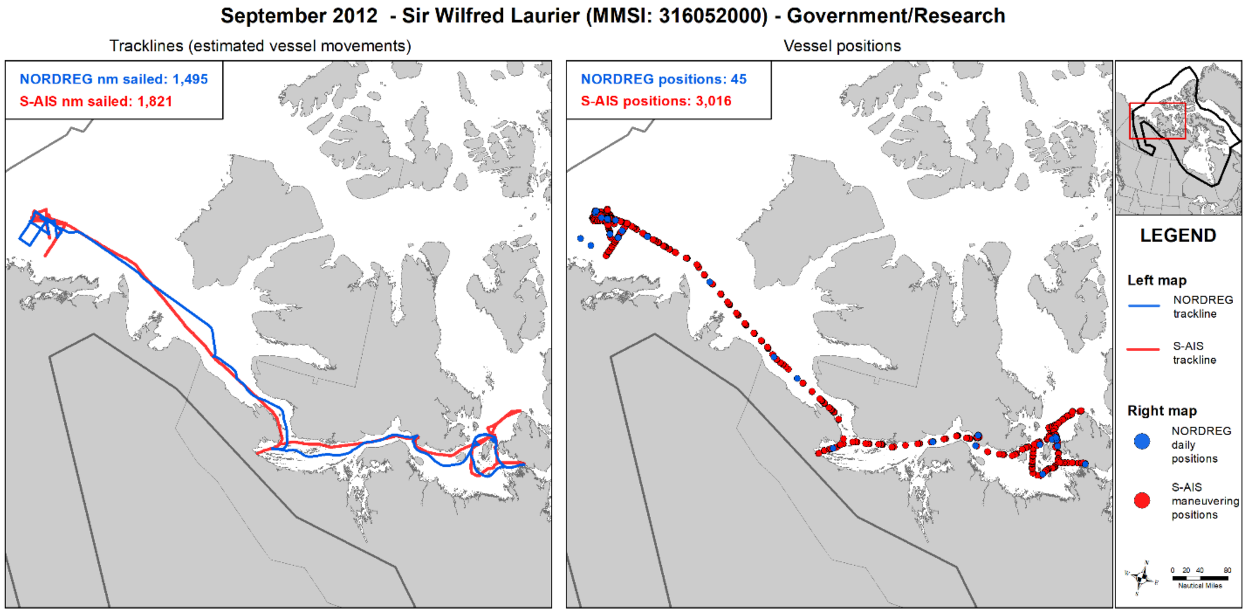


Figure 2.4: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the Sir Wilfred Laurier (government/research) from September 2012.

2.4.1.3 Mitiq (cargo) – September 2013

In the NORDREG database, there were 39 recorded positions, whereas there were 7,514 S-AIS positions (+19,167% more positions recorded from S-AIS). Distance sailed from the NORDREG dataset was 4,246 nm sailed, and 3,698 nm sailed from the S-AIS dataset (-13% less distance sailed from the S-AIS dataset). In the NORDREG dataset, it seems that the vessel went to the northwestern portion of Baffin Island; however, in the S-AIS dataset, it was not the case. We also see that in the NORDREG dataset, the vessel does not travel past the southern portion of King William Island loops around the northern portion of the island, when, as shown by the S-AIS dataset, the vessel does indeed pass through the southern portion of the island.

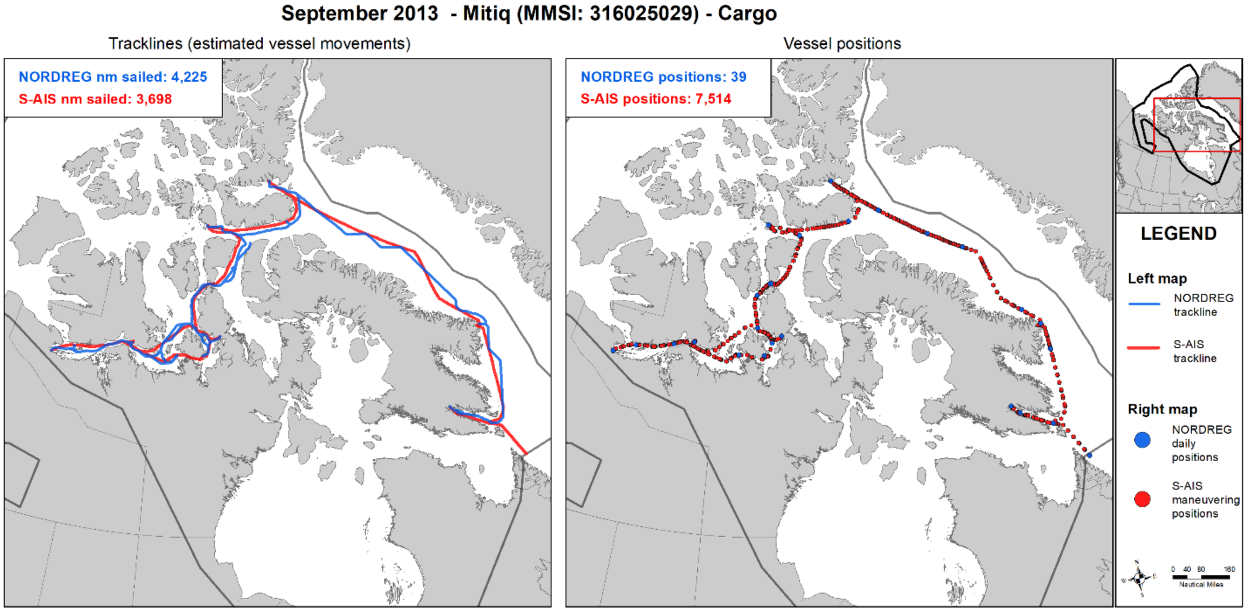


Figure 2.5: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the Mitiq (cargo) from September 2013.

2.4.1.4 Amundsen (government/research) – September 2014

In the NORDREG database, there were 27 recorded positions, whereas there were 14,480 S-AIS positions (+53,530% more positions recorded from S-AIS). Distance sailed from the NORDREG dataset was 2,471 nm sailed, and 2,970 nm sailed from the S-AIS dataset (+20% more distance sailed from the S-AIS dataset). In the NORDREG dataset, the vessels seem to stay relatively south while passing through the Northwestern Passage, wherein the S-AIS dataset moves more north relative to the NORDREG trackline. The NORDREG dataset does not pass through the south of Bylot Island but loops back through the north of Bylot Island, where the S-AIS dataset does indeed pass through the south of Bylot Island.

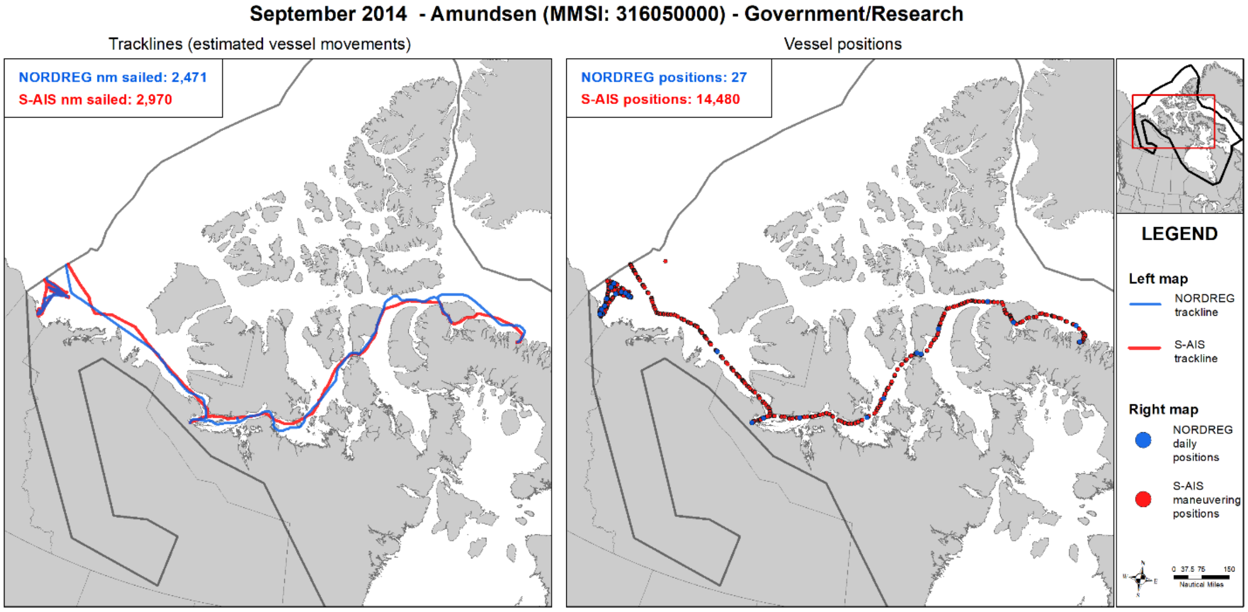


Figure 2.6: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the Amundsen (government/research) from September 2014.

2.4.1.5 Travestern (tanker) – September 2015

In the NORDREG database, there were 30 recorded positions, whereas there were 10,655 S-AIS positions (+35,417% more positions recorded from S-AIS). Distance sailed from the NORDREG dataset was 3,514 nm sailed, and 3,154 nm sailed from the S-AIS dataset (-10% less distance sailed from the S-AIS dataset). In the NORDREG dataset, the vessel completely passes by the northern portion of Bylot Island, wherein in the S-AIS dataset, the vessel passes the southern portion of Bylot Island.

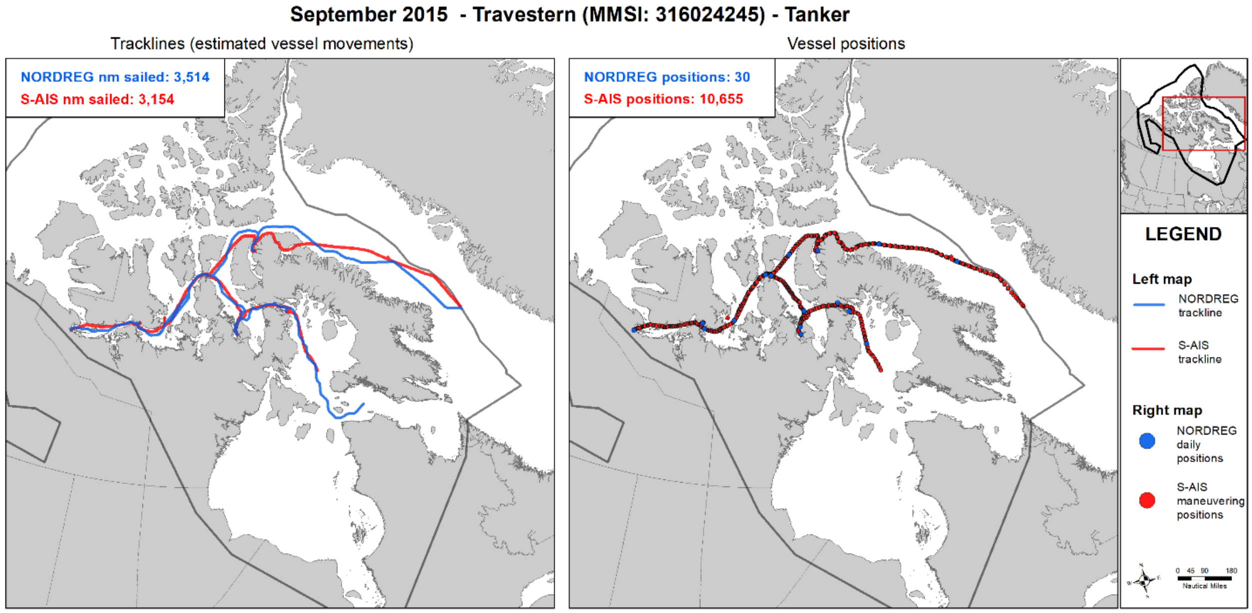


Figure 2.7: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the Travestern (tanker) from September 2015.

2.4.1.6 Kiviuq I (fishing) – September 2016

In the NORDREG database, there were 29 recorded positions, whereas there were 810 S-AIS positions (+2,693% more positions recorded from S-AIS). Distance sailed from the NORDREG dataset was 3,514 nm sailed, and 3,154 nm sailed from the S-AIS dataset (+22% more distance sailed from the S-AIS dataset). In the NORDREG dataset, the movements (i.e., tracklines) are much more linear (i.e., from start to endpoint), whereas, in the S-AIS, the movements are more sporadic and non-linear when looking at the trackines near Clyde River.

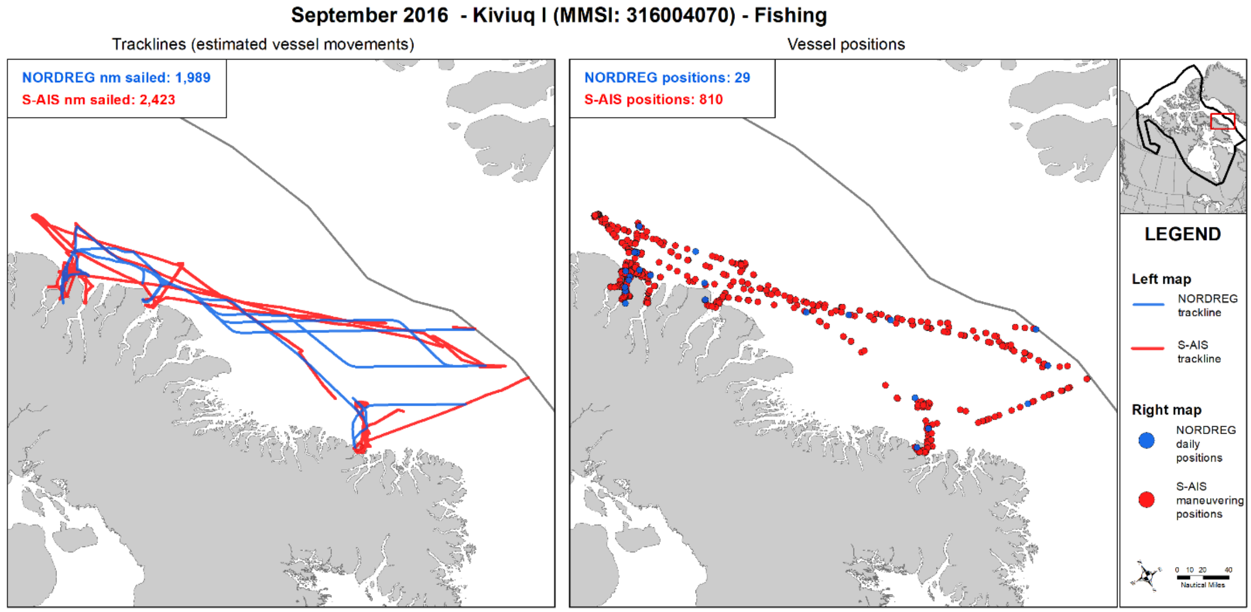


Figure 2.8: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the Kiviuq I (fishing) from September 2016.

2.4.1.7 NS Energy (dry bulk) – September 2017

In the NORDREG database, there were 12 recorded positions, whereas there were 5,731 S-AIS positions (+47,658% more positions recorded from S-AIS). Distance sailed from the NORDREG dataset was 1,418 nm sailed, and 1,408 nm sailed from the S-AIS dataset (+<1% more distance sailed from the S-AIS dataset). In this example, the tracklines from the S-AIS dataset are more linear than the entry and exit from this vessel as recorded in the NORDREG dataset.

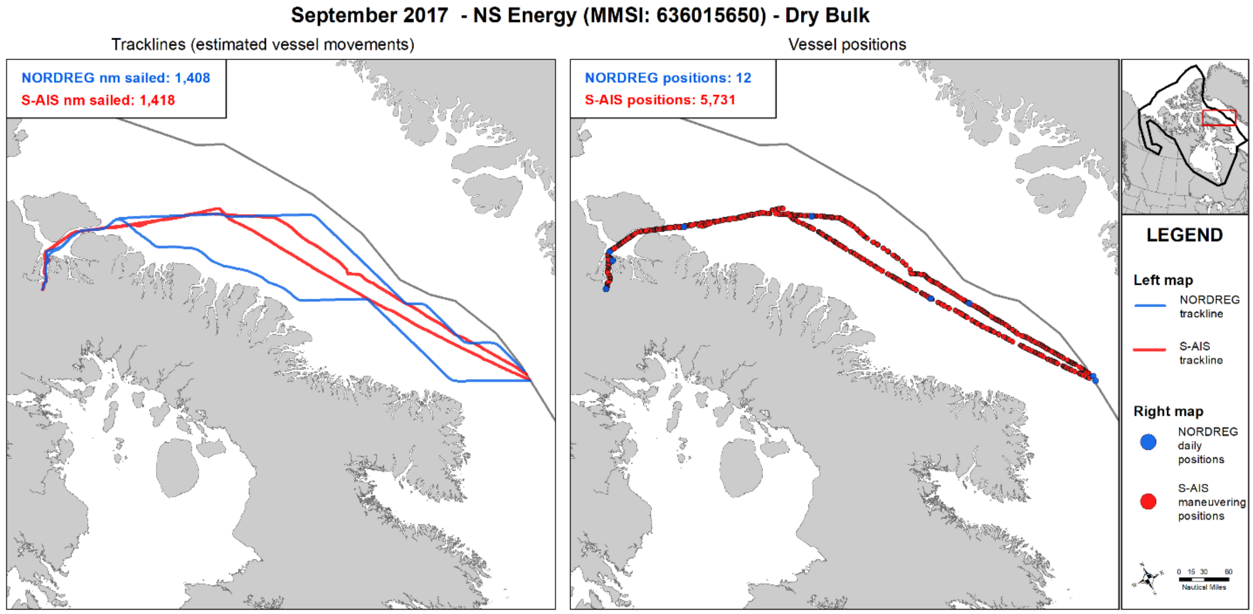


Figure 2.9: Comparison of unique monthly vessel in NORDREG (blue) compared to in S-AIS (red). Left map represents vessel movements from both datasets; right map represents recorded vessel positions from both databases. This example uses the NS Energy (dry bulk) from September 2017.

2.4.2 Comparison of unique ships

Referring to table 2.2a and 2.2b, there were a total of 435 unique monthly ships recorded from both databases in 2011; 49.2% were recorded within both, 26.4% only in NORDREG, and 24.4% only in S-AIS, indicative that NORDREG captured more unique ships in 2011. From 2012 onwards, 53.1 to 73.6% of unique monthly ships were recorded within both databases; S-AIS captures more unique ships from 2012 to 2018. The largest differences between unique monthly ships from the databases are driven by non-commercial ships, such as fishing, pleasure vessels and tugs/barges. Whereas commercial (e.g., cargo, dry bulk, tanker) are relatively consistent.

Table 2.2a: Comparison of unique monthly vessels only in AIS (A), NORDREG (N), or contained within both (B) databases from 2011 to 2019 per ship type.

Year	All ships			Cargo			Dry bulk			Ferry/Ro-Ro/ passenger			Fishing		
	A	N	B	A	N	B	A	N	B	A	N	B	A	N	B
2011	107	145	214	10	18	32	9	8	13	6	2	12	25	60	51
2012	118	130	234	12	12	33	4	4	16	3	2	14	31	43	63

2013	92	101	312	17	12	35	1	0	27	8	4	18	28	26	91
2014	102	70	318	13	7	43	2	8	29	6	5	14	31	7	102
2015	96	56	341	0	5	44	4	2	39	8	6	19	27	3	106
2016	102	57	354	1	5	41	0	0	59	4	4	21	34	0	108
2017	166	78	430	7	11	58	1	0	70	2	2	23	45	8	128
2018	184	38	435	16	5	59	11	1	89	2	0	18	40	0	120

Table 2.2b: Continued, comparison of unique monthly vessels only in AIS (A), NORDREG (N), or contained within both (B) databases from 2011 to 2019 per ship type.

Year	Government/ research			Others/ special ships			Pleasure vessels			Tanker			Tugs/barge		
	A	N	B	A	N	B	A	N	B	A	N	B	A	N	B
2011	18	8	35	1	30	0	14	0	9	11	13	36	13	6	26
2012	26	12	33	1	40	0	18	1	6	16	8	37	7	8	32
2013	17	3	36	0	40	0	9	0	19	7	2	48	5	14	38
2014	18	4	36	0	33	0	25	0	26	4	1	45	3	5	23
2015	17	3	41	0	27	0	17	1	14	3	0	52	20	9	26
2016	22	3	35	2	30	0	7	0	23	9	4	39	23	11	28
2017	41	3	55	0	40	0	10	0	27	10	7	41	50	7	28
2018	39	3	47	0	23	0	11	0	14	10	2	51	55	4	37

2.4.3 Statistical comparison of distance sailed by shared unique ships

In 2011, NORDREG derived data proves to be more accurate in terms of overall distance sailed for all ships, and for each ship type (tables 2.3 to 2.11). This also holds true for the monthly mean distance sailed (nautical miles) per unique ship, where NORDREG is more accurate on a ship-by-ship level in 2011. However, we see from 2012 onwards that AIS is more accurate in terms of distance sailed, with NORDREG underestimating the total distance sailed as well as per unique ship. For all ship types, we see that there are statistically significant differences between the mean nm sailed for all years except 2014, indicating the two databases were relatively similar for this year (table 2.2a-b).

The largest differences in distance sailed are driven by two ship types, this includes fishing (table 2.7) and pleasure vessels (table 2.9). Fishing vessels from NORDREG underestimate the distance sailed overall and per unique ship for all the years, including 2011. Where pleasure vessels from NORDREG overestimate the distance sailed overall and per unique ship for each year; however, the years of 2017 and 2018 are relatively like each other (no statistically significant differences).

Table 2.3: Comparison for all ships of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

All ships in AIS and NORDREG within NORDREG zone from 2011-2018									
	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	187,610	294,421	-106,811	877	1,376	-499	8.26E-10	**3.73E-13**	**W**
2012	305,020	281,016	24,004	1,304	1,201	103	1.60E-08	**2.06E-03**	**W**
2013	394,787	353,188	41,599	1,265	1,132	133	2.19E-11	**4.03E-07**	**W**
2014	423,315	410,852	12,463	1,331	1,292	39	2.42E-12	0.40	W
2015	411,971	403,560	8,410	1,208	1,183	25	5.28E-12	**0.03**	**W**
2016	489,290	421,441	67,848	1,378	1,187	191	3.37E-14	**1.27E-14**	**W**
2017	560,881	511,130	49,751	1,304	1,189	116	6.59E-13	**3.85E-08**	**W**
2018	602,588	518,440	84,149	1,376	1,184	192	4.19E-16	**4.47E-11**	**W**

Table 2.4: Comparison for cargo ships of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

Cargo ships in AIS and NORDREG within NORDREG zone from 2011-2018									
	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	32,042	58,881	-26,838	1,001	1,840	-839	1.61E-04	**7.95E-07**	**W**
2012	46,951	51,805	-4,854	1,423	1,570	-147	2.68E-03	0.20	W
2013	64,225	65,125	-900	1,835	1,861	-26	0.45	0.91	T
2014	67,649	80,832	-13,183	1,573	1,880	-307	0.09	0.15	T
2015	73,874	79,891	-6,017	1,679	1,816	-137	0.35	0.49	T
2016	79,588	78,918	670	1,941	1,925	16	0.66	0.94	T
2017	96,801	105,239	-8,439	1,669	1,814	-145	0.17	0.39	T
2018	107,290	113,435	-6,145	1,818	1,923	-104	0.02	**0.03**	**W**

Table 2.5: Comparison for dry bulk ships of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

Dry bulk in AIS and NORDREG within NORDREG zone from 2011-2018			
	Total NM sailed	Mean NM sailed for unique monthly ships	Statistical tests between the mean NM sailed for unique monthly ships

Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	10,079	17,024	-6,945	775	1,310	-534	0.07	**3.03E-03**	**T**
2012	21,718	23,979	-2,261	1,357	1,499	-141	0.25	0.49	T
2013	36,326	37,615	-1,289	1,345	1,393	-48	0.11	0.75	T
2014	31,780	32,347	-567	1,096	1,115	-20	5.42E-04	0.37	W
2015	30,622	29,474	1,148	785	756	29	2.10E-04	0.10	W
2016	49,989	40,973	9,016	847	694	153	0.06	**0.03**	**T**
2017	68,323	61,977	6,346	976	885	91	0.24	0.12	T
2018	78,799	79,841	-1,042	885	897	-12	0.02	0.51	W

Table 2.6: Comparison for ferry/Ro-Ro/passenger ships of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

	Ferry/Ro-Ro/passenger in AIS and NORDREG within NORDREG zone from 2011-2018								
	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	13,378	26,450	-13,073	1,115	2,204	-1,089	0.24	**0.01**	**T**
2012	19,025	22,270	-3,245	1,359	1,591	-232	0.74	0.52	T
2013	31,927	35,572	-3,646	1,774	1,976	-203	0.11	0.70	T
2014	36,624	40,920	-4,296	2,616	2,923	-307	0.98	0.52	T
2015	31,915	37,731	-5,815	1,680	1,986	-306	0.31	0.41	T
2016	46,089	44,187	1,902	2,195	2,104	91	0.35	0.81	T
2017	43,069	47,985	-4,916	1,873	2,086	-214	0.36	0.47	T
2018	35,150	37,134	-1,984	1,850	1,954	-104	0.59	0.78	T

Table 2.7: Comparison for fishing vessels of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

	Fishing in AIS and NORDREG within NORDREG zone from 2011-2018								
	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	40,999	24,643	16,356	804	483	321	0.02	**7.82E-07**	**W**
2012	66,534	30,498	36,035	1,056	484	572	9.61E-04	**8.98E-11**	**W**
2013	88,336	38,666	49,670	971	425	546	2.34E-05	**8.40E-15**	**W**
2014	108,578	55,823	52,755	1,064	547	517	1.01E-05	**2.38E-15**	**W**
2015	104,798	59,611	45,187	989	562	426	3.73E-06	**2.59E-13**	**W**

2016	133,865	60,701	73,164	1,228	557	671	8.60E-06	**3.63E-17**	**W**
2017	143,757	75,302	68,455	1,123	588	535	2.46E-06	**4.57E-17**	**W**
2018	157,061	80,361	76,700	1,287	659	629	1.99E-05	**2.94E-18**	**W**

Table 2.8: Comparison for government/research vessels of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

Government/research in AIS and NORDREG within NORDREG zone from 2011-2018									
	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	41,459	82,109	-40,651	1,185	2,346	-1,161	0.05	**1.03E-03**	**T**
2012	46,444	52,391	-5,948	1,407	1,588	-180	0.02	**0.02**	**W**
2013	58,834	65,134	-6,300	1,634	1,809	-175	0.15	0.57	T
2014	72,965	79,530	-6,564	2,027	2,209	-182	0.21	0.58	T
2015	68,437	76,911	-8,475	1,669	1,876	-207	0.01	0.88	W
2016	77,218	93,107	-15,889	2,206	2,660	-454	0.12	0.28	T
2017	99,101	100,017	-916	1,802	1,818	-17	4.13E-04	0.53	W
2018	104,492	88,720	15,772	2,223	1,888	336	0.01	**9.98E-04**	**W**

Table 2.9: Comparison for pleasure vessels of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

Pleasure vessels in AIS and NORDREG within NORDREG zone from 2011-2018									
	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
Year	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	5,412	12,577	-7,164	601	1,397	-796	0.06	0.09	T
2012	4,021	9,035	-5,014	670	1,506	-836	0.04	0.09	W
2013	15,187	19,611	-4,423	799	1,032	-233	0.00	**1.41E-03**	**W**
2014	17,374	24,658	-7,284	668	948	-280	0.00	**2.40E-03**	**W**
2015	6,327	13,358	-7,031	452	954	-502	0.01	**4.03E-03**	**W**
2016	22,562	28,699	-6,137	981	1,248	-267	0.01	**4.34E-03**	**W**
2017	28,577	30,215	-1,639	1,058	1,119	-61	0.03	0.90	W
2018	10,357	9,453	905	740	675	65	0.68	0.66	T

Table 2.10: Comparison for tankers of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

Tankers in AIS and NORDREG within NORDREG zone from 2011-2018

Year	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	28,355	46,601	-18,246	788	1,294	-507	3.56E-03	**8.03E-05**	**W**
2012	49,925	48,715	1,210	1,349	1,317	33	0.05	0.13	W
2013	67,979	62,504	5,475	1,416	1,302	114	0.01	**0.04**	**W**
2014	64,586	72,653	-8,067	1,435	1,615	-179	3.10E-03	**1.58E-05**	**W**
2015	67,045	77,011	-9,966	1,289	1,481	-192	1.43E-03	**1.63E-03**	**W**
2016	54,447	48,665	5,782	1,396	1,248	148	6.86E-04	**3.54E-03**	**W**
2017	54,720	66,428	-11,708	1,335	1,620	-286	1.95E-04	0.15	W
2018	72,304	75,790	-3,486	1,418	1,486	-68	0.01	0.07	W

Table 2.11: Comparison for tug/barge of distance sailed (nautical miles – NM) by matched unique vessels within both AIS and NORDREG derived databases (left); comparison of the mean distance sailed per unique month ship (centre); statistical tests between the mean distance sailed for unique ships to test for statistical differences between the distance sailed for each unique vessel – bold indicates statistical significance at an alpha of 0.05.

Tugs/barge in AIS and NORDREG within NORDREG zone from 2011-2018

Year	Total NM sailed			Mean NM sailed for unique monthly ships			Statistical tests between the mean NM sailed for unique monthly ships		
	AIS	NORDREG	Difference	AIS	NORDREG	Difference	Shapiro-Wilk p-val.	t-test or Wilcoxon p-val.	Test used
2011	15,886	26,136	-10,250	611	1,005	-394	0.04	**1.57E-03**	**W**
2012	50,403	42,321	8,082	1,575	1,323	253	2.56E-03	0.13	W
2013	31,973	28,960	3,013	841	762	79	1.68E-03	**0.03**	**W**
2014	23,759	24,090	-331	1,033	1,047	-14	0.19	0.92	T
2015	28,952	29,572	-620	1,114	1,137	-24	0.43	0.89	T
2016	25,530	26,190	-660	912	935	-24	2.81E-03	0.75	T
2017	26,534	23,966	2,568	948	856	92	0.04	0.21	T
2018	37,136	33,706	3,430	1,004	911	93	0.24	0.48	T

2.5 Discussion

This study helps to provide a quantitative comparative analysis between two typically utilized data sources for research focused on understanding shipping traffic trends in the Canadian Arctic. The analysis was conducted to provide insight into the utility of these data sources and to support researchers and decision makers to better understand the potential uses, limitations, and differences between the data sources so that adjustments and considerations can be made as is deemed necessary. Overall, the study reveals that both sources of data have high utility but that one or the other may be more useful in certain circumstances. For example, the NORDREG database is a comprehensive shipping database that extends historically much further than AIS and therefore, it is recommended for use when examine trends or conditions prior to 2012. Results also show that the spatial database that has been derived from the non-spatial (static) CCG NORDREG data performed by Pizzolato et al. (2016) is indeed highly robust and can be considered a reasonable proxy for understanding the spatial distribution of shipping traffic prior to 2012 when AIS became more readily available. As noted by Pizzolato et al. (2016) there remain some limitations with these historic data considering it is statistically derived and, in some locations, there are inaccuracies in exact ship routings. However, based on this analysis, this historical spatial database is highly useful and displays historic spatial shipping trends to a high level of accuracy. It is clear based on the comparative and statistical analyses that 2012 onward, AIS most accurately captures distance sailed, unique vessels, and distance sailed per unique vessel more than NORDREG does. It is therefore recommended that AIS should be used from 2012 and moving forward in future years for this region.

2.6 Conclusion

This study provided a fulsome descriptive and quantitative comparative analysis between these two data sources within the Canadian Arctic that had not been completed before. In conclusion, this comparative analysis will help inform analysts, and decision-makers on the differences between the two sources prior and provide a foundation for performing analyses/studies underlying policy decisions. The analysis also directly links into Chapter 3 of this thesis and justifies the use of the combination of the two data sources (NORDREG from 1990 to 2011; and S-AIS from 2012 to 2019) to be used to create a comprehensive ship traffic database to determine long-term ship traffic statistics in the Canadian Arctic.

Acknowledgements

This work was funded by the Marine Environmental Observation Prediction & Response Network (MEOPAR) and Clear Seas. Satellite-based AIS data were provided by exactEarth Ltd., 2019 through partnership with MEOPAR. The NORDREG nonspatial data was provided by the Canadian Coast Guard (CCG).

2.7 References cited in chapter 2

Akhtar, J., Bjørnskau, T., & Jean-Hansen, V. (2011). Oil spill risk analysis of routeing heavy ship traffic in Norwegian waters. WMU Journal of Maritime Affairs, 11(2), 233-247. doi:10.1007/s13437-011-0016-8

Altan, Y. C., & Otay, E. N. (2018). Spatial mapping of encounter probability in congested waterways using AIS. Ocean Engineering, 164, 263-271. doi:10.1016/j.oceaneng.2018.06.049

Bennett, M. M., Stephenson, S. R., Yang, K., Bravo, M. T., & De Jonghe, B. (2020). The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. Marine Policy, 121, 104178. doi:10.1016/j.marpol.2020.104178

Brooks, M. R., & Frost, J. D. (2012). Providing freight services to remote Arctic communities: Are there lessons for practitioners from services to Greenland and Canada's Northeast? Research in Transportation Business & Management, 4, 69-78. doi:10.1016/j.rtbm.2012.06.005

Bintanja, R., & Van der Linden, E. C. (2013). The changing seasonal climate in the Arctic. Scientific Reports, 3(1). doi:10.1038/srep01556

Bystrowska, M. (2019). The impact of sea ice on cruise tourism on Svalbard. ARCTIC, 72(2), 151-165. doi:10.14430/arctic68320

Balduzzi, M., Pasta, A., & Wilhoit, K. (2014). A security evaluation of AIS automated identification system. In Proceedings of the 30th Annual Computer Security Applications Conference on - ACSAC ’14 (pp. 436–445). New Orleans, Louisiana: ACM Press. https://doi.org/10.1145/2664243.2664257

Bye, R. J., & Aalberg, A. L. (2018). Maritime navigation accidents and risk indicators: An exploratory statistical analysis using AIS Data and accident reports. Reliability Engineering & System Safety, 176, 174-186. doi:10.1016/j.ress.2018.03.033

Calder BR, and Schwehr K. (2009). Traffic analysis for the calibration of risk assessment methods. US Hydro. 11–14.

Carson-Jackson, J. (2012). Satellite AIS – Developing Technology or Existing Capability? Journal of Navigation, 65(02), 303–321. https://doi.org/10.1017/S037346331100066X

Carter, N.A., Dawson, J., Knopp, J., Joyce, J., Weber, M., Kochanowicz, Z., & Mussells, O. (2018). Arctic corridors and northern voices: Governing marine transportation in the Canadian Arctic (Cambridge Bay, Nunavut community report). Ottawa, Canada: University of Ottawa.

Carter, N.A., Dawson, J., Weber, M. (2020). Arctic Corridors and Northern Voices: Governing marine transportation in the Canadian Arctic (Iqaluit, Nunavut community report). (http://www.arcticcorridors.ca/?acr_download=%2Fwp-content%2Fuploads%2F2020%2F05%2FUofO_CommReport_Iqaluit_FINAL_LO.pdf)

Claes, D. H., & Moe, A. (2018). Arctic Offshore Petroleum: Resources and Political Fundamentals. Arctic Governance: Volume 2. doi:10.5040/9781350985384.ch-001

Chénier, R., Abado, L., Sabourin, O., & Tardif, L. (2017). Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. Transactions in GIS, 21 (6), 1085–1097

Cheng, L., Yan, Z., Xiao, Y., Chen, Y., Zhang, F., & Li, M. (2018). Using big data to track marine oil transportation along the 21st-century Maritime Silk Road. Science China Technological Sciences, 62(4), 677-686. doi:10.1007/s11431-018-9335-1

Christiansen, J. S., Mecklenburg, C. W., & Karamushko, O. V. (2013). Arctic marine fishes and their fisheries in light of Global Change. Global Change Biology, 20(2), 352-359. doi:10.1111/gcb.12395

Copland, L., Dawson, J., Tivy, A., Delaney, F., Cook, A., and Creed, I. (2021). Changes in shipping navigability in the Canadian Arctic between 1972 and 2016. Facets 6, 1069–1087. doi: 10.1139/facets-2020-0096

Dawson, J., Stewart, E. J., Lemelin, H., & Scott, D. (2009). The carbon cost of polar bear viewing tourism in Churchill, Canada. Journal of Sustainable Tourism, 18(3), 319-336. doi:10.1080/09669580903215147

Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., & Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015 + Supplementary Appendix 1: Figs. S1–S7 (See Article Tools). ARCTIC, 71(1), 15. https://doi.org/10.14430/arctic4698

Dawson, J., Cook, A., Holloway, J., & Copland, L. (2022). Analysis of changing levels of ice strengthening (ice class) among vessels operating in the Canadian arctic over the past 30 Years. ARCTIC. doi:10.14430/arctic75553

Eide, M. S., Endresen, Ø, Brett, P. O., Ervik, J. L., & Røang, K. (2007). Intelligent ship traffic monitoring for oil spill prevention: Risk based decision support building on AIS. Marine Pollution Bulletin, 54(2), 145-148. doi:10.1016/j.marpolbul.2006.11.004

Eriksen, T., & Olsen, Ø. (2018). Vessel Tracking Using Automatic Identification System

Data in the Arctic. In L. P. Hildebrand, L. W. Brigham, & T. M. Johansson (Eds.), Sustainable Shipping in a Changing Arctic (Vol. 7, pp. 115–136). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-78425-0_7

Galappaththi, E. K., Ford, J. D., Bennett, E. M., & Berkes, F. (2019). Climate change and community fisheries in the Arctic: A case study from Pangnirtung, Canada. Journal of Environmental Management, 250, 109534. doi:10.1016/j.jenvman.2019.109534

Giguère, M., Comtois, C., & Slack, B. (2017). Constraints on canadian arctic maritime connections. Case Studies on Transport Policy, 5(2), 355-366. doi:10.1016/j.cstp.2017.03.004

Guzman, H. M., Gomez, C. G., Guevara, C. A., & Kleivane, L. (2012). Potential vessel collisions with southern hemisphere humpback whales wintering off Pacific Panama. Marine Mammal Science. doi:10.1111/j.1748-7692.2012.00605.x

Haley, S., Klick, M., Szymoniak, N., & Crow, A. (2011). Observing trends and assessing data for Arctic Mining. Polar Geography, 34(1-2), 37-61. doi:10.1080/1088937x.2011.584449

Halliday, W. D., Insley, S. J., Hilliard, R. C., De Jong, T., & Pine, M. K. (2017). Potential impacts of shipping noise on marine mammals in the Western Canadian Arctic. Marine Pollution Bulletin, 123(1-2), 73-82. doi:10.1016/j.marpolbul.2017.09.027

Halliday, W.D., P.L. Têtu, J. Dawson, S.J. Insley, and R.D. Hilliard. (2018). Tourist vessel traffic in important whale areas in the western Canadian Arctic: Risks and possible management solutions. Marine Policy97: 72–81. (5)

Halliday, W., Pine, M., Citta, J., Harwood, L., Hauser, D., Hilliard, R., . . . Insley, S. (2021). Potential exposure of beluga and bowhead whales to underwater noise from ship traffic in the Beaufort and Chukchi Seas. Ocean & Coastal Management, 204, 105473. doi:10.1016/j.ocecoaman.2020.105473

Harsem, Ø, Eide, A., & Heen, K. (2011). Factors influencing future oil and gas prospects in the Arctic. Energy Policy, 39(12), 8037-8045. doi:10.1016/j.enpol.2011.09.058

Hasle, J. R., Kjellén, U., & Haugerud, O. (2009). Decision on oil and gas exploration in an Arctic area: Case study from the Norwegian barents sea. Safety Science, 47(6), 832-842. doi:10.1016/j.ssci.2008.10.019

Howell, S. E. L., Derksen, C., Dawson, J., & Copland, L. (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Climatic Change, 123(2), 161–173. https://doi.org/10.1007/s10584-013-1038-3

Huebert, R. (2001). Climate change and Canadian sovereignty in the Northwest Passage Canadian Journal of Policy Research, 2 (4) (2001), pp. 86-94.
Huntington, H. P. (2009). A preliminary assessment of threats to Arctic marine mammals and their conservation in the coming decades. Marine Policy, 33(1), 77-82. doi:10.1016/j.marpol.2008.04.003

Islam, S., Goerlandt, F., Feng, X., Uddin, M. J., Shi, Y., & Hilliard, C. (2020). Improving disasters preparedness and response for coastal communities using AIS ship tracking data. International Journal of Disaster Risk Reduction, 51, 101863. doi:10.1016/j.ijdrr.2020.101863

Keil, K. (2013). The Arctic: A new region of conflict? the case of oil and Gas. Cooperation and Conflict, 49(2), 162-190. doi:10.1177/0010836713482555

Kochanowicz, Z., Dawson, J., Halliday, W. D., Sawada, M., Copland, L., Carter, N. A., Nicoll, A., Ferguson, S. H., Heide-Jørgensen, M. P., Marcoux, M., Watt, C., &; Yurkowski, D. J. (2021). Using western science and Inuit knowledge to model ship-source noise exposure for cetaceans (marine mammals) in Tallurutiup Imanga (lancaster sound), Nunavut, Canada. Marine Policy, 130, 104557.

Lalonde, S., & Lasserre, F. (2013). The position of the United States on the Northwest Passage: Is the fear of creating a precedent warranted? Ocean Development & International Law, 44(1), 28-72. doi:10.1080/00908320.2012.726832

Lasserre, F., & Têtu, P. (2013). The cruise tourism industry in the Canadian arctic: Analysis of activities and perceptions of cruise ship operators. Polar Record, 51(1), 24-38. doi:10.1017/s0032247413000508

Löptien, U., & Axell, L. (2014). Ice and AIS: Ship speed data and sea ice forecasts in the Baltic Sea. The Cryosphere, 8(6), 2409-2418. doi:10.5194/tc-8-2409-2014

Lu, D., Park, G., Choi, K., & Oh, S. (2014). An economic analysis of container shipping through Canadian northwest passage. International Journal of E-Navigation and Maritime Economy, 1, 60-72. doi:10.1016/j.enavi.2014.12.001

Martin, M. J., Halliday, W. D., Storrie, L., Citta, J. J., Dawson, J., Hussey, N. E., Juanes, F., Loseto, L. L., MacPhee, S. A., Moore, L., Nicoll, A., O'Corry-Crowe, G., & Insley, S. J. (2022). Exposure and behavioral responses of tagged beluga whales (Delphinapterus leucas) to ships in the Pacific Arctic. Marine Mammal Science, 1–35. https://doi.org/10.1111/mms.12978

Marty, J., A. Nicoll, S. Potter, M. Wallace, and C. Lumière. (2016). Evaluation of the Risk of Oil Spills in Canadian Arctic Waters. Proceedings of the Thirty-ninth AMOP Technical Seminar, Environment and Climate Change Canada. Ottawa, ON. 1035-1046.

Miller, G. H., Alley, R. B., Brigham-Grette, J., Fitzpatrick, J. J., Polyak, L., Serreze, M. C., & White, J. W. (2010). Arctic amplification: Can the past constrain the future?

Quaternary Science Reviews, 29(15-16), 1779-1790. doi:10.1016/j.quascirev.2010.02.008

Mou, J. M., Tak, C. V., & Ligteringen, H. (2010). Study on collision avoidance in busy waterways by using AIS Data. Ocean Engineering, 37(5-6), 483-490. doi:10.1016/j.oceaneng.2010.01.012

Natale, F., Gibin, M., Alessandrini, A., Vespe, M., & Paulrud, A. (2015). Mapping Fishing Effort through AIS Data. PLOS ONE, 10(6), e0130746. https://doi.org/10.1371/journal.pone.0130746

Palma, D., Varnajot, A., Dalen, K., Basaran, I. K., Brunette, C., Bystrowska, M., . . . Ronge, T. A. (2019). Cruising the marginal ice zone: Climate change and arctic tourism. Polar Geography, 42(4), 215-235. doi:10.1080/1088937x.2019.1648585

Pizzolatto, L., Howell, S. E. L., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic: SEA ICE AND SHIPPING, CANADIAN ARCTIC. Geophysical Research Letters, 43(23), 12,146-12,154. https://doi.org/10.1002/2016GL071489

Ray, C., Gallen, R., Iphar, C., Napoli, A., & Bouju, A. (2015). DeAIS project: Detection of AIS spoofing and resulting risks. In OCEANS 2015 - Genova (pp. 1–6). Genova, Italy: IEEE. https://doi.org/10.1109/OCEANS-Genova.2015.7271729

Schultz, M., & Bourne, S. (2019). Using automatic identification system (AIS) data to assess collision and grounding risk in U.S. coastal ports. doi:10.21079/11681/33343

Shelmerdine, R. L. (2015). Teasing out the detail: How our understanding of marine AIS data can better inform industries, developments, and planning. Marine Policy, 54, 17-25. doi:10.1016/j.marpol.2014.12.010

Shephard, G. E., Dalen, K., Peldszus, R., Aparício, S., Beumer, L., Birkeland, R., . . . Zhilina, I. (2016). Assessing the added value of the recent declaration on unregulated fishing for sustainable governance of the Central Arctic Ocean. Marine Policy, 66, 50-57. doi:10.1016/j.marpol.2016.01.013

Steiner, N., J. Bowman, K. Campbell, M. Chierici, E. Eronen-Rasimus, M. Falardeau, H. Flores, A. Frasson, et al. (2021). Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene 9: 1.

Stewart, E. J., Howell, S., Draper, D., Yackel, J., & Tivy, A. (2009). Sea ice in Canada's arctic: Implications for cruise tourism. ARCTIC, 60(4). doi:10.14430/arctic194

Stewart, E., Dawson, J., Howell, S., Johnston, M., Pearce, T., & Lemelin, H. (2013). Local-level responses to sea ice change and cruise tourism in Arctic Canada's Northwest Passage. Polar Geography, 36(1-2), 142-162. doi:10.1080/1088937x.2012.705352

Stewart, E., Tivy, A., Howell, S., Dawson, J., & Draper, D. (2010). Cruise tourism and sea ice in Canada's Hudson Bay Region. ARCTIC, 63(1). doi:10.14430/arctic647

Tai, T. C., Steiner, N. S., Hoover, C., Cheung, W. W., & Sumaila, U. R. (2019). Evaluating present and future potential of Arctic Fisheries in Canada. Marine Policy, 108, 103637. doi:10.1016/j.marpol.2019.103637

Têtu, P., Pelletier, J., & Lasserre, F. (2015). The mining industry in Canada north of the 55th Parallel: A Maritime Traffic Generator? Polar Geography, 38(2), 107-122. doi:10.1080/1088937x.2015.1028576

Tolvanen, A., Eilu, P., Juutinen, A., Kangas, K., Kivinen, M., Markovaara-Koivisto, M., . . . Similä, J. (2019). Mining in the Arctic Environment – a review from ecological, socioeconomic and legal perspectives. Journal of Environmental Management, 233, 832-844. doi:10.1016/j.jenvman.2018.11.124

Van Iperen, E. (2015). Classifying ship encounters to monitor traffic safety on the North Sea from AIS Data. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 9(1), 51-58. doi:10.12716/1001.09.01.06

Winther, M., Christensen, J. H., Plejdrup, M. S., Ravn, E. S., Eriksson, Ó. F., & Kristensen, H. O. (2014). Emission inventories for ships in the arctic based on satellite sampled AIS data. Atmospheric Environment, 91, 1–14. https://doi.org/10.1016/j.atmosenv.2014.03.006

Zeng, Q., Lu, T., Lin, K., Yuen, K. F., & Li, K. X. (2020). The competitiveness of Arctic shipping over Suez Canal and China-europe railway. Transport Policy, 86, 34-43. doi:10.1016/j.tranpol.2019.11.005

Zhang, W., Goerlandt, F., Montewka, J., & Kujala, P. (2015). A method for detecting possible near Miss Ship Collisions from AIS Data. Ocean Engineering, 107, 60-69. doi:10.1016/j.oceaneng.2015.07.046

Chapter 3: Evaluating the changing level of shipping accidents between commercial and non-commercial vessels operating in the Canadian Arctic during the open water season from 1990-2019

Adrian Nicoll[1 2], *Jackie Dawson*[1], *Jérôme Marty*[34], *Luke Copland*[1], *Michael Sawada*[1]
[1] Department of Geography, Environment, and Geomatics, University of Ottawa, Canada
[2] Transport Canada
[3] Council of Canadian Academies
[4] International Association for Great Lakes Research

Planned submission to: *TBD*

Authors declaration: *I am the first author on this scientific paper, performed all the data analyses, and contributed significantly to the methodology design and writing of the final manuscripts. This was scientific paper was designed in partnership with Drs. Jackie Dawson and Jérôme Marty, and written revised with the input of Drs. Jackie Dawson, Jérôme Marty, Luke Copland, and Michael Sawada.*

3.1 Abstract

Over the past two decades there have been reported decreases in sea-ice extent concurrent with increases in ship traffic in the Canadian Arctic. It has been hypothesized that an ongoing increase in Arctic ship traffic in these waters as a result of sea ice variability could lead to higher numbers of shipping accidents that could be detrimental to the local environment, economy, and culture. In this study, we perform descriptive and statistical (correlations and trends) analysis on ship traffic, accidents, accident rates, and compare this with sea-ice extent and variability during the shipping season (July to October) from 1990 to 2019. Results indicate that there are significant positive trends in overall ship traffic for all ship types (+9,275 nm yr^{-1}) including both commercial ships (+5,011 nm yr^{-1}) and non-commercial ships (+4,658 nm yr^{-1}). Over the same time-period of increased overall traffic, there have been significant negative trends in ship accidents for commercial ships (-0.06 accidents yr^{-1}), ship accident rates, for all ship types (-6.31E-07 accidents/nm yr^{-1}). At the monthly level, there are significant negative trends in sea ice extent (-3,193 km^2 mo^{-1}). Results also indicate that there are significant positive correlations between monthly ship traffic and sea ice extent for all ships, commercial ships, and non-commercial ships (-0.50, -0.49, -0.48), Overall, our results show that as sea-ice extent decreases in the Canadian Arctic, commercial and non-commercial ship traffic is increasing while commercial ship accidents and accident rates are declining.

Keywords: *Ship traffic; accidents; accident rates; sea ice; Canadian Arctic; AIS; NORDREG; trends; correlations*

3.2 Introduction

Over the past decade, a rapid decline in sea ice extent and thickness has been observed throughout the Arctic Ocean (Ding et al., 2017; Onarheim et al., 2018), and it is expected that the Arctic could be completely ice-free in the summers sometime around the mid to late century (Laliberté et al., 2016; IPCC, 2019; Constable et al., 2022). Concurrently, there has also been a noticeable increase in ship activity through the global Arctic over the same period (Huntington et al., 2015; Eguíluz et al., 2016; Eriksen et al., 2018). Several studies have given specific attention to the Canadian Arctic given that it is home to over 60 coastal communities, several operational mines, tourism hot spots and also to the Northwest Passage, a trans-Arctic Sea route linking the Atlantic and Pacific oceans that has captured the imaginations of global leaders for centuries, but which has yet become viable (Stephenson et al., 2014; Aksenov et al., 2015). Increases in shipping traffic over the past decade in Arctic Canada have increased by approximately 75% (Pizzolato et al., 2014; Pizzolato et al., 2016; Chénier et al., 2017; Dawson et al., 2018). Past studies that have focused on the implications of sea ice for shipping traffic trends have shown weak but increasing correlations (Pizzolato et al., 2014; Pizzolato et al., 2016), with many more recent studies suggesting that sea ice variability in the Canadian Arctic, particular the Northwest Passage, will continue to impact safe ship navigability now and into mid-century (Haas & Howell, 2015; Howell et al., 2021)

Sea ice loss has been strongly linked with warmer trends in atmospheric conditions in the summer shipping season (Outten et al., 2011; Frey et al., 2015; Ding et al., 2017; Onarheim et al., 2018), and it is expected that ship traffic will indeed continue to grow in the Arctic as sea ice continues to decline (Smith & Stephenson, 2013; Melia et al., 2016), Among the concerns associated with the projected increase in Arctic shipping traffic is the potential for oil spills such as refined products and fuel oil from marine navigation accidents (Marty et al., 2016), other marine navigational related accidents, such as ship-ship and ship-ice collisions (Stevenson et al., 2019), increases in ship-source underwater noise (Halliday et al., 2018; Kochanowicz et al., 2020), navigational challenges in key hot spot risk areas and for non-ice strengthened vessels (Johnston et al., 2017; Dawson et al., 2018; Copland et al., 2021; Dawson et al., 2022). Relative to other regions across Canada, the Arctic has the highest accident rate per ship movement for commercial ships (e.g., cargo, dry bulk, tankers) at approximately ten accidents per 1,000 commercial ship movements. The St. Lawrence region, where sea ice is also present for a part of the shipping season, has the second-highest accident rate per ship movement (Council of Canadian Academies, 2016) and is one of the most at-risk areas south of the 60th parallel in Canada for a ship-source oil spill (Marty et al., 2014).

This study examines statistical associations and trends for ship traffic, ship accidents, accident rates, and sea-ice extent within the Canadian Arctic (figure 2) during the shipping season (July to October) from 1990 to 2019. Studies have quantified the link between sea-ice and ship traffic within the Canadian Arctic (Pizzolato et al., 2014; Pizzolato et al., 2016); where this study builds on those before it by incorporating new and more recent data as well as attempting to quantify the link between ship accident rates and sea-ice extent, which has not been quantified within the Canadian Arctic.

The objectives for this study are as follows:

1. Descriptive analysis of ship traffic, accidents, accident rates, and sea ice extent during the shipping season from 1990-2019.

2. Determine the statistical associations between monthly ship traffic, accidents, accident rates, and sea ice extent during the shipping season from 1990-2019.

3. Determine statistical trends for vessel traffic, accidents, accident rates, and sea ice extent during the shipping season from 1990-2019.

3.3 Methods

3.3.1 Data description

The data used in this study was limited to the shipping season (July to October) and between the years 1990 to 2019. This study focuses on ships that are greater than 300 gross tonnes (GT), as this ensures the uniformity in datasets:

- Participation is mandatory for all ships >300 GT in NORDREG, and
- IMO and Canadian AIS carriage requirements make it mandatory for all ships >300 GT engaged on an international trip to have a Class A transponder.
- Ships >15 GT involved in accidents should be reporting to the Transportation Safety Board (TSB).

3.3.1.1 Ship traffic data and preparation

For this study, we used pre-existing tracklines (i.e., ship movement) created by Pizzolato et al. (2016). The ship tracklines were constructed based on daily position reports to the Canadian Coast Guard (CCG) from prescribed ships within the Northern Canada Vessel Traffic Services Zone (NORDREG) along with weekly sea ice data from the Canadian Ice Service Digital Archive (CISDA) from 1990 to 2018 using a Least Cost Path (LCP) approach. Reporting is not mandatory for all ships, but a 98% reported compliance rate (Pizzolato et al., 2016). Static ship information (e.g., ship type, name, size) was readily available in the dataset. Derived data from NORDREG for the years 1990 to 2018 were available for the study; however, only the years of 1990 to 2011 from the derived NORDREG dataset were included in the consolidated ship traffic dataset used throughout this chapter as data from this period is considered to be most accurate compared to other data sources (refer to Chapter 2).

We also used eight years (2012-2019) of decoded S-AIS data provided by exactEarth (now Spire) via a data license from MEOPAR were used. NORDREG provides better accuracy from 1990 to 2011, however S-AIS provides better accuracy from 2012 to 2019. From the S-AIS, we used positional AIS messages (1-3, 18, 27). This data was then converted into spatial points by month and year, which were then converted into tracklines in order to visualize ship movements over space and time. The data was converted in this manner to replicate the same type of data created by Pizzolato et al.

(2016) for the NORDREG dataset.

The ship movements (tracklines) were generated by sorting the AIS transmissions by Maritime Mobile Service Identity (MMSI) and the date/time of the position. Trips were then created for each MMSI if the positions were between a time and distance threshold of 50 miles (80 kilometres) and 300 minutes (5 hours). Each trip was then converted into a GIS polyline to represent a unique ship movement. The large threshold applied is in part due to the fact that there could be large temporal gaps in S-AIS, especially within regions such as the Arctic (Winther et al., 2014). Static ship information (e.g., vessel type, size) was collected from online sources (MarineTraffic.com, MyShipTracking.com, and Industry Canada), and combined with the data by MMSI to classify into different ship types and sizes. In addition, the tracklines are queried to only include valid ship MMSIs (e.g., MMSIs with valid country codes are between 201000000 to 775999999). NORDREG tracklines for 1990 to 2011 were combined with the S-AIS tracklines for 2012 to 2019. S-AIS was chosen for the later years, as it proves to have higher accuracy in ship movements (i.e., nautical miles sailed), which is one of the key metrics used throughout this study (refer to *Chapter 2*). The ship types within the derived NORDREG and S-AIS datasets were reclassified into nine general ship types (table 1).

3.3.1.2 Ship accident data and preparation

The ship accident data used in the analysis was acquired from the Transportation Safety Board's (TSB) Marine Safety Information System (MARSIS) database containing information on ships involved in accidents and incidents in Canadian water and international waters when a Canadian-flagged ship is involved. The TSB-MARSIS database is publicly available and contains information from 1975 to the present. The dataset used included the occurrence and ship tables; and both tables were joined together based on the occurrence and ship identifier numbers to understand the number of ships involved in occurrences. Combining the two tables provides information on the ship(s) involved (e.g., size, flag, type), the exact geographic coordinates time of occurrence, occurrence type (accident/incident), accident or incident type (e.g., collision, striking, total mechanical failure, sustaining damage rendering ship unseaworthy, injury to persons, fire, explosions).

As per the TSB, a marine accident can be defined as an occurrence resulting directly from the operation of a ship in which a person is injured/killed or the ship:

1. sinks, founders or capsizes;
2. is involved in a collision;
3. sustains a fire or explosion;
4. goes aground;
5. sustains damage that affects its seaworthiness or renders it unfit for purpose; and/or
6. is missing or abandoned.

In addition to this, the ship operator (other than a pleasure ship) that has direct knowledge of the occurrence must report the previous accidents to the TSB[4]. For our analysis, we only looked at select accidents and reclassified specific TSB accident types into five general accident types (table 3.1)[5]. The TSB ship types were also reclassified to the nine general ship types (table 3.2).

Table 3.1: Ship accident types and definitions of accidents used in the study.

General accident type	TSB accident types	Definition
Capsize, sinking/ foundering	Capsizes, sank-flooding, sank-founders (taking on water above the waterline)	Vessel sank/foundered or capsized.

---

[4] https://laws-lois.justice.gc.ca/eng/regulations/SOR-2014-37/page-2.html#h-5

[5] Although total failure of any machinery or technical system are often considered in accident related work (i.e., a failure could lead to a drifting event, which could lead to an accident), they were excluded from this analysis for two reasons: (1) they are classified as marine incidents and (2) there has been a change in reporting of said events since 2014, which has led to an increase in incidents of the category since.

Collision/striking (allision)	Collision-struck by vessel, collision-with another vessel or other floating object, striking-allision with a fixed object (striking-includes berthed/docked vessels)	Striking or being struck by another vessel while maneuvering. Striking any fixed or floating object, or a maneuvering vessel striking a non-maneuvering vessel.
Fire/explosion	Fire, explosion	A fire or explosion on board the vessel.
Grounding (powered/ non-powered)	Grounding-not under power (includes drifting/non-intentional), grounding-under power (non-intentional)	Vessel being aground or hitting/touching shore or sea bottom or underwater objects.
Sustains damage render unseaworthy	Sustains damage rendering unseaworthy/unfit for purpose	Vessel sustains damage rendering unseaworthy (due to weather, ice, etc.).

Table 3.2: Ship (vessel) type classification scheme between NORDREG, derived AIS, and TSB datasets.

General ship type	Example NORDREG ship types	Example AIS ship types	Example TSB ship types
Cargo (commercial)	General cargo, heavy load vessel	Cargo, container ship, general cargo, heavy load carrier, reefer.	General cargo, container ship.
Dry bulk (commercial)	Bulk carrier, grain ship	Bulk carrier	Bulk carrier, combination carrier (OBO)
Ferry/Ro-Ro/passenger (commercial)	Passenger ship	Passenger, ro-ro/passenger ship	Passenger, ferry, ro-ro-cargo
Fishing (non-commercial)	Fishing vessel	Factory trawler, fishing vessel, trawler	Gillnetter, long liner, trawler
Government/research (non-commercial)	Icebreaker, fisheries patrol/research, navy ship, oceanographic research, research	Icebreaker, fishery patrol/research, military ops, pilot ship, search and rescue	Coastguard, icebreaker, oceanographic/hydrographic survey, patrol vessel, rescue, seismic survey
Others/special ships	Drill rig, drill ship	Diving support vessel, drill ship	Dredger, hopper, drillship, workboat

Pleasure vessels (non-commercial)	Adventurer, pleasure craft	Cruiser, pleasure craft, sailing vessel, sloop, yacht	Recreational craft, sailing vessel
Tankers (commercial)	Tanker	Chemical carrier, chemical tanker, crude oil tanker, oil/chemical tanker	Chemical tanker, product tanker
Tugs/barge (non-commercial)	Self-powered barge, tug	Anchor handling vessel, port tender, tug	Barge (bulk, OBO, product), tug

3.3.1.3 Sea ice data

The data used for sea ice concentration is based on Nimbus-7, SMMR and DMSP SSM/I-SSMIS passive microwave data from the National Snow & Ice Data Center (NSIDC, product 0051) with a monthly temporal resolution and a spatial resolution of 25 kilometres². Multiple studies have used this data as one of the main bases to identify sea ice trends in the Arctic (Ding et al., 2017; Petty et al., 2017; Onarheim et al., 2018).

3.4 Analytical steps taken

The consolidated ship traffic dataset (1990 to 2019) was summarized for the NORDREG zone into a monthly (120 data points) and annual (i.e., full shipping season) time-series (30 data points) for all ships and by ship type. The TSB-MARSIS accidents (number of ships involved in accidents) were also summarized into a monthly and annual time-series. Finally, the NSIDC sea-ice extent (sea-ice extent in km²) datasets were summarized and converted into monthly and yearly (average sea-ice extent) time-series datasets. Annual shipping-season accident rates for the years 1990 to 2019 were then computed using the number of ships involved in accidents combined with the number of nm sailed by ships in a given shipping-season year. Average ship type shipping-season accident rates were also computed for the entire 30-year time period (1990-2019) using the total number of ships involved in accidents combined with the total number of nm sailed by ship types for the shipping-season.

To investigate statistical associations between monthly and yearly ship traffic, ship accidents & accident rates, and sea-ice extent within the Canadian Arctic, we use the monthly and yearly time-series data for ship traffic and sea-ice extent during the shipping-season for the entire 30-year time period (1990-2019) to perform correlation analysis, using the non-parametric Kendall Tau approach. The monthly and yearly time-series data for ship traffic, accidents, accident rates, and sea-ice extent were detrended before the correlation analysis to ensure correlation is due to a shared trend.

We then used the monthly and yearly time series to investigate the statistical trends during the shipping season on a monthly and annual scale for ship traffic, accidents, accident rates, and sea-ice extent. The trends were computed for the entire 30-year period (1990-2019). Trends were computed using the non-parametric Sen’s estimator of slope test. The Mann-Kendall test (Mann, 1945; Kendall, 1975) determined if a statistically significant (alpha of 0.05) trend existed. To perform the tests, a similar approach to Partal et al. (2006) and Gocic et al. (2013) was implemented, where there were essentially three components:

a) All of the time-series variables were assessed to determine whether or not lag-1 autocorrelation (i.e., serial correlation) was present, using the Rank von Neumann test for lag-1 autocorrelation, at an alpha of 0.05.

b) If lag-1 autocorrelation were present, then the variables would be prewhitened using the Zhang et al. (2000) approach for Sen’s estimator of slope and the Mann-Kendall tests.

c) If no lag-1 autocorrelation were present, Sen’s estimator of slope and Mann-Kendall test would apply to the original data.

3.5 Results

3.5.1 Ship traffic analysis (shipping season 1990-2019)

Most ship traffic occurs during the shipping-season months from July to October, annually (88-100%). Most of the recorded ship traffic[6] during the shipping season comes from ships that are >300 GT (89-100%). On average (1990-2019), during the shipping season months for ships >300 GT, commercial ship traffic contributes 55.8%, where non-commercial ship traffic contributes 42.9% of total ship traffic. Specifically, government/research ships contribute the most traffic (22.8%), followed by cargo (20.1%), tankers (14.5%), dry bulk (12.0%), tugs/barge (9.8%), fishing (9.7%), ferry/Ro-Ro/passenger (9.2%), others/special ships (1.3%), and pleasure vessels (0.7%). During the shipping-season months, relatively high ship traffic density occurs through the Hudson Strait into Hudson Bay, off the East coast of Baffin Island, and through the NWP (figure 3.1).

All ship traffic from 1990-2019 during the shipping season is increasing at a statistically significant annual rate of 9,275 nm yr^{-1}, commercial ship traffic at 5,011 nm yr^{-1}, and non-commercial ship traffic 4,658 nm yr^{-1}. Fishing vessels are the ship type that has the highest increasing rate that is statistically significant at 4,658 nm yr^{-1}, followed by cargo (1,671 nm yr^{-1}), tankers (1,385 nm yr^{-1}), ferry/Ro-Ro/passenger (1,303 nm yr^{-1}), dry bulk (378 nm yr^{-1}) and pleasure vessels (427 nm yr-1). Government/research and tugs/barge are both increasing, at respective rates of 1,252 and 308 nm yr^{-1}, respectively; however, they are not statistically significant.

---

[6] It is voluntary for <300 GT to carry AIS or report to NORDREG; therefore, we refer to the ship traffic as recorded ship traffic.

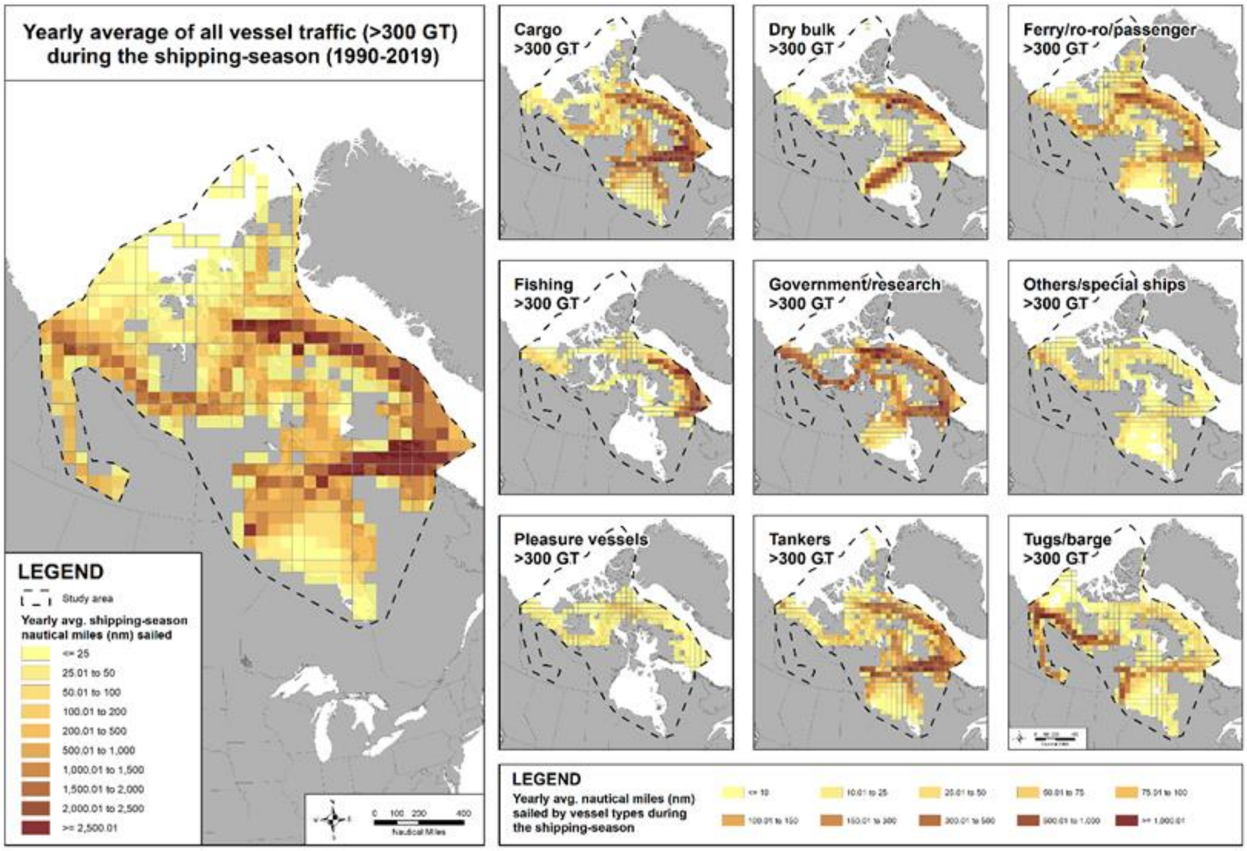


Figure 3.1: Map of the yearly average (1990-2019) number of nautical miles (nm) sailed by ship traffic (>300 GT) during the shipping season, broken down by general vessel types. The full Mackenzie River is shown for visualization purposes, however the southern portion is excluded from the study.

Referring to table 3.3, all ship traffic from 1990 compared to 2019 has increased by +243.6%, non-commercial ship traffic increasing (+328.1%) even more than commercial ship traffic (+224.6%).In terms of ship types, the largest relative traffic changes are seen from non-commercial ships such as fishing vessels (+1,111.5%), and tugs/barge (+391.5%) along with commercial ships such as ferry/ro-ro/passenger vessels (+443.9%), dry bulk (+254.5%), and cargo ships (206.2%).

Table 3.3: Number of nautical miles (nm) sailed by ships >300 GT during the shipping season from 1990 to 2019 (+ represents more in 2019; - represents more in 1990.

Ship traffic 1990 vs 2019 (>300 GT) traffic (nautical miles sailed) during the shipping-season			
Ship type	**1990**	**2019**	**% change**
Cargo	44,157	135,195	+ 206.2%

Dry bulk	32,530	115,307	+ 254.5%
Ferry/ro-ro/passenger	8,376	45,559	+ 443.9%
Fishing	8,450	102,381	+ 1,111.5%
Government/research	38,494	89,053	+ 131.3%
Others/special ships	6,802	0	-100.00%
Pleasure vessels	0	5,276	+ 100.00%
Tankers	30,597	79,382	+ 159.4%
Tugs/barge	6,730	33,077	+ 391.5%
Commercial	**115,660**	**375,442**	**+ 224.6%**
Non-commercial	**53,674**	**229,787**	**+ 328.1%**
Total	**176,136**	**605,229**	**+ 243.6%**

3.5.2 Ship accidents and accident rates (shipping season 1990-2019)

From 1990-2019, 111 ships (>300 GT) were involved in accidents as reported to the TSB within the study area. Vessels involved in occurrences where a vessel sustains damage rendering unseaworthy[7] (38.8%) are the most common, followed by groundings (32.4%), then by collision/striking's[8] (14.4%), fire/explosions (12.6%) and capsize/sinking/foundering (1.8%) (table 3.4). Spatially, we see that most groundings occur near/around the Mackenzie River, where a large majority of sustains damage rendering unseaworthy have occurred south of Iqaluit and near Resolute (figure 3.2). Commercial ships have been involved in 51.4%, whereas non-commercial ships have been involved in 48.6% of vessels involved in accidents.

Table 3.4: The total number of ships (>300 GT) involved in accidents from 1990 to 2019 during the shipping season, broken down by accident type.

Total number of ships (>300 GT) involved in accidents from 1990 to 2019 (shipping-season)					
Year	Collisions/ striking's	Fire/explosions	Groundings	Sank/ foundered/ capsized	Sustains damage rendering unseaworthy
1990	0	2	1	0	2
1991	0	1	3	0	3
1992	0	0	1	0	6

---

[7] Which includes accidents involving ice.

[8] One collision/striking occurrence might involve two or more vessels – the numbers presented are not absolute accidents, but vessels involved in accidents.

1993	0	0	1	0	1
1994	0	0	1	0	2
1995	1	2	1	0	2
1996	0	0	2	1	5
1997	0	0	0	0	1
1998	0	0	1	0	1
1999	1	2	1	0	1
2000	0	0	0	0	2
2001	1	1	1	0	1
2002	0	0	0	0	0
2003	0	1	2	0	1
2004	2	1	0	0	1
2005	1	0	1	0	0
2006	0	0	0	0	1
2007	4	0	3	0	3
2008	0	1	0	0	1
2009	0	1	2	1	1
2010	0	1	3	0	0
2011	0	0	0	0	1
2012	0	0	2	0	1
2013	0	0	2	0	0
2014	0	0	1	0	0
2015	0	0	0	0	0
2016	4	0	2	0	0
2017	0	0	3	0	4
2018	0	1	1	0	2
2019	2	0	1	0	0
Total	**16**	**14**	**36**	**2**	**43**

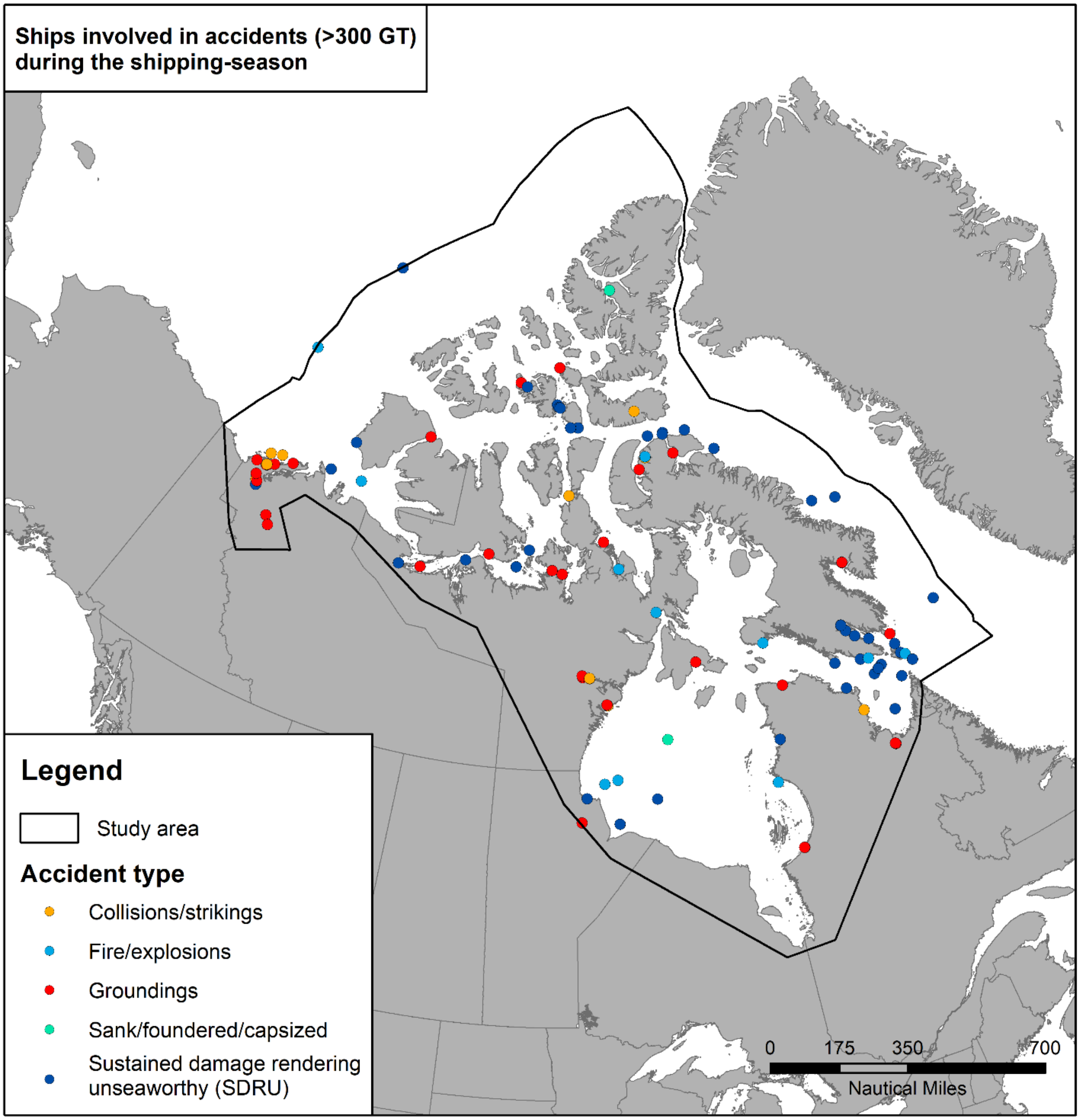


Figure 3.2: Locations of ships (>300 GT) involved in accidents from 1990-2019 during the shipping season, mapped by accident type, as recorded by the TSB.

Overall, during the shipping season from 1990-2019, we see a statistically significant negative trend in ship accidents for commercial ships (-0.06 accidents yr^{-1}). We also see a decrease for all ships (-0.06 accidents yr^{-1}*)*; however, it is not statistically significant.

For all ship types, the accident rate from 1990 (2.84E-05 accidents/nm) compared to that from 2019 (4.96E-06 accidents/nm) has decreased by -82.5%. The accident rate for commercial and non-commercial ships from 1990 (2.59E-05; 3.73E-05 accidents/nm) compared to that from 2019 (5.33E-06; 4.35E-06 accidents/nm) have decreased by -79.4%, and -88.3%, respectively.

Overall, during the shipping season from 1990-2019, we are seeing statistically significant decreases in accident rates for all ships (-6.31E-07 accidents/nm yr^{-1}). There are also decreasing trends for commercial ships (-8.64E-07 accidents/nm yr^{-1}), and non-commercial ship accident rates (-3.97E-07 accidents/nm yr^{-1}), however not statistically significant.

The only statistically significant correlation between ship traffic and accidents is at the monthly level, between all ship traffic and all ship accidents (0.14) indicating that higher amounts of ship traffic is associated with a higher number of vessels involved in accidents.

In terms of correlations between ship traffic and accident rates, there is again only one statistically significant correlation, at the monthly level. This is between commercial ship traffic and commercial accident rates (-0.14), indicating that as there is more ship traffic the respective accident rate is lower.

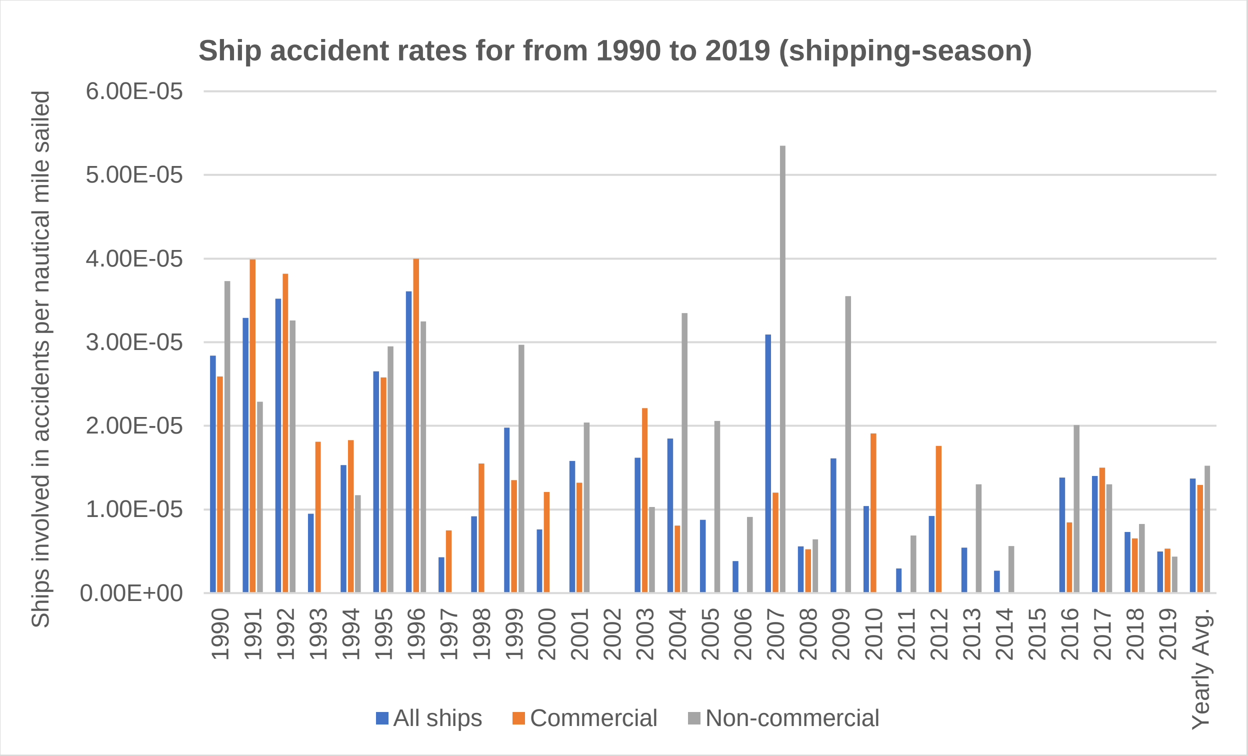


Figure 3.3: Accident rates for each high-level ship type, per year high-level ship type.

3.5.3 Sea ice and shipping in the Canadian Arctic

Sea ice extent is generally at its minimum within the study area during the shipping-season months, specifically so in September. During the shipping season, the maximum sea-ice extent occurs typically during the first month of the shipping season, July. The minimum and maximum sea ice extent in the study area in 1990 were 1,472,745 and 2,675,785 km² and in 2019 it decreased to 1,126,765 and 2,005,956 km² (-24% & -25%), respectively. Sea ice extent during the shipping season at the monthly level from 1990-2019 is decreasing at a statistically significant rate of -3,193 km² mo^{-1}.

Monthly ship traffic and sea-ice extent during the shipping season for all ships (-0.5), commercial ships (-0.49), and non-commercial ships (-0.48) all exhibit statistically significant moderate negative correlations from 1990-2019 (table 3.5) (i.e., higher ship traffic when there is less sea ice extent). The negative correlations between ship traffic and sea ice are consistent with Pizzolato et al. (2014); however, our results indicate an even stronger association between ship traffic and sea ice.

Table 3.1: Detrended monthly correlations (Kendall's Tau) between ship traffic, accidents, accident rates, and sea ice extent during the shipping season from 1990-2019, at the monthly and annual (full-shipping season) levels.

Monthly and full shipping-season detrended correlations (Kendall's Tau) from 1990 to 2019				
	Monthly		Full shipping-season	
Traffic, accidents, accident rates and sea ice extent (SIE)	*KT*		*KT*	
All ship traffic & SIE	**-0.50**	*	-0.13	
Commercial traffic & SIE	**-0.49**	*	-0.07	
Non-commercial traffic & SIE	**-0.48**	*	-0.16	
All ship accidents & SIE	-0.06		0.06	
Commercial accidents & SIE	0.01		-0.19	
Non-commercial accidents & SIE	-0.07		0.21	
All ship accident rates & SIE	0.12		0.11	
Commercial accident rates & SIE	**0.17**	*	-0.16	
Non-commercial accident rates & SIE	0.01		**0.26**	*
Accidents, accident rates and traffic	*KT*		*KT*	
All ship traffic & all accidents	**0.14**	*	0.02	
Commercial traffic & commercial accidents	0.03		0.13	
Non-commercial traffic & non-commercial accidents	0.13		-0.06	
All ship traffic & all accident rates	-0.10		0.00	
Commercial traffic & commercial accident rates	**-0.14**	*	0.05	
Non-commercial traffic & non-commercial accident rates	0.01		-0.15	

** & **bold** indicates statistical significance at an alpha of 0.05*

At the monthly level, there exists a significant positive correlation between accident rates from commercial ships and sea ice extent (0.17), indicating that higher commercial accident rates are slightly associated with months with more sea ice extent. There is a bit stronger of a correlation at the yearly level between non-commercial accident rates and average sea ice extent (0.26).

Table 3.2: Statistical trends (Sen's slope estimator) for ship traffic, accidents, accident rates, and sea ice extent during the shipping season from 1990-2019 for monthly and yearly (full shipping-season). Bold and star indicate statistical significance at an alpha of 0.05.

Ship traffic, accidents, accident rates, and sea ice extent trends (Sen's Slope) during the shipping season from 1990 to 2019				
Ship traffic (nm sailed)	Monthly		Full shipping-season	
All ship traffic	**612**	*	**9,275**	*
Commercial ship traffic	**309**	*	**5,011**	*
Cargo	**118**	*	**1,671**	*
Dry bulk	41		**378**	*
Ferry/Ro-Ro/ passenger	**48**	*	**1,237**	*
Tanker	101		**1,385**	*
Non-commercial ship traffic	**301**	*	**4,658**	*
Fishing	165		**2,802**	*
Government/research	**76**	*	1,252	
Pleasure vessels	0		**127**	*
Tugs/barge	25		308	
Ships involved in accidents				
All accidents	0.00		-0.06	
Collisions/strikings	0.00		0.00	
Fire/explosions	0.00		0.00	
Groundings	0.00		0.00	
Sank/foundered/capsized	0.00		0.00	
Sustains damage rendering unseaworthy (SDRU)	**0.00**	*	**-0.06**	*
Commercial ship accidents	0.00		**-0.06**	*
Non-commercial ship accidents	0.00		0.00	
Accident rates (nm sailed per accident)				
All ship accident rate	0		**-6.31E-07**	*
Collision/striking accident rate	0		0	
Fire/explosion accident rate	0		0	
Grounding accident rate	0		-9.85E-08	
Sank/foundered/capsized accident rate	0		0	
SDRU accident rate	0		**-3.38E-07**	*
Commercial ship accident rate	0		-8.64E-07	
Non-commercial ship accident rate	0		-3.97E-07	
Sea ice extent (km²)				
Sea ice extent (monthly/avg.)	**-3,193**	*	-14,618	

3.6 Discussion

As sea ice continues to decrease, ship traffic, specifically commercial ship traffic, increases. Although decreases in sea ice extent are not the only drivers in the increase of ship traffic (e.g., last chance tourism) (Lemelin et al., 2010; Dawson et al., 2010; Dawson et al., 2014; D’Souza et al., 2021), we are seeing a correlation between ship traffic and sea ice extent, which is even stronger in more recent years. The link between the decrease in sea ice extent and increase in ship traffic during the shipping season is further quantified in the Canadian Arctic with moderately strong statistically significant negative correlations between ship traffic and sea-ice extent at the monthly level, and statistically significant increasing trends in ship traffic and decreasing trends in sea-ice extent at the monthly scale.

With increases in ship traffic comes increases in ship accidents, which can increase the likelihood of ship-source spills from said events that can be very problematic for the economy and environment in the Canadian Arctic. Although we are seeing increases in ship traffic and decreases in sea ice extent, accident rates are decreasing for all and commercial ships over the entire period.

There are study limitations associated with the accident data, AIS data, NORDREG data, combined ship traffic databases, and associated accident rates. For the accident data it is important to note that accident data and corresponding databases, in general, have many limitations associated with them, such as (i) underreporting, (ii) incompleteness, and (iii) change in reporting standards (Psarros et al., 2010; Hassel et al., 2011; Hanninen et al., 2014; Council of Canadian Academies, 2016; Sormunen et al., 2016; Du et al., 2020), this can, in turn, lead to biases in accidents statistics and corresponding accident rates. In addition, the analysis does not capture the variability of the severity of accidents due to the aggregation of accident types. Within an accident type, there could be different severities associated with each specific accident (e.g., low to high severity events). In terms of overall AIS limitations, there are no non-AIS vessels captured (i.e., smaller vessels like pleasure or fishing vessels). Class B transponders have become more affordable over the years; therefore, a potential increase in smaller vessel (non-commercial traffic) recorded by AIS in more recent years. Therefore, there is the potential that the increase in pleasure vessel traffic could be in part due to an increase in pleasure vessels with AIS transponders. When creating the overall ship traffic database used in this study, two different reporting sources of ship traffic were used (NORDREG and satellite-based AIS). NORDREG is a manual entry database, where SB-AIS is automatic. However, reporting requirements are similar. NORDREG only began to include vessel reports in Mackenzie River in recent years. Lastly there are limitations associated with the accident rates presented in this study. Accident rates can vary greatly depending on the exposure variable used (e.g., ship transits, hours of operations, distance sailed, port calls) as the denominator in the normalization of accident data (Bye et al., 2019).

3.7 Conclusion

This study's results can help inform an understanding of reported ship traffic, accidents, and corresponding accident rates within the Canadian Arctic from 1990 to 2019. Although there is a public perception that large commercial vessels currently and will continue to contribute the greatest risk in the Canadian Arctic, commercial vessels accident rates are decreasing at a statistically significant yearly level. However, it is true that the large commercial vessels will contribute the most in terms of the consequence side of the risk equation (i.e., large vessels carry more oil); no matter, non-commercial ships have higher accident rates.

Acknowledgements

This work was funded by the Marine Environmental Observation Prediction & Response Network (MEOPAR) and Clear Seas. Satellite-based AIS data were provided by exactEarth Ltd., 2019 through partnership with MEOPAR.

3.7 References cited in chapter 3

Aksenov, Y., Popova, E. E., Yool, A., Nurser, A. J. G., Williams, T. D., Bertino, L., & Bergh, J. (2017). On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice. Marine Policy, 75, 300–317. https://doi.org/10.1016/j.marpol.2015.12.027

Bye, R.J. Almklov, P.G. (2019). Normalization of maritime accident data using AIS. Mar. Policy 109, 103675.

Chénier, R., Abado, L., Sabourin, O., & Tardif, L. (2017). Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. Transactions in GIS, 21 (6), 1085–1097

Constable, A. J., Harper, S., Dawson, J., Holsman, K., Mustonen, T. , Piepenburg, D., Rost, B., Bokhorst, S., Boike, J., Cunsolo, A., Derksen, C., Feodoroff, P., Ford, J. D., Howell, S. E., Katny, A. C., MacDonald, J. P., Ønvik, Å., Robinson, S. A., Dorough, D. S., Shadrin, V., Skern-Mauritzen, M., Smith, S. L., Streletskiy, D., Tsujimoto, M. and Van Dam, B. (2022): Cross-Chapter Paper 6: Polar Regions , In: Climate Change 2022: Impacts, adaptation and vulnerability. Contribution of the WGII to the 6th assessment report of the intergovernmental panel on climate change, IPCC AR WGII, Cambridge University Press.

Copland, L., Dawson, J., Tivy, A., Delaney, F., Cook, A., and Creed, I. (2021). Changes in shipping navigability in the Canadian Arctic between 1972 and 2016. Facets 6, 1069–1087. doi: 10.1139/facets-2020-0096

Council of Canadian Academies. (2016). Commercial marine shipping accidents: understanding the risks in Canada : workshop report. Available at https://clearseas.org/wp-content/uploads/2016/04/CofCA_16-111_Clear-Seas_Book_e_web.pdf. Accessed March 2019.

Dawson, J., Stewart, E., & Scott, D. (2010). Climate change and polar bear viewing: A case study of visitor demand, carbon emissions and mitigation in Churchill, Canada. In C. M. Hall & J. Saarinen (Eds.), Tourism and change in polar regions: Climate, environment and experience (pp. 89–103). Routledge.

Dawson, J., Johnston, M. E., & Stewart, E. J. (2014). Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. Ocean & Coastal Management, 89, 88–99. https://doi.org/10.1016/j.ocecoaman.2013.12.005

Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., & Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015 + Supplementary Appendix 1: Figs. S1–S7 (See Article Tools). ARCTIC, 71(1), 15. https://doi.org/10.14430/arctic4698

Dawson, J., Cook, A., Holloway, J., & Copland, L. (2022). Analysis of changing levels of ice strengthening (ice class) among vessels operating in the Canadian arctic over the past 30 Years. ARCTIC. doi:10.14430/arctic75553

Ding, Q., Schweiger, A., L'Heureux, M., Battisti, D. S., Po-Chedley, S., Johnson, N. C., … Steig, E. J. (2017). Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. Nature Climate Change, 7(4), 289–295. https://doi.org/10.1038/nclimate3241

D'Souza, J., Dawson, J., & Groulx, M. (2021). Last chance tourism: A decade review of a case study on Churchill, Manitoba's polar bear viewing industry. Journal of Sustainable Tourism. https://doi.org/10.1080/09669582.2021.1910828

Du, Lei & Goerlandt, Floris & Kujala, Pentti, (2020). Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data. Reliability Engineering and System Safety, Elsevier, vol. 200.

Eguíluz, V. M., Fernández-Gracia, J., Irigoien, X., & Duarte, C. M. (2016). A quantitative assessment of Arctic shipping in 2010–2014. Scientific Reports, 6(1). https://doi.org/10.1038/srep30682

Eriksen, T., & Olsen, Ø. (2018). Vessel Tracking Using Automatic Identification System Data in the Arctic. In L. P. Hildebrand, L. W. Brigham, & T. M. Johansson (Eds.), Sustainable Shipping in a Changing Arctic (Vol. 7, pp. 115–136). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-78425-0_7

Frey, K. E., Moore, G. W. K., Cooper, L. W., & Grebmeier, J. M. (2015). Divergent patterns of recent sea ice cover across the Bering, Chukchi, and Beaufort seas of the Pacific Arctic Region. Progress in Oceanography, 136, 32–49. https://doi.org/10.1016/j.pocean.2015.05.009

Gocic, M., Trajkovic, S. (2013). Analysis of changes in meteorological variables using MannKendall and Sen's slope estimator statistical tests in Serbia. Glob. Planet. Chang.100, 172–182

Haas, C., & Howell, S. E. (2015). Ice thickness in the northwest passage. Geophysical Research Letters, 42(18), 7673-7680. doi:10.1002/2015gl065704

Halliday, W.D., P.L. Tetu, J. Dawson, S.J. Insley, and R.D. Hilliard. (2018). Tourist vessel traffic in important whale areas in the western Canadian Arctic: Risks and possible management solutions. Marine Policy 97: 72–81. (5)

Hanninen, M., Kujala, P. (2014). Bayesian network modeling of Port State Control inspection findings and ship accident involvement. Expert Syst. Appl. 41, 1632e1646. http://dx.doi.org/10.1016/j.eswa.2013.08.060.

Hassel, M., Asbjørnslett, B.E., Hole, L.P. (2011). Underreporting of maritime accidents to vessel accident databases. J. Accid. Anal. Prevent. 4 (6), 2053–2063

Howell, S. E., Babb, D. G., Landy, J. C., & Brady, M. (2022). Multi-year sea ice conditions in the northwest passage: 1968–2020. Atmosphere-Ocean, 1-15.

doi:10.1080/07055900.2022.2136061

Huntington, H. P., Daniel, R., Hartsig, A., Harun, K., Heiman, M., Meehan, R., … Stetson, G. (2015). Vessels, risks, and rules: Planning for safe shipping in Bering Strait. Marine Policy, 51, 119–127. https://doi.org/10.1016/j.marpol.2014.07.027

IPCC. (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

Johnston, M., Dawson, J., De Souza, E., & Stewart, E. (2017). Management challenges for the fastest growing marine shipping sector in Arctic Canada: Pleasure crafts. Polar Record, 53(1), 67-78. https://doi:10.1017/S0032247416000565

Kendall, M.G. (1975). Rank Correlation Measures. Charles Griffin, London

Kochanowicz, Z., Dawson, J., Halliday, W. D., Sawada, M., Copland, L., Carter, N. A., Nicoll, A., Ferguson, S. H., Heide-Jørgensen, M. P., Marcoux, M., Watt, C., &; Yurkowski, D. J. (2021). Using western science and Inuit knowledge to model ship-source noise exposure for cetaceans (marine mammals) in Tallurutiup Imanga (lancaster sound), Nunavut, Canada. Marine Policy, 130, 104557. https://doi.org/10.1016/j.marpol.2021.104557

Laliberté, F., Howell, S. E. L., & Kushner, P. J. (2016). Regional variability of a projected sea ice-free Arctic during the summer months: REGIONAL SUMMER SEA ICE PROJECTIONS. Geophysical Research Letters, 43(1), 256–263. https://doi.org/10.1002/2015GL066855

Lemelin, H., Dawson, J., Stewart, E. J., Maher, P., & Lueck, M. (2010). Last-chance tourism: The boom, doom, and gloom of visiting vanishing destinations. Current Issues in Tourism, 13(5), 477-493.

Mann, H.B. (1945). Nonparametric tests against trend, Econometrica, 13, 245-259

Marty, J., & Potter, S. (2014). Risk Assessment for Marine Spills in Canadian Waters, Phase 1: Oil Spills South of the 60th Parallel. WSP Canada.

Marty, J., A. Nicoll, S. Potter, M. Wallace, and C. Lumière. (2016). Evaluation of the Risk of Oil Spills in Canadian Arctic Waters. Proceedings of the Thirty-ninth AMOP Technical Seminar, Environment and Climate Change Canada. Ottawa, ON. 1035-1046.

Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st century trans-Arctic shipping routes: Trans-Arctic shipping in the 21st Century. Geophysical Research Letters, 43(18), 9720–9728. https://doi.org/10.1002/2016GL069315

Onarheim, I. H., Eldevik, T., Smedsrud, L. H., & Stroeve, J. C. (2018). Seasonal and Regional Manifestation of Arctic Sea Ice Loss. Journal of Climate, 31(12), 4917–4932. https://doi.org/10.1175/JCLI-D-17-0427.1

Outten, S. D., & Esau, I. (2012). A link between Arctic sea ice and recent cooling trends over Eurasia. Climatic Change, 110(3–4), 1069–1075. https://doi.org/10.1007/s10584-011-0334-z

Partal, T., Kahya, E. (2006). Trend analysis in Turkish precipitation data. Hydrological Processes 20, 2011–2026

Petty, A. A., Schröder, D., Stroeve, J. C., Markus, T., Miller, J., Kurtz, N. T., … Flocco, D. (2017). Skillful spring forecasts of September Arctic sea ice extent using passive microwave sea ice observations: September Arctic Sea Ice Forecasts. Earth's Future, 5(2), 254–263. https://doi.org/10.1002/2016EF000495

Pizzolato, L., Howell, S. E. L., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic: SEA ICE AND SHIPPING, CANADIAN ARCTIC. Geophysical Research Letters, 43(23), 12,146-12,154. https://doi.org/10.1002/2016GL071489

Pizzolato, L., Howell, S. E. L., Derksen, C., Dawson, J., & Copland, L. (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Climatic Change, 123(2), 161–173. https://doi.org/10.1007/s10584-013-1038-3

Psarros, G., Skjong, R., Eide, M.S. (2010). Under-reporting of maritime accidents. Accid.Anal. Prev. 42, 619–625.

Smith, L. C., & Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by midcentury. Proceedings of the National Academy of Sciences, 110(13), E1191–E1195. https://doi.org/10.1073/pnas.1214212110

Sormunen, O., Hanninen, M. and Kujala, P. (2016). Marine Traffic, Accidents, and Underreporting in the Baltic Sea. Zeszyty Naukowe, 46(118), 163–177

Stephenson, S. R., Brigham, L. W., & Smith, L. C. (2014). Marine accessibility along Russia's Northern Sea Route. Polar Geography, 37(2), 111–133. https://doi.org/10.1080/1088937X.2013.845859

Stevenson, T. C., Davies, J., Huntington, H. P., & Sheard, W. (2019). An examination of trans-Arctic vessel routing in the Central Arctic Ocean. Marine Policy, 100, 83–89. https://doi.org/10.1016/j.marpol.2018.11.031

Winther, M., Christensen, J. H., Plejdrup, M. S., Ravn, E. S., Eriksson, Ó. F., &

Kristensen, H. O. (2014). Emission inventories for ships in the arctic based on satellite sampled AIS data. Atmospheric Environment, 91, 1–14. https://doi.org/10.1016/j.atmosenv.2014.03.006

Zhang X, Vincent LA, Hogg WD, Niitsoo A. (2000). Temperature and precipitation trends in Canada during the 20th century. Atmos Ocean 38(3):395–429

Chapter 4: Shipping traffic accident trends across the global Arctic (60th parallel) (2012-19)

Adrian Nicoll[1 2], Jackie Dawson[1], and Jérôme Marty[34], Luke Copland[1], Michael Sawada[1]
[1] Department of Geography, Environment, and Geomatics, University of Ottawa, Canada
[2] Transport Canada
[3] Council of Canadian Academies
[4] International Association for Great Lakes Research

Planned submission to: *Polar Geography or Arctic Science*

Authors declaration: *I am the first author on this scientific paper, performed all the data analyses, and contributed significantly to the methodology design and writing of the final manuscripts. This was scientific paper was designed in partnership with Drs. Jackie Dawson and Jérôme Marty, and written revised with the input of Drs. Jackie Dawson, Jérôme Marty, Luke Copland, and Michael Sawada.*

4.1 Abstract

In recent years ship traffic has been increasing in the global Arctic; concerns are raised that increases in shipping traffic through sensitive areas could lead to increases in ship accidents and pollution events. Current shipping routes in the Arctic (Northwest Passage and Northern Sea Route) are much shorter in transit time and, in turn, can have lower transit costs for the commercial shipping industry compared to routes through the Panama Canal and Suez Canal. It is expected that many of these areas in the Arctic will be ice-free and for longer periods in the coming decades, which could help to drive further increases in ship traffic in the Arctic. This is the first study to use Automatic Identification System (AIS) data with Lloyd's Register FairPlay (LRFP) accident data to derive and assess annual statistical trends for accident rates North of the 60th (N60) parallel and encompassing Exclusive Economic Zones (EEZ). We perform a statistical (trends) analysis on ship traffic, accidents, and accident rates from 2012 to 2019 for N60 and EEZs within the N60. For N60 from 2012 to 2019, there are positive statistically significant trends for all ship traffic (+2.655 million nm yr^{-1}), commercial ships (+1.598 million nm yr^{-1}), and non-commercial ships (+1.446 million nm yr^{-1}); where there are statistically significant annual decreases in ship accident rates for all ships (-3.64E-07 ship accidents/nm yr^{-1}), commercial ships (-9.39E-07 ship accidents/nm yr^{-1}), and non-commercial ships (-1.19E-07 ship accidents/nm yr^{-1}). Geographically, Russia, Norway, and Iceland exhibit the largest absolute positive statistically significant commercial and non-commercial ship traffic trends. Norway has the largest statistically significant negative trend for all ship and commercial ship accident rates. Overall, our results show that, for the most part, as ship traffic increases at the global (N60) and geographic (EEZ) levels, ship accident rates are decreasing.

Keywords: *Ship traffic; accidents; accident rates; Arctic; AIS; Lloyd's; trends*

4.2 Introduction

It has been reported that there have been recent increases in ship traffic for the entire Arctic (Eguíluz et al., 2016), which is even more apparent in different regions, including the Canadian Arctic (Pizzolato et al., 2014; Chénier et al., 2017; Dawson et al., 2018), Russian Arctic (Gunnarsson, 2021), and portions of the Norwegian Arctic (Olsen et al., 2020; Stocker et al., 2020). As ship traffic has increased, it has also been reported that there have been decreases in sea ice within the Arctic over the past years due to the role of climate change; the expectation is that many areas within the Arctic will be ice-free in the coming decades (Barnhart et al., 2015; Laliberté et al., 2016; Notz & Stroeve, 2016; Comiso et al., 2017; Kwok, 2018; Notz et al., 2020; Mudryk et al., 2021).

Current Arctic shipping routes, like the Northwest Passage (NWP) and the Northern Sea Route (NSR), could reduce transit times by commercial vessels from major ports by multiple days and have lower costs for the commercial shipping industry (Borgerson, 2008; Lasserre & Pelletier, 2011; Beveridge et al., 2016), from routes that currently transit through the Panama Canal and Suez Canal, respectively. In addition to the commercial shipping industry, tourism, such as last-chance tourism, is expected to increase in the coming years (Lemelin et al., 2012; Stewart et al., 2013; Dawson et al., 2014; Lasserre & Têtu, 2015).

One of the main immediate concerns from increased ship traffic within the Arctic is oil spills from ship accidents (Nevalainen et al., 2017; Stevenson et al., 2019), as, before a ship-source oil spill, an accident likely needs to occur (i.e., top-event). As ship traffic increases in the portions of the Arctic, there could also be an increase/higher probability of ship accidents and pollution events (Hartsig et al., 2012; Marchenko et al., 2018). Regionally in Canada, the Arctic has the highest accident rate (i.e., accident/incidents per vessel movement) compared to other higher ship traffic locations in Canada, which is in part due to the lack of charts/aids to navigation, infrastructure/capacity, and ocean/weather conditions (Council of Canadian Academies, 2016).

This is the first study to use Automatic Identification System (AIS) data with Lloyd's Register FairPlay (LRFP) accident data to derive and assess annual statistical trends for accident rates North of the 60th (N60) parallel and encompassing Exclusive Economic Zones (EEZ). This study provides a high-level understanding of reported ship traffic, accidents, and consequent accident rates from 2012 to 2019 N60 parallel. It should be noted that there are limitations associated with ship-accident databases, as information can be underreported, incomplete, and can be subject to the potential of change in reporting standards (Psarros et al., 2010; Hassel et al., 2011; Hanninen et al., 2014; Council of Canadian Academies, 2016; Sormunen et al., 2016; Du et al., 2020). This can, in turn, bias accident and accident rate statistics.

This study focuses on waters that are N60 parallel with a specific focus on EEZs encompassing said waters (figure 4.1). The two main objectives for this study were to 1) derive and compare ship traffic accident rates from 2012 to 2019 for all ship types, commercial ships, and non-commercial ships (>300 GT), and 2) assess and determine if there are annual statistically significant trends in ship traffic, accidents, and accident rates from 2012 to 2019, for all ship types, commercial ships, and non-commercial ships (>300 GT).

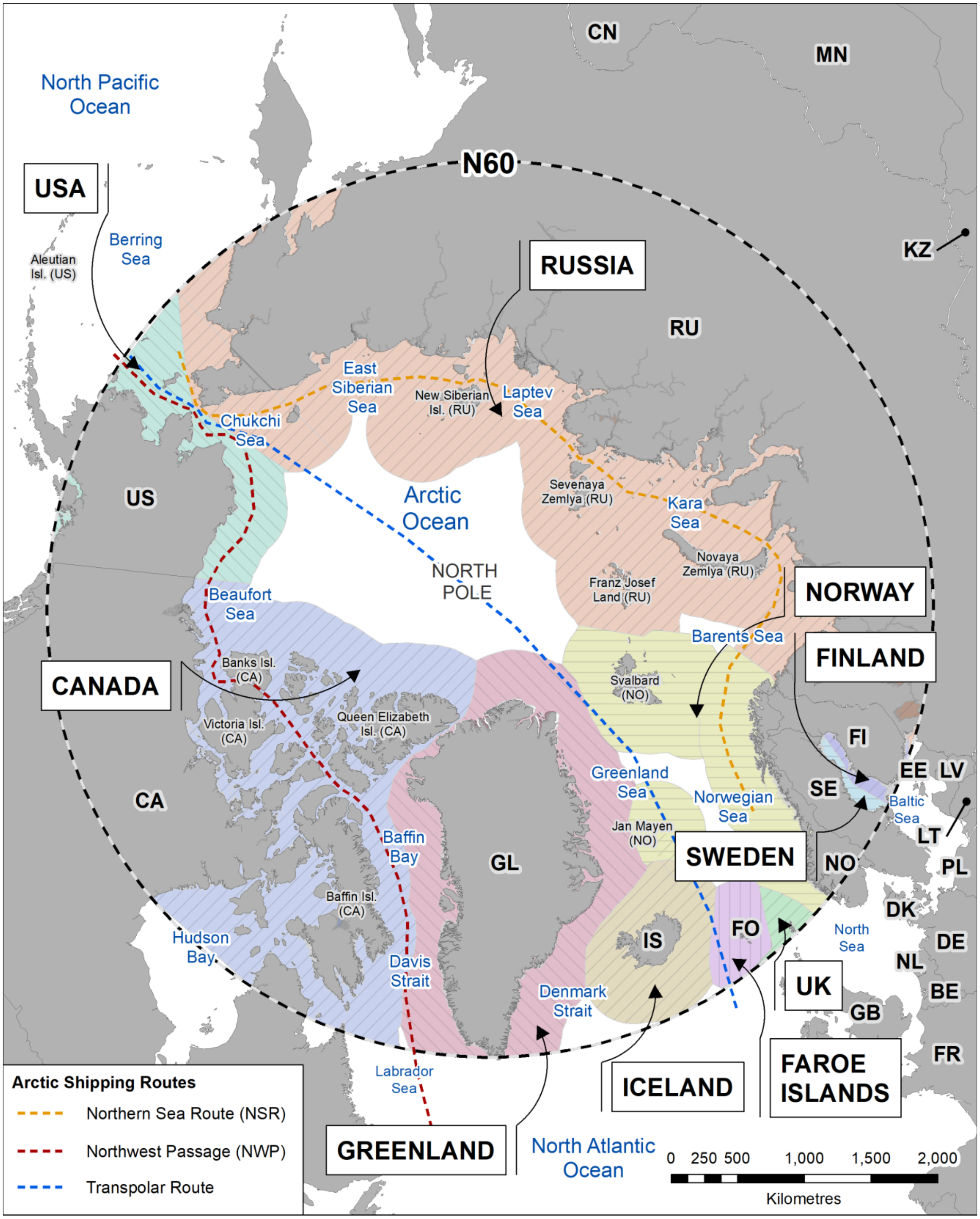


Figure 4.1: Map of the study area N60 parallel, with major Arctic shipping routes, and the EEZs N60 parallel.

4.3 Data description and analytical steps

***4.3.1 Ship traffic data** (satellite-based AIS (S-AIS))*

Decoded S-AIS dynamic Class A (messages 1, 2, 3), Class B (message 18), and LRIT (message 27) data from 2012 to 2019, provided by exactEarth Ltd. via MEOPAR for N60 parallel were used in this study. Class B AIS is voluntary and generally equipped aboard smaller ships (e.g., pleasure vessels and small fishing vessels). Internationally, Class A AIS is required aboard all vessels that are greater than 300 GT and engaged in an international voyage, or cargo vessels >500 GT not engaged in an international voyage, or all passenger ships, regardless of size as per regulation 19 of the International Convention for the Safety of Life at Sea (SOLAS) Chapter V (December 31, 2004).

S-AIS dynamic messages (1-3, 18, and 27) were converted into spatial points and stored within geodatabases by year and month and contained information on the ship's Maritime Mobile Service Identity (MMSI), position (latitude and longitude), speed over ground (SOG), course over ground (COG), and time recorded in UTC. The spatial points were queried to include moving vessels with a SOG of >= 0.2 (knots) and were converted into spatial tracklines stored within a geodatabase to analyze vessel movements over space and time.

The way that the tracklines were generated was by sorting the dynamic messages by MMSI and date time, then applying a distance and time threshold (80 kilometres and 300 minutes) to define trips. If the distance and time threshold was exceeded, the trip would be ended. Each trip was then converted into a GIS polyline (trackline), which was combined with statice vessel information (e.g., vessel type and size) from online marine intelligence databases (MarineTraffic, MyShipingTracking, Industry Canada). The large thresholds were used to remedy issues with potential temporal gaps present in positional data collected via Satellite for AIS (i.e., S-AIS positional messages), which is true in regions like the Arctic (Winther et al., 2014).

Nautical miles (nm) sailed (a distance-based ship traffic metric) were computed per EEZ (Flanders Marine Institute, 2019) N60 parallel as well as the entire area N60 parallel. An annual time-series per EEZ N60 and the entire area N60 of nm sailed from 2012 to 2019 for all ships, commercial ships, and non-commercial ships (table 4.1) >300 GT were used throughout the study. Commercial and non-commercial ships were defined based on the movement of vessels, often commercial as defined in table 4.1 follow defined routes (i.e., route bound ships) whereas non-commercial vessels routes are more sporadic (i.e., non-route bound ships).

Table 4.1: General, specific, and aggregated ship types used in this study.

General ship type	Specific ship type examples	Aggregated ship type for study
Cargo	General cargo, vehicle carrier, livestock carrier	Commercial
Container	Container ship, reefer	Commercial
Dry bulk	Bulk carrier, cement carrier, ore carrier	Commercial
Ferry/Ro-Ro	Ferry, Ro-Ro cargo, Ro-Ro	Commercial
Fishing	Fish carrier, fishing vessel, trawler	Non-commercial
Government/research	Anti-pollution, icebreaker, law enforcement, search and rescue	Non-commercial
Others/special ships	Cable layer, dive vessel, dredger	
Passenger	Passenger ship (cruise)	Non-commercial

Pleasure vessels	Pleasure craft, sailing vessel, yacht	Non-commercial
Tankers	Asphalt/bitumen tanker, chemical tanker, crude oil tanker	Commercial
Tugs/barge	Anchor handling vessel, pusher/tug, towing vessel	Non-commercial

4.3.2 Ship accident data *(LRFP database)*

Casualty data from the LRFP (2021) accident database (January 2012 to December 2019) contain information on worldwide accidents for vessels >100 GT. The accident types used in the study include collisions, contacts (i.e., striking's), fire/explosions, foundering's, hull damage, machinery damage, and strandings (i.e., groundings). The database also included information on the location (latitude and longitude) of the event, vessel name, vessel type, vessel size (e.g., Gross Tonnage), date, and other ship particulars.

The LRFP accident data was queried to include all ships involved in accidents N60 parallel (e.g., in one event, a ship could have a fire/explosion and then a collision – which would be counted as two accidents). The data was further queried only to include ships >300 GT to be consistent with the AIS. Data were then converted into a spatial format and aggregated per EEZ N60 parallel. An annual time-series per EEZ N60 and the entire area of vessels involved in accidents from 2012 to 2019 for all ships, commercial ships, and non-commercial ships >300 GT were used throughout this study.

LRFP data on the number of ships involved in accidents was also combined with the number of nautical miles (nm) sailed derived from S-AIS for the entire area N60 parallel and per EEZ N60 parallel for the entire period of 2012 to 2019, and per year from 2012 to 2019. AR = ships involved in accidents/nm sailed.

4.3.3 Analytical steps

Annual statistical trends from 2012 to 2019 for ship traffic, accidents, and accident rates by all commercial and non-commercial ships per EEZ N60 and the entire area N60. Trends were computed using the non-parametric Sen’s estimator of slope test, where the Mann-Kendall test (Mann, 1945; Kendall, 1975) was implemented to determine statistically significant trends at alphas of 0.1, 0.05, and 0.01.

Using a similar approach to Partal et al. (2006) and Gocic et al. (2013), there were three components to determining the annual statistical trends. First, all annual time-series variables were assessed to determine if lag-1 autocorrelation (i.e., serial correlation) was present, using the Rank von Neumann test (alpha of 0.05). Second, if lag-1 autocorrelation were present, the variables would be prewhitended using the Zhang et al. (2000) approach for Sen’s estimator of slope and the Mann-Kendall test. Third, if no lag-1 autocorrelation existed, the original Sen’s estimator of slope and Mann-Kendall test would apply to the original time series.

Relative yearly spatial accident rate differences are derived by taking the overall baseline ship accident rate from 2012 to 2019 (N60 parallel) and calculating the relative difference (%) per EEZ N60 parallel for the entire 2012 to 2019 period and each year from 2012 to 2019. This is done for all ships, commercial ships, and non-commercial ships to compare accident rates from each EEZ to the overall baseline accident rate.

4.4 Results

4.4.1 Ship traffic trends

Referring to table 4.2 and figure 4.2A, there are statistically significant increasing annual trends for all ship traffic (+2.655 million nm yr^{-1}), commercial ships (+1.598 million nm yr^{-1}), and non-commercial ships (+1.446 million nm yr^{-1}) at the global level (N60 parallel) from 2012 to 2019.

There are statistically significant increasing annual trends for all ship traffic within EEZs N60 parallel for Canada (+0.060 million nm yr^{-1}), Faeroe Islands (+0.130 million nm yr^{-1}), Greenland (+0.141 million nm yr^{-1}), Iceland (+0.307 million nm yr^{-1}), Norway (+1.099 million nm yr^{-1}), Russia (+1.034 million nm yr^{-1}), and the USA (+0.058 million nm yr^{-1}).

In terms of commercial ship traffic, there are also statistically significant increasing annual trends for select EEZs N60 parallel, including Canada (+0.054 million nm yr^{-1}), Faroe Islands (+0.076 million nm yr^{-1}), Greenland (+0.076 million nm yr^{-1}), Iceland (+0.131 million nm yr^{-1}), Norway (+0.795 million nm yr^{-1}), Russia (+0.449 million nm yr^{-1}), the UK (+0.028 million nm yr^{-1}), and the USA (+0.014 million nm yr^{-1}).

Increasing annual trends also hold for non-commercial ship traffic for select EEZs N60 parallel. Canada (+0.022 million nm yr^{-1}), Finland (+0.012 million nm yr^{-1}), Greenland (+0.074 million nm yr^{-1}), Iceland (+0.228 million nm yr^{-1}), Norway (+0.348 million nm yr^{-1}), Russia (+0.548 million nm yr^{-1}), and the USA (+0.046 million nm yr^{-1}).

Table 4.2: Ship traffic (nautical miles sailed) for ships >300 GT, annual trends from 2012 to 2019 for N60 parallel and EEZs that encompass N60 parallel, using Sen's Slope Estimator. Bold indicates statistical significance; *** < 0.01; ** < 0.05; * < 0.1.

Ship traffic (nautical miles sailed) annual trends (Sen's Slope) from 2012 to 2019 N60 parallel						
Ships >300 GT	All		Commercial		Non-commercial	
Canada	**59,890**	*	**54,417**	**	**21,845**	***
Faroe Islands	**130,390**	*	**76,268**	***	62,480	
Finland	51,230		-2,522		**11,679**	**
Greenland	**140,973**	***	**75,866**	***	**74,243**	***
Iceland	**307,398**	**	**131,319**	***	**228,070**	**
Norway	**1,098,765**	**	**794,517**	**	**347,628**	*
Russia	**1,033,581**	***	**449,353**	***	**548,339**	***
Sweden	20,225		-5,303		1,349	
UK	63,732		**28,334**	**	49,910	
USA	**58,342**	**	**14,023**	**	**46,074**	***
Arctic (N60)	**2,654,889**	***	**1,597,957**	***	**1,445,652**	**

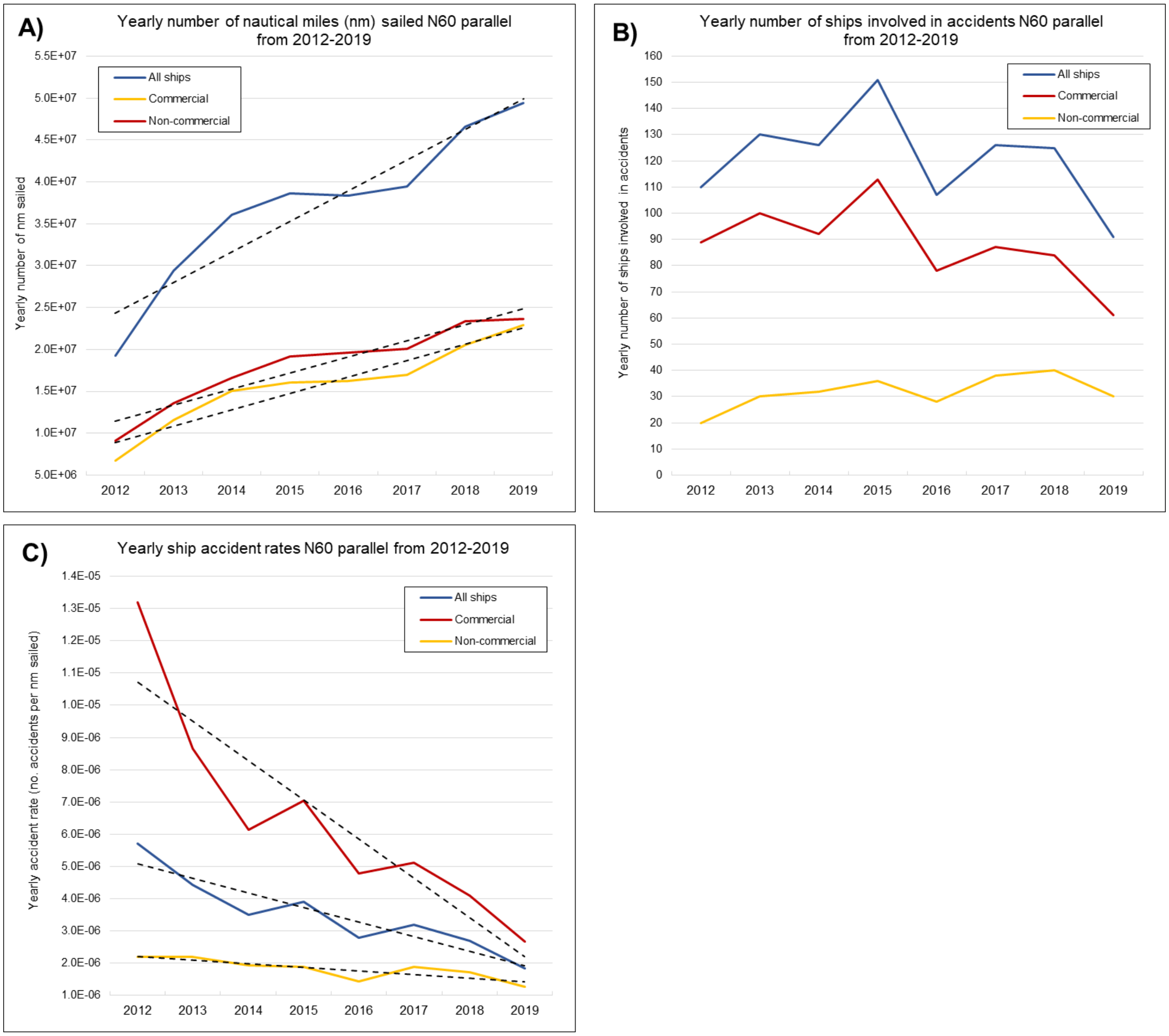


Figure 4.2: A) Yearly number of nautical miles (nm) sailed by all, commercial, and non-commercial ships (>300 GT) from 2012 to 2019 N60 parallel as recorded by S-AIS; dotted lines indicate trend(s). B) Yearly number of vessels involved in accidents by all, commercial, and non-commercial ships (>300 GT) from 2012 to 2019 N60 parallel as recorded by Lloyd's. C) Yearly accident rate (number of vessels involved in accidents per nm sailed) by all, commercial, and non-commercial ships (>300 GT) from 2012 to 2019 N60 parallel; dotted lines indicate trend(s).

4.4.2 Ship accident trends

Referring to table 4.3 and figure 4.2B, there are no statistically significant trends at the global level (N60 parallel) from 2012 to 2019 for ship accidents. However, we see an annual decrease of -1.00 ship accidents yr^{-1} for all ships, -3.23 ship accident yr^{-1} for commercial ships, and +2.00 ship accidents yr^{-1} for non-commercial ships. There are only two EEZs with statistically significant trends in ship accidents, the Faroe Islands for all ships (-0.33 ship accidents yr^{-1}) and Norway for commercial ships (-3.15 accidents yr^{-1}).

There are three EEZs with annual increases in all ship accidents (not statistically significant); Iceland (+0.20 ship accidents yr^{-1}), Russia (+2.33 ship accidents yr^{-1}), and the UK (+0.46 ship accidents yr^{-1}). Four EEZs with annual decreases in all ship accidents (not statistically significant except for the Faroe Islands); Faroe Islands (-0.33 ship accidents yr^{-1}), Finland (-0.63 ship accidents yr^{-1}), Norway (-2.50 ship accidents yr^{-1}), and the USA (-0.07 ship accidents yr^{-1}).

There are also three EEZs with annual increases in commercial ship accidents (not statistically significant); Iceland (+0.08 ship accidents yr^{-1}), Russia (+0.25 ship accidents yr^{-1}), and the UK (+0.41 ship accidents yr^{-1}), where there were three EEZs with annual decreases in commercial ship accidents (not statistically significant except for Norway); Finland (-0.90 ship accidents yr^{-1}), Greenland (-0.17 ship accidents yr^{-1}), and Norway (-3.15 ship accidents yr^{-1}).

For non-commercial ships, there are four EEZs with annual increases in non-commercial ship accidents (not statistically significant); Iceland (+0.10 ship accidents yr^{-1}), Norway (+0.50 ship accidents yr^{-1}), Russia (+0.42 ship accidents yr^{-1}), and the UK (+0.08 ship accidents yr^{-1}). Faroe Islands is the only EEZ that exhibited an annual decrease (not statistically significant) in shipping accidents per year (-0.08 ship accidents yr^{-1}).

Table 4.3: Ship accidents (ships involved in accidents) for ships >300 GT, annual trends from 2012 to 2019 for N60 parallel and EEZs that encompass N60 parallel, using Sen's Slope Estimator. Bold indicates statistical significance; *** < 0.01; ** < 0.05; * < 0.1.

Ship accidents (ships involved in accidents) annual trends (Sen's Slope) from 2012 to 2019 N60 parallel					
Ships >300 GT	All		Commercial		Non-commercial
Canada	0.00		0.00		0.00
Faroe Islands	**-0.33**	*	0.00		-0.08
Finland	-0.63		-0.90		0.00
Greenland	0.00		-0.17		0.00
Iceland	0.18		0.08		0.10
Norway	-2.50		**-3.15**	*	0.50
Russia	2.33		0.25		0.42
Sweden	0.00		0.00		0.00
UK	0.46		0.41		0.08
USA	-0.07		0.00		0.00
Arctic (N60)	-1.00		-3.23		2.00

4.4.3 Ship accident rate trends

Referring to table 4.4 and figure 4.2C, we see that there are statistically significant annual decreases in ship accident rates at the global level (N60 parallel) for all ships (-3.64E-07 ship accidents/nm yr^{-1}), commercial ships (-9.39E-07 ship accidents/nm yr^{-1}), and non-commercial ships (-1.19E-07 ship accidents/nm yr^{-1}).

All EEZs (except for Finland) show annual decreases in ship accident rates for all ships; Faroe Islands (-3.82E-07 ship accidents/nm yr^{-1}) and Norway (-5.77E-07 ship accidents/nm yr^{-1}) are the two that are statistically significant.

For commercial vessels, most EEZs (except for Finland and the UK) show annual decreases in ship accident rates. Faroe Islands (-7.40E-07 ship accidents/nm yr^{-1}), Greenland (-5.07E-07 ship accidents/nm yr^{-1}), Norway (-1.14E-06 ship accidents/nm yr^{-1}), and Russia (-2.63E-07 ship accidents/nm yr^{-1}) are the EEZs that exhibit statistical significance for trends.

There are no statistically significant annual trends in shipping accident rates for non-commercial vessels.

Table 4.4: Ship accident rates (ships involved in accidents per nautical miles sailed) for ships >300 GT, annual trends from 2012 to 2019 for N60 parallel and EEZs that encompass N60 parallel, using Sen's Slope Estimator. Bold indicates statistical significance; *** < 0.01; ** < 0.05; * < 0.1.

Ship accident rates (ships involved in accidents per nm sailed) annual trends (Sen's Slope) from 2012 to 2019 N60 parallel						
Ships >300 GT	All		Commercial		Non-commercial	
Canada	-4.11E-07		-4.97E-07		-8.04E-07	
Faroe Islands	**-3.82E-07**	***	**-7.40E-07**	**	-3.10E-07	
Finland	2.22E-08		1.92E-07		0.00E+00	
Greenland	-1.55E-07		**-5.07E-07**	**	0.00E+00	
Iceland	-3.04E-08		-3.85E-07		-9.30E-09	
Norway	**-5.77E-07**	***	**-1.14E-06**	***	-1.95E-07	
Russia	-1.32E-07		**-2.63E-07**	*	-2.86E-07	
Sweden	-5.52E-07		-9.05E-07		0.00E+00	
UK	-2.93E-07		8.13E-07		-1.10E-06	
USA	-1.30E-07		-2.47E-07		0.00E+00	
Arctic (N60)	**-3.64E-07**	**	**-9.39E-07**	**	**-1.19E-07**	**

4.4.4 Relative yearly spatial accident rate differences

The baseline accident rate from 2012 to 2019 for all ships (>300 GT) N60 parallel is 3.25E-06 ship accidents/nm sailed. Referring to figure 4.3, the baseline accident rate within the Canadian and Finnish EEZs has positive relative differences greater than +80% compared to the general area, where the United Kingdom and Norwegian EEZs also had positive relative differences +40.1 to +60% and +20.1 to +40%, respectively. The remaining EEZs all had negative relative differences, Russia & Sweden with relative differences of -39.9 to -20%, the United States with a relative difference of -59.9 to -40%, and Faroe Islands, Greenland, & Iceland with relative differences of -79.9 to -60%.

When comparing the yearly accident rate for each EEZ N60 to the baseline accident rate for overall area for all ships, the Finnish EEZ had a positive relative difference of greater than +80% for seven years (2012-2015, 2017-2019) and +40.1 to 60% for one year (2016). EEZs with negative relative differences for each year from 2012 to 2019 include the Faroe Islands[9], Greenland[10] and Iceland. Canadian, Norwegian and the UK EEZs had positive relative differences for six years (2012-2016, 2018; 2012-2017; and 2012-2013, 2016-2019, respectively). Russia had negative relative differences for seven years (2013-2019), whereas the US had negative relative differences for six years[11] (2012, 2014-2018). Sweden had three years with positive relative differences (2012-2013, 2017) and three years with negative relative differences (2014-2016).

---

[9] No accidents recorded within Faroe Island's EEZ during 2019.

[10] No accidents recorded within Greenland's EEZ during 2015.

[11] No accidents recorded within the US EEZ during 2019.

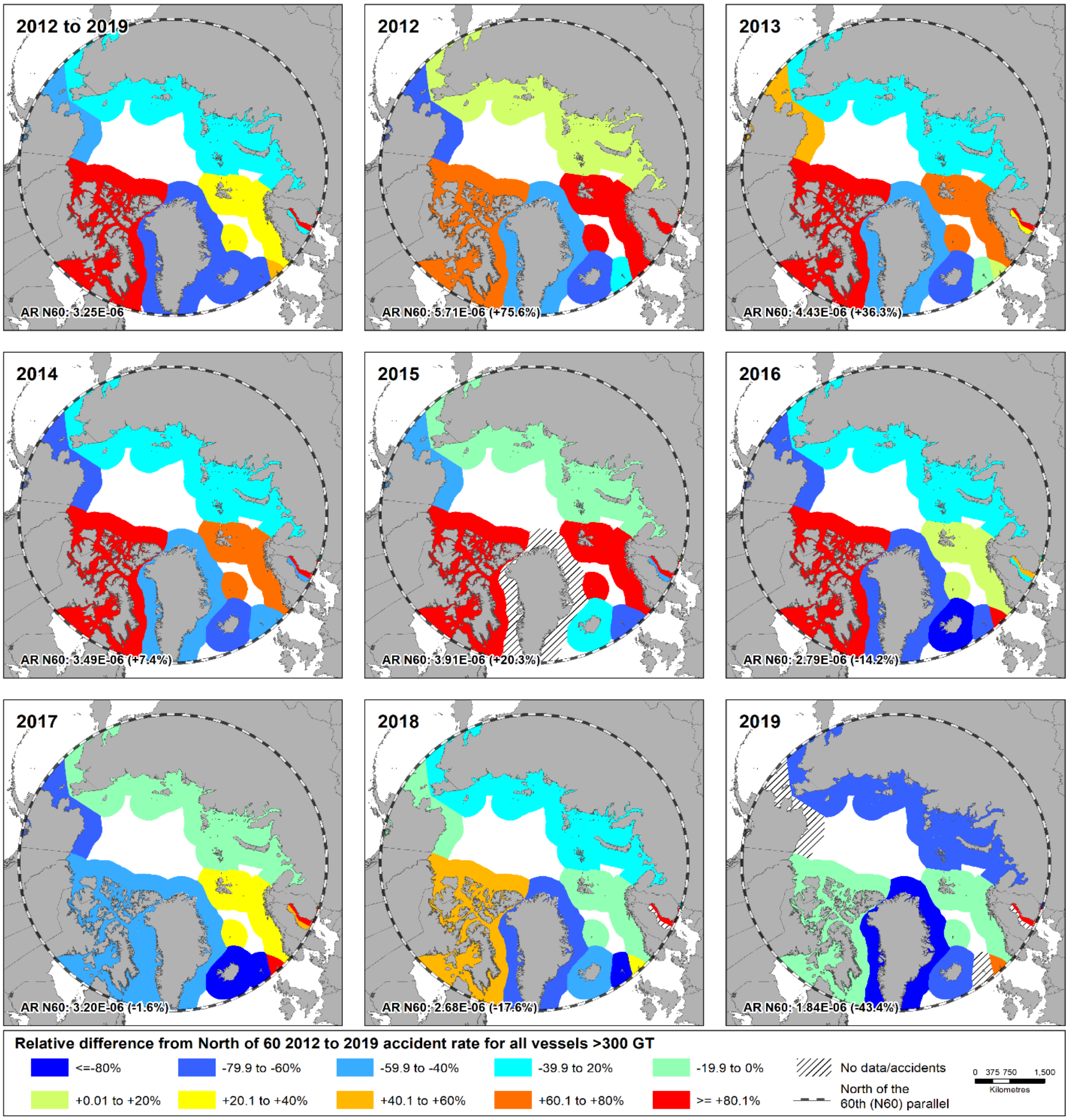


Figure 4.3: Maps of the relative difference (%) per EEZ from the N60 2012 to 2019 accident rate for all ships >300 GT, for 2012 to 2019 and for each year from 2012 to 2019. Locations in blue indicate a negative difference (i.e., lower accident rate), whereas locations in red indicate a positive difference (i.e., higher accident rate) from the N60 2012 to 2019 accident rate for all ships >300 GT. Text on bottom left of each sub-map indicate the accident rate for all ships >300 GT for the time-period, where the percentage represents the relative difference of the year compared to N60 2012 to 2019 accident rate.

From 2012 to 2019 N60 parallel, the baseline commercial accident rate is 5.59E-06 ship accidents/nm sailed (71.8% and 219.3% greater than the baseline accident rate for all ships and the baseline accident rate for non-commercial ships, respectively). Referring to figure 4.4, the majority of EEZs, including Canada (-19.9 to 0%), Faroe Islands (-79.9 to -60.0%), Greenland (-79.9 to -60.0%), Iceland (-59.9 to -40%), Russia (-59.9 to -40%), Sweden (-59.9 to -40%), and USA (-39.9 to -20%), all have negative relative differences for the baseline commercial ship accident rate compared to the overall area, where EEZs with positive relative differences include Finland (> +80%), Norway (+20.1 to +40%), and the UK (+40.1 to +60%).

When comparing the yearly commercial ship accident rates for each EEZ N60 to the baseline commercial ship accident for the entire period, Canada had positive differences for three years (2012, 2016, 2018) and negative differences for four years (2014-2015, 2017, 2019). Greenland had negative differences for six years (2012-2014, 2016-2018). Iceland had one year with positive differences (2012) and six years with negative differences (2013-2019). The Faroe Islands has one year with positive differences (2013) and five years with negative differences (2012; 2015-2018). The UK with four years of positive differences (2012, 2016, 2018-2019) and two years of negative differences (2014, 2017). Norway had six years of positive differences (2012-2017) and two years of negative differences (2018-2019). Sweden had two years of positive differences (2012-2013) and four years of negative differences (2014-2017). All eight years were positive in Finland (2012-2019), whereas all eight years were negative in Russia. The US had three positive (2013, 2015, 2018) and three negative years (2014, 2016-2017).

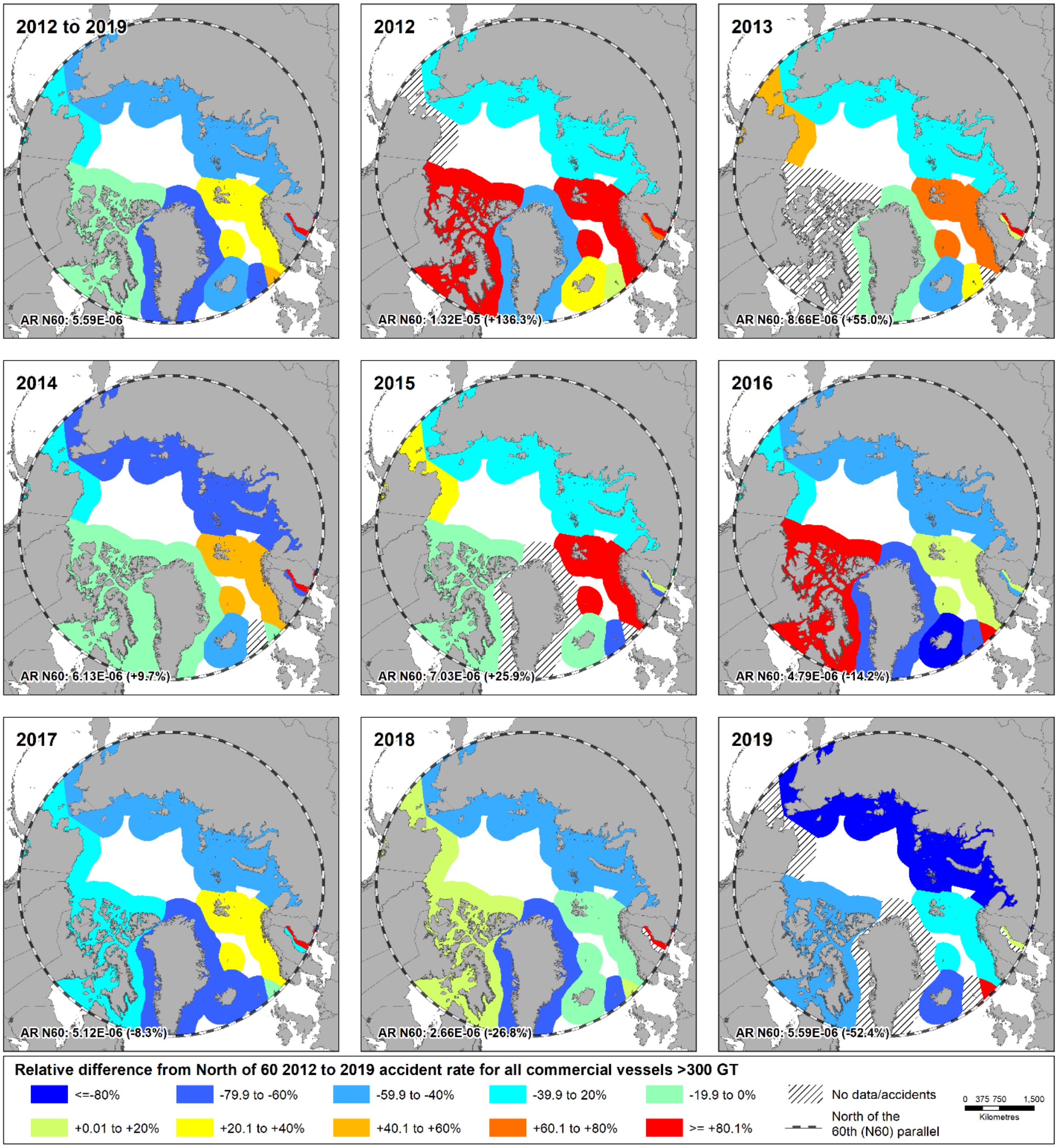


Figure 4.4: Maps of the relative difference (%) per EEZ from the N60 2012 to 2019 accident rate for all commercial ships >300 GT, for 2012 to 2019 and for each year from 2012 to 2019. Locations in blue indicate a negative difference (i.e., lower accident rate), whereas locations in red indicate a positive difference (i.e., higher accident rate) from the N60 2012 to 2019 accident rate for all commercial ships >300 GT. Text on bottom left of each sub-map indicate the accident rate for all commercial ships >300 GT for the time-period, where the percentage represents the relative difference of the year compared to N60 2012 to 2019 accident rate.

The baseline non-commercial accident rate from 2012 to 2019 N60 parallel is 1.75E-06 ship accidents/nm sailed (46.2% and 68.7% less than the baseline accident rate for all ships and the baseline accident rate for commercial ships, respectively). Referring to figure 5, EEZs with positive relative differences for the baseline non-commercial ship accident rate compared to the overall area include Canada (> +80%), Finland (+20.1 to +40%), Russia (+20.1 to +40%), Sweden (+20.1 to +40%), and the UK (+40.1 to +60%). Where EEZs with negative relative differences include Faroe Islands (-59.9 to -40%), Greenland (-59.9 to -40%), Iceland (-79.9 to -60%), and the US (-59.9 to -40%).

When comparing the yearly commercial ship accident rates for each EEZ N60 to the baseline commercial ship accident for the entire period, Canada had positive differences for seven years (2013-2016, 2018-2019). Greenland had positive differences for three years (2012, 2016, 2017) and negative differences for two years (2018-2019). Iceland had negative differences for seven years (2013-2019). The Faroe Islands had positive differences for three years (2013-2014, 2016) and negative differences for five years (2012, 2015-2018). The UK had positive differences for four years (2012, 2016, 2018-2019) and negative differences for one year (2015). Norway had a positive difference for eight years (2012-2019). Sweden had a positive difference for only one year (2017). Finland had positive differences for two years (2015, 2019). Russia had positive differences for six years (2012, 2014-2018) and negative differences for two years (2013, 2019). For three years (2012-2013, 2016), the US had positive differences and a negative difference for one year (2018).

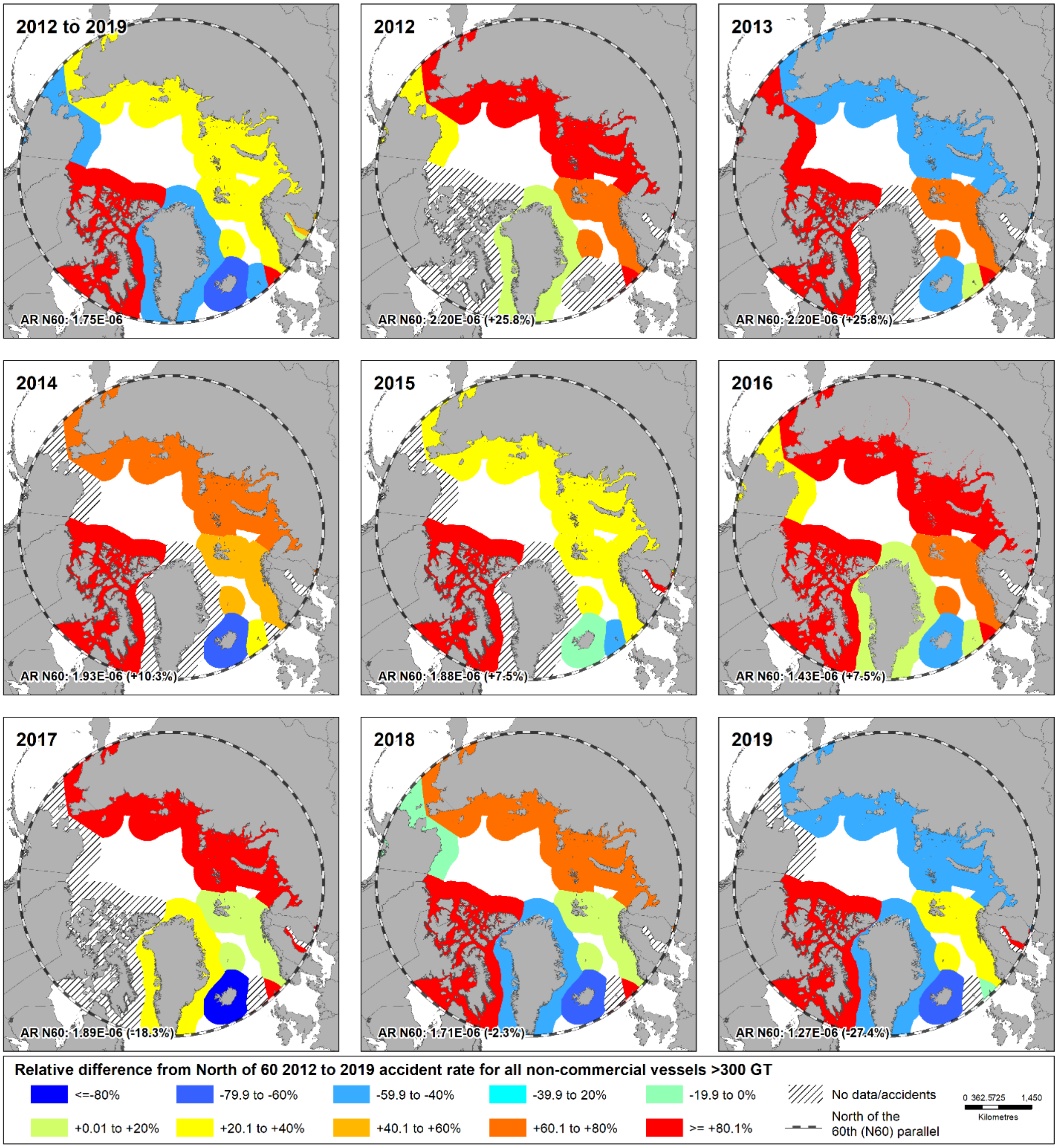


Figure 4.5: Maps of the relative difference (%) per EEZ from the N60 2012 to 2019 accident rate for all non-commercial ships >300 GT, for 2012 to 2019 and for each year from 2012 to 2019. Locations in blue indicate a negative difference (i.e., lower accident rate), whereas locations in red indicate a positive difference (i.e., higher accident rate) from the N60 2012 to 2019 accident rate for all non-commercial ships >300 GT. Text on bottom left of each sub-map indicate the accident rate for all non-commercial ships >300 GT for the time-period, where the percentage represents the relative difference of the year compared to N60 2012 to 2019 accident rate.

4.5 Discussion

This study finds positive statistically significant annual trends for ship traffic at the global Arctic scale for all commercial and non-commercial ship traffic. Commercial ship traffic has a slightly larger trend than non-commercial ship traffic (+10.5%). The trending increase in ship traffic will likely continue due to many factors. Some factors that will contribute to the increase in ship traffic in the future will be due to areas that will be ice-free in the coming decades (Overland & Wang, 2013; Screen & Williamson, 2017; Notz & Stroeve, 2018). As climate change continues, routes for commercial ships in the Arctic, such as the Northwest Passage and Northern Sea Route, are becoming more navigable (Stephenson et al., 2011; Smith & Stephenson, 2013; Haas & Howell, 2015; Melia et al., 2016; Howell et al., 2021) and are economically friendly (Xu et al., 2011; Furuichi & Otsuka, 2014; Crépin et al., 2017) in comparison to other global shipping routes such as routes through the Suez Canal. For non-commercial ships, it is anticipated that ship traffic will continue to increase due to factors such as adventure and last-chance tourism (Dawson et al., 2009; Stewart et al., 2009; Stewart et al., 2010; Lasserre & Têtu, 2013; Stewart et al., 2013; Bystrowska, 2019; Palma et al., 2019; Steiner et al., 2021).

Geographically, the largest absolute statistically significant positive annual trends for all ship and commercial ship traffic are found in Norway, Russia, and Iceland. For non-commercial ship traffic, the largest statistically significant annual trends are in Russia, Norway, and Iceland. The increasing trends in ship traffic are consistent with other studies specific to the global Arctic (Eguíluz et al., 2016) and regionally in the Canadian Arctic (Pizzolato et al., 2014; Chénier et al., 2017; Dawson et al., 2018), Russian Arctic (Gunnarsson, 2021), and portions of the Norwegian Arctic (Olsen et al., 2020; Stocker et al., 2020).

There are no statistically significant annual trends at the global Arctic scale for ship accidents. At this global Arctic scale, the non-statistically significant trends indicate negative slopes for all commercial ship accidents but a positive slope for non-commercial ship accidents. Geographically, Norway has the largest negative absolute annual slope for all ship accidents, whereas Russia has the largest positive absolute annual slope for all ship accidents. Although the result is not statistically significant, the positive slope for all ship accidents in Russia could be a warning sign that there is the potential for more ship accidents and other events (e.g., pollution) to occur as we are observing increases in ship traffic to the Northern Sea Route, which is located within the Russian EEZ, due to the economic and navigational viability of this route (Radushinsky et al., 2017; Wang et al., 2019; Boylan, 2021). In addition, the Arctic is one of the most challenging areas in the world to navigate due to extreme weather conditions, poor infrastructure, and services (Beveridge et al., 2016; Leppala et al., 2019), which could further contribute to an increase in ship accidents in this area.

There are statistically significant negative annual trends for ship accident rates at the global Arctic scale for all commercial and non-commercial ship traffic. Norway has the largest statistically significant negative trend for all ship and commercial accident rates. There is a larger negative trend for commercial ship accident rates than non-commercial ship accident rates (+689.1%). For the most part, accident rates have been decreasing recently, but this is not to say they are not lower than in other areas of the world. For example, the Arctic accident rate is one of the highest rates in Canada (Council of Canadian Academies, 2016).

4.6 Limitations

In addition to the limitations referenced in the introduction, this analysis does not capture the variability of the severity of accidents due to the aggregation of accident types. Different severities could be associated with each specific accident (e.g., low to high-severity events).

This study uses AIS as the basis for ship traffic data and therefore has AIS-related limitations such as; no non-AIS vessels were captured (i.e., smaller vessels like pleasure or fishing vessels), class B transponders have become more affordable over the years, there is potential for an increase in smaller vessels (non-commercial traffic) recorded by AIS in more recent years. This means that the pleasure vessel traffic could be partly due to increased pleasure vessels with AIS transponders. This study is limited to vessels >300 GT only; many non-commercial ships are <300 GT in size and might not have AIS onboard them.

EEZs are limited to areas within the N60 parallel threshold, and areas outside the N60 parallel are not considered, even though the EEZs cover the area outside the N60 parallel.

The statistical trends computed in the study are based on a small amount of data (8 years); adding more years of data to this study in the future will ensure results have higher statistical accuracy. In short, the results presented in this paper present the recent/short-term statistical trends.

Lastly, accident rates, in general, can vary greatly depending on the exposure variable used (e.g., ship transits, hours of operations, distance sailed, port calls) as the denominator in normalizing accident data (Bye et al., 2019).

4.7 Conclusion

The results from this study help to provide a snapshot of recent trends in ship traffic, accidents, and accident rates for all ships, commercial ships, and non-commercial ships North of the 60th parallel and the EEZs encompassing this area. At N60 for commercial and non-commercial ships, traffic is increasing at a similar rate, whereas the accident rate for commercial ships is decreasing more rapidly than for non-commercial ships. While the accident rate for commercial ships shows that rates are decreasing over time, the period is relatively small and might not truly capture the long-term trends in this region. It does not indicate that the Arctic has a low accident rate compared to other areas in the world; it is still among one of the most challenging areas to navigate. A positive slope (not statistically significant) for all ship accidents has been detected within the Russian EEZ, which could be an indication that there might be more accidents in this region in the future as the Northern Sea Route is becoming a more viable route for ships to travel. for all ship accidents.

As more years of data become available and new commercial ship operators potentially re-route through the Arctic, similar analyses should be conducted to understand whether statistical trends still hold.

Acknowledgements

This work was funded by the Marine Environmental Observation Prediction & Response Network (MEOPAR) and Clear Seas. Satellite-based AIS data were provided by exactEarth Ltd., 2019 through partnership with MEOPAR. LRFP data was provided by Lloyd’s Registry.

4.8 References cited in chapter 4.

Barnhart, K. R., C. R. Miller, I. Overeem, and J. E. Kay (2015), Mapping the future expansion of Arctic open water, Nat. Clim. Change, 6, 280–285, doi:10.1038/nclimate2848

Beveridge, L., M. Fournier, F. Lasserre, L. Huang, and P. L. Tetu. (2016). Interest of Asian Shipping Companies in Navigating the Arctic.” Polar Science 10: 404–414. doi:10.1016/j.polar.2016.04.004.

Borgerson SG. (2008). Arctic meltdown: the economic and security implications of global warming. Foreign Aff 2008;87(2):63–77

Boylan, B. M. (2021). Increased maritime traffic in the arctic: Implications for governance of Arctic Sea Routes. Marine Policy, 131, 104566. doi:10.1016/j.marpol.2021.104566

Bye, R.J.; Almklov, P.G. (2019). Normalization of maritime accident data using AIS. Mar. Policy 2019, 109, 103675

Bystrowska, M. (2019). The impact of sea ice on cruise tourism on Svalbard. ARCTIC, 72(2), 151-165. doi:10.14430/arctic68320

Chénier, R., Abado, L., Sabourin, O., & Tardif, L. (2017). Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. Transactions in GIS, 21 (6), 1085–1097

Comiso, J. C., Gersten, R. A., Stock, L. V., Turner, J., Perez, G. J., and Cho K (2017). Positive Trend in the Antarctic Sea Ice Cover and Associated Changes in Surface Temperature. Journal of Climate, 30(6):2251–2267, 03 2017. ISSN 0894-8755. doi: 10.1175/JCLI-D-16-0408.1.

Council of Canadian Academies, (2016). Commercial Marine Shipping Accidents: Understanding the Risks in Canada. Ottawa (ON); Workshop Report.

Crépin, A., Karcher, M., & Gascard, J. (2017). Arctic climate change, economy and Society (ACCESS): Integrated perspectives. Ambio, 46(S3), 341-354. doi:10.1007/s13280-017-0953-3

Dawson, J., Stewart, E. J., Lemelin, H., & Scott, D. (2009). The carbon cost of polar bear viewing tourism in Churchill, Canada. Journal of Sustainable Tourism, 18(3), 319-336. doi:10.1080/09669580903215147

Dawson, J., M. Johnston, and E. Stewart, (2014). Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. Ocean Coastal Manage., 89, 88–99, doi:10.1016/j.ocecoaman.2013.12.005.

Dawson, J., Pizzolato, L., Howell, S. E., Copland, L., & Johnston, M. E. (2018). Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015). Arctic, 71(1), 15–26.

Du, Lei & Goerlandt, Floris & Kujala, Pentti, (2020). Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data. Reliability Engineering and System Safety, Elsevier, vol. 200.

Eguíluz, V. M., Fernández-Gracia, J., Irigoien, X., and Duarte, C. M. (2016). A quantitative assessment of Arctic shipping in 2010–2014. Sci. Repts. 6:30682. doi: 10.1038/srep30682

Flanders Marine Institute (2019). Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. Available online at https://www.marineregions.org/ https://doi.org/10.14284/386.

Furuichi, M., & Otsuka, N. (2014). Proposing a common platform of shipping cost analysis of the Northern Sea Route and the Suez Canal Route. Maritime Economics & Logistics, 17(1), 9-31. doi:10.1057/mel.2014.29

Gunnarsson, B. (2021). Recent ship traffic and developing shipping trends on the Northern Sea Route—Policy implications for future arctic shipping. Mar. Policy, 124, 104369.

Gocic, M., Trajkovic, S., (2013). Analysis of changes in meteorological variables using MannKendall and Sen's slope estimator statistical tests in Serbia. Glob. Planet. Chang.100, 172–182

Haas, C., & Howell, S. E. (2015). Ice thickness in the northwest passage. Geophysical Research Letters, 42(18), 7673-7680. doi:10.1002/2015gl065704

Hanninen, M., Kujala, P. (2014). Bayesian network modeling of Port State Control inspection findings and ship accident involvement. Expert Syst. Appl. 41, 1632e1646. http://dx.doi.org/10.1016/j.eswa.2013.08.060.

Hartsig, A., I. Frederickson, C. Yeung, and S. Senner. (2012). Arctic Bottleneck: Protecting the Bering Strait Region from Increased Vessel Traffic. Ocean & Coastal LJ 18 35–88.

Hassel, M., Asbjørnslett, B.E., Hole, L.P. (2011). Underreporting of maritime accidents to vessel accident databases. J. Accid. Anal. Prevent. 4 (6), 2053–2063.

Howell, S. E., Babb, D. G., Landy, J. C., & Brady, M. (2022). Multi-year sea ice conditions in the northwest passage: 1968–2020. Atmosphere-Ocean, 1-15. doi:10.1080/07055900.2022.2136061

Kendall, M.G. (1975). Rank Correlation Measures. Charles Griffin, London

Kwok, R. (2018). Arctic sea ice thickness, volume, and multiyear ice coverage: Losses and coupled variability (1958–2018). Environmental Research Letters, 13(10), 105005.

Laliberté, F., Howell, S. E. L., and Kushner, P. J. (2016). Regional variability of a projected sea ice-free Arctic during the summer months, Geophys. Res. Lett., 43, 256–263 https://doi.org/10.1002/2015GL066855.

Lasserre, F., and S. Pelletier. (2011). Polar Super Seaways? Maritime Transport in the Arctic: An Analysis of Shipowners' Intentions. Journal of Transport Geography 19: 1465–1473. doi:10.1016/j.jtrangeo.2011.08.006

Lasserre, F., & Têtu, P. (2013). The cruise tourism industry in the Canadian arctic: Analysis of activities and perceptions of cruise ship operators. Polar Record, 51(1), 24-38. doi:10.1017/s0032247413000508

Lasserre, F.; Têtu, P.L. (2015). The cruise tourism industry in the Canadian Arctic: Analysis of activities and perceptions of cruise ship operators. Polar Rec. 51, 24–38.

Lemelin, R.H., Dawson, J. and Stewart, E.J. (eds) (2012). Last Chance Tourism: Adapting Tourism Opportunities in a Changing World (Abingdon: Routledge).

Leppala, L., Honkala, S., Ferrara, G., Kirkko-Jaakkola, M., Kuusniemi, H., & Miettinen-Bellevergue, S. (2019). Challenges in arctic navigation: The user perspective. 2019 European Navigation Conference (ENC). doi:10.1109/euronav.2019.8714187

LRFP. (2021). Lloyd’s Register FairPlay Casualty Database (January 2021 version)

Mann, H.B. (1945). Nonparametric tests against trend, Econometrica, 13, 245-259

Marchenko, N.A.; Andreassen, N.; Borch, O.J.; Kuznetsova, S.Y.; Ingimundarson, V.; Jakobsen, U. (2018). Arctic shipping and risks: emergency categories and response capacities. Int. J. Mar. Navig. Saf. Sea Transp., 12, 107–114

Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st Century trans-arctic shipping routes. Geophysical Research Letters, 43(18), 9720-9728. doi:10.1002/2016gl069315

Mudryk, L.R., Dawson, J., Howell, S.E.L., Derksen, C., Zagon, T.A., Brady, M. (2021). Impact of 1, 2 and 4 ◦C of global warming on ship navigation in the Canadian Arctic. Nat. Clim. Change 11 (8), 673–679.

Nevalainen, M., Helle, I., & Vanhatalo, J. (2017). Preparing for the unprecedented — Towards quantitative oil risk assessment in the Arctic marine areas. Marine Pollution Bulletin, 114(1), 90-101. doi:10.1016/j.marpolbul.2016.08.064

Notz, D. & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. Science 354, 747–750/

Notz, D., & Stroeve, J. (2018). The trajectory towards a seasonally ice-free Arctic

Ocean. Current Climate Change Reports, 4(4), 407-416. doi:10.1007/s40641-018-0113-2

Notz, D., & SIMIP Community (2020). Arctic sea ice in CMIP6. Geophysical Research Letters, 47, e2019GL086749. https://doi.org/10.1029/2019GL086749

Olsen, J., Hovelsrud, G. K. & Kaltenborn, B. P. (2020). Increasing Shipping in the Arctic and Local Communities' Engagement: A Case from Longyearbyen on Svalbard. In Arctic Marine Sustainability (eds Pongrácz, E. et al.) 305–331

Overland, J. E., & Wang, M. (2013). When will the summer arctic be nearly sea ice free? Geophysical Research Letters, 40(10), 2097-2101. doi:10.1002/grl.50316

Palma, D., Varnajot, A., Dalen, K., Basaran, I. K., Brunette, C., Bystrowska, M., . . . Ronge, T. A. (2019). Cruising the marginal ice zone: Climate change and arctic tourism. Polar Geography, 42(4), 215-235. doi:10.1080/1088937x.2019.1648585

Partal, T., Kahya, E. (2006). Trend analysis in Turkish precipitation data. Hydrological Processes 20, 2011–2026

Pizzolato, L., S. E. L. Howell, C. Derksen, J. Dawson, and L. Copland. (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012, Clim. Change, 123, 161– 173, doi:10.1007/s10584-013-1038-3.

Psarros, G., Skjong, R., Eide, M.S. (2010). Under-reporting of maritime accidents. Accid.Anal. Prev. 42, 619–625.

Radushinsky, D., Mottaeva, A., Andreeva, L., & Dyakova, G. (2017). The evaluation of the modernization cost of the transport infrastructure of the Northern Sea Route in the Arctic Zone of the Russian Federation. IOP Conference Series: Earth and Environmental Science, 90, 012137. doi:10.1088/1755-1315/90/1/012137

Screen, J. A., & Williamson, D. (2017). Ice-free Arctic at 1.5 °C? Nature Climate Change, 7(4), 230-231. doi:10.1038/nclimate3248

Smith, L. C., & Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by Midcentury. Proceedings of the National Academy of Sciences, 110(13). doi:10.1073/pnas.1214212110

Steiner, N., J. Bowman, K. Campbell, M. Chierici, E. Eronen-Rasimus, M. Falardeau, H. Flores, A. Frasson, et al. (2021). Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene 9: 1.

Stephenson, S. R., Smith, L. C., & Agnew, J. A. (2011). Divergent long-term trajectories of human access to the Arctic. Nature Climate Change, 1(3), 156-160. doi:10.1038/nclimate1120

Stewart, E. J., Howell, S., Draper, D., Yackel, J., & Tivy, A. (2009). Sea ice in Canada's arctic: Implications for cruise tourism. ARCTIC, 60(4). doi:10.14430/arctic194

Stewart, E., Tivy, A., Howell, S., Dawson, J., & Draper, D. (2010). Cruise tourism and sea ice in Canada's Hudson Bay Region. ARCTIC, 63(1). doi:10.14430/arctic647

Stewart, E., Dawson, J., Howell, S., Johnston, M., Pearce, T., & Lemelin, H. (2013). Local-level responses to sea ice change and cruise tourism in Arctic Canada's Northwest Passage. Polar Geography, 36(1-2), 142-162. doi:10.1080/1088937x.2012.705352

Stevenson, T.C., J. Davies, H.P. Huntington, and W. Sheard. (2019). An Examination of Trans-Arctic Vessel Routing in the Central Arctic Ocean. Marine Policy 100: 83–89.

Stocker, A. N., Renner, A. H. H., & Knol-Kauffman, M. (2020). Sea ice variability and maritime activity around Svalbard in the period 2012–2019. Scientific Reports, 10(1), 17043. https://doi.org/10.1038/s41598-020-74064-2

Sormunen, O., Hanninen, M. and Kujala, P. (2016). Marine Traffic, Accidents, and Underreporting in the Baltic Sea. Zeszyty Naukowe, 46(118), 163–177

Wang, D., Li, D., Gong, Y., Wang, R., Wang, J., & Huang, X. (2019). Development situation and future demand for the ports along the Northern Sea Route. Research in Transportation Business & Management, 33, 100465. doi:10.1016/j.rtbm.2020.100465

Winther, M., Christensen, J. H., Plejdrup, M. S., Ravn, E. S., Eriksson, Ó. F., & Kristensen, H. O. (2014). Emission inventories for ships in the arctic based on satellite sampled AIS data. Atmospheric Environment, 91, 1–14. https://doi.org/10.1016/j.atmosenv.2014.03.006

Xu, H., Yin, Z., Jia, D., Jin, F., & Ouyang, H. (2011). The potential seasonal alternative of Asia–europe container service via Northern Sea Route under the Arctic Sea Ice retreat. Maritime Policy & Management, 38(5), 541-560. doi:10.1080/03088839.2011.597449

Zhang X, Vincent LA, Hogg WD, Niitsoo A (2000). Temperature and precipitation trends in Canada during the 20th century. Atmos Ocean 38(3):395–429

Chapter 5: Discussion and conclusions

5.1 Contributions

5.1.1 Scientific contributions

The scientific paper presented in Chapter 2 provided the first detailed descriptive and quantitative comparative analysis between the NORDREG and S-AIS datasets within the Canadian Arctic from 2011 to 2018. In general, ship traffic data has been used to support many marine related assessments and policy development, such as marine protected areas management (Shelmerdine, 2015), model underwater noise impacts assessment (Halliday et al., 2017; Halliday et al., 2021), navigation risk assessment (Van Iperen, 2015; Zhang et al., 2015; Altan & Otay, 2018; Schultz & Bourne, 2019), and links with climate change impacts (Löptien et al., 2014; Copland et al. 2021, Dawson et al., 2022). There have been many studies looking at ship traffic trends in the Canadian Arctic, relying on different data sets, including NORDREG and AIS. However, only anecdotal evidence suggested differences between these 2 data sets prior to this study. A comparative analysis was needed to establish the commonalities and differences between theme and in turn inform which data source may provide the highest level of accuracy for historical, current, and future ship traffic analyses in the Canadian Arctic. Findings of the comparative and statistical data analysis revealed that NORDREG in comparison to AIS captures more unique ships (9 more unique ships) and is more accurate in distance sailed metric for all ships contained within both databases (106,811 more nm sailed) in 2011. From 2012 onwards, AIS captures more unique ships and is more accurate in distance sailed metrics for ships contained within both databases, highlighted by 2018 (169 more unique ships; 84,149 more nm sailed).

Chapter 3 provided an understanding of reported ship traffic, accidents, and corresponding accident rates within the Canadian Arctic from 1990 to 2019, by building on research from Pizzolato et al., (2014). The results show that as monthly sea-ice extent decreases during the shipping-season in the Canadian Arctic (-3,193 km^2 mo^{-1}), commercial (+5,011 nm yr^{-1}) and non-commercial ship (+4,658 nm yr^{-1}) traffic is increasing while commercial ship accidents (-0.06 accidents yr^{-1}) and all ship accident rates (-6.31E-07 accidents/nm yr^{-1}) are declining. One of the main drivers of increases in ship traffic, in addition to the decrease in sea ice, can be attributed to adventure and last chance tourism (Lemelin et al., 2010; Dawson et al., 2010; Dawson et al., 2014; D'Souza et al., 2021), which can be linked with non-commercial vessels as defined in chapter 3 (e.g., pleasure vessels/yachts). The influence of the increased in non-commercial vessels on accident rate requires further research to inform future regulations for non-commercial ship operators.

Chapter 4 is the first study to use Automatic Identification System (AIS) data with Lloyd's Register FairPlay (LRFP) accident data to derive and assess annual statistical trends for accident rates North of the 60th (N60) parallel and encompassing Exclusive Economic Zones (EEZ). The results from the study provide a snapshot of recent trends in ship traffic, accidents, and accident rates for all ships, commercial ships, and non-commercial ships within North of the 60th (N60) parallel and the EEZs that encompass this area. Results show that, for N60 from 2012 to 2019, ship traffic is significantly increasing for all ship traffic (+2.655 million nm yr^{-1}), commercial ships (+1.598 million nm yr^{-1}), and non-commercial ships (+1.446 million nm yr^{-1}). This increasing trend in traffic can be attributed to multiple factors, including longer ice-free period in the coming decades (Overland & Wang, 2013; Screen & Williamson, 2017; Notz & Stroeve, 2018), routes in the Arctic such as the Northwest Passage and Northern Sea Route are becoming more navigable (Stephenson et al., 2011; Smith & Stephenson, 2013; Haas & Howell, 2015; Melia et al., 2016; Howell et al., 2021) and economically friendly (Xu et al., 2011; Furuichi & Otsuka, 2014; Crépin et al., 2017). Although traffic is increasing over time, there are statistically significant annual decreases in ship accident rates for all ships (-3.64E-07 ship accidents/nm yr^{-1}), commercial ships (-9.39E-07 ship accidents/nm yr^{-1}), and non-commercial ships (-1.19E-07 ship accidents/nm yr^{-1}). Although not statistically significant, a positive trend was observed for all ship accidents within the Russian EEZ, where the Northern Sea Route is located. This could be an indication that there might be more accidents in this region in the future as the Northern Sea Route is becoming a more viable route for ships to travel for all ship accidents.

5.1.2 Methodological contributions

All scientific papers (Chapters 2 to 4) use AIS data as one of the bases for ship traffic data. The AIS data was provided by exactEarth via MEOPAR in compressed CSV format (over 100 GB), and the AIS data was converted into Parquet format (open-source columnar-oriented storage) for further analysis and storage purposes (<10 GB). Parquet format saves storage space and enables quicker computational processes compared to CSV format (i.e., saves file space and fast computation).

A custom Python tool using open-source libraries (e.g., geopandas, shapely, Fiona) was created to replicate the process of NOAA's trackline builder (used in Chapters 2 to 4). The custom trackline builder is much more efficient in terms of openness, storage, and computation, for example:

- **Openness:** NOAA's trackline builder uses proprietary Python libraries (e.g., arcpy); whereas the custom trackline builder uses open-source Python libraries.

- **Storage:** NOAA's trackline builder must have data created on disk in an intermediate format prior to the creation of tracklines (e.g., AIS data must be converted into an ESRI point feature class first); whereas the custom trackline builder reads the Parquet data directly, in physical memory creates spatial points, and creates the tracklines (i.e., no intermediate storage of data – saving disk space).

- **Computation:** Using an example of 20 million positional AIS data points (e.g., one month of global Arctic positional AIS data); for usage within NOAA's trackline builder, data must be converted to a point feature class (approximately 1 hour), then the point feature class will be transformed into tracklines (approximately 20 minutes) for a total of 1 hour and 20 minutes; whereas the custom trackline builder process all of the data into tracklines within 10 minutes.

Chapter 2 identified the most appropriate databases (a combination of NORDREG and AIS) to be used in the Canadian Arctic when performing long or short-term data analyses relating to shipping traffic (e.g., descriptive analyses, statistical trends, geospatial analyses).

The creation of Canadian Arctic (*Chapter 3*) and global Arctic (*Chapter 4*) accident rates that can be used within ship accident models such as SAMSON (IALA, 2014) and IWRAP (IALA, 2012), where the accident rates in those models are static rates from regions that are not similar to current Arctic conditions (e.g., accident rates derived from the North Sea from outdated data). They can also be implemented in new dynamic ship accident models such as Transport Canada's (TC) MNRA (Transport Canada, 2022). These ship models are often used within Formal Safety Assessments (FSA) that are formally submitted to the IMO to help identify risk in a given region and implement certain safety measures (e.g., Traffic Separation Scheme, Area to be Avoided).

5.1.3 Policy contributions

Findings from this study may contribute to the development of policies aiming at managing marine shipping in the Arctic.

Chapter 2 will help inform analysts and decision-makers on the differences between the two sources of ship traffic in the Canadian Arctic prior and provide a foundation for performing analyses/studies underlying policy decisions.

Chapter 3 provides evidence that accident rates within the Canadian Arctic for non-commercial vessels have been increasing over time, meaning that focusing on these types of vessels in terms of safety and monitoring should be the priority. This could include further amendments to AIS carriage regulation and requirements in Canadian waters to ensure that smaller vessels can communicate with ships around them (e.g., safety from ship-to-ship communication via AIS) and be monitored by the Governments.

The accident rates derived from *Chapters 3 and 4* can be applied to model future ship accidents (e.g., SAMSON, IWRAP, TC-MNRA) and inform risk assessments within the Canadian Arctic or global Arctic, so that accident rates are representative of the conditions as recorded in these regions, rather than rates from different regions or outdated data. Ultimately, the information from these risk assessments can help inform future regional safety measures (e.g., more Traffic Separation Schemes, Areas to be Avoided).

5.2 Study limitations

The limitations associated with data and analytical methods are highlighted within each chapter.. This section will provide a summary of the main limitations.

For *Chapter 2*, the results are only valid for ships that are >300 GT. They do not capture non-mandatory ships (i.e., Class B AIS vessels or non-mandatory reporting ships to NORDREG).

For *Chapter 3* the limitations are as follows:

- Accident data:
    - It is important to note that accident data and corresponding databases, in general, have many limitations associated with them, such as (i) underreporting, (ii) incompleteness, and (iii) change in reporting standards (Psarros et al., 2010; Hassel et al., 2011; Hanninen et al., 2014; Council of Canadian Academies, 2016; Sormunen et al., 2016; Du et al., 2020), this can, in turn, lead to biases in accidents statistics and corresponding accident rates.
    - The analysis does not capture the variability of the severity of accidents due to the aggregation of accident types. Within an accident type, there could be different severities associated with each specific accident (e.g., low to high severity events).

- AIS limitations:
    - No non-AIS vessels captured (i.e., smaller vessels like pleasure or fishing vessels);

    - Class B transponders have become more affordable over the years; therefore, a potential increase in smaller vessel (non-commercial traffic) recorded by AIS in more recent years. Therefore, there is the potential that the increase in pleasure vessel traffic could be in part due to an increase in pleasure vessels with AIS transponders.

- Ship traffic database:
    - Two different reporting sources of ship traffic were used (NORDREG and satellite-based AIS).
    - NORDREG is a manual entry database, where SB-AIS is automatic. However, reporting requirements are similar.
    - NORDREG only began to include vessel reports in Mackenzie River in recent years.

- Accident rate limitations.
    - Accident rates can vary greatly depending on the exposure variable used (e.g., ship transits, hours of operations, distance sailed, port calls) as the denominator in the normalization of accident data (Bye et al., 2019).

For *Chapter 4* the limitations are as follows:

- Accident data limitations (refer to the above accident data limitations).

- AIS based limitations (refer to the above AIS based limitations).

- The study was limited to vessels >300 GT only; many non-commercial ships are <300 GT in size.

- The Exclusive Economic Zones (EEZ) are limited to areas within the N60 parallel threshold, and areas outside the N60 parallel are not considered, even though the EEZs cover the area outside the N60 parallel, and if the entire area was to be considered results will likely be significantly different for each EEZ.

- Statistical trends are based on a small amount of data (8 years); adding more years of data to this study in the future will ensure results have higher statistical accuracy.

- Accident rate limitations (refer to the above accident rate limitations).

5.3 Future research needs

As more years of ship traffic, ship accident, and sea ice data become available, analyses like those presented in Chapter 3 should be carried out. A focus should be placed on the statistical trend analyses for ship accident rates from non-commercial ships, as there is evidence from the paper that accident rates associated with non-commercial ships are increasing over time.

It is possible to expand on the work presented in Chapter 4 by incorporating more years of data as they become available to perform trend analyses for traffic, accidents, and corresponding accident rates. It would also be beneficial to create accident rates per accident and incident types (e.g., collisions, hull/machinery damage, groundings, fire/explosions, sinking/foundering, striking's) to identify if there exist trends per accident types, as well as have more detailed accident rates that can be entered into ship accident models (e.g., SAMSON, IWRAP, TC-MNRA). Prior to deriving accident rates for specific accident types, including collisions, groundings (powered), and striking's, appropriate ship traffic metrics for the entire period using AIS must be computed to create the accident rates, as different accident types generally have a different level of exposures (i.e., vessel traffic metrics such as distance sailed, operation time, and encounters) associated with them.

5.4 References cited in chapter 5

Altan, Y. C., & Otay, E. N. (2018). Spatial mapping of encounter probability in congested waterways using AIS. Ocean Engineering, 164, 263-271.

doi:10.1016/j.oceaneng.2018.06.049

Bye, R.J.; Almklov, P.G. Normalization of maritime accident data using AIS. Mar. Policy 2019, 109, 10367

Copland, L., Dawson, J., Tivy, A., Delaney, F., Cook, A., and Creed, I. (2021). Changes in shipping navigability in the Canadian Arctic between 1972 and 2016. Facets 6, 1069–1087. doi: 10.1139/facets-2020-009

Council of Canadian Academies, (2016). Commercial Marine Shipping Accidents: Understanding the Risks in Canada. Ottawa (ON); Workshop Report.

Dawson, J., Stewart, E., & Scott, D. (2010). Climate change and polar bear viewing: A case study of visitor demand, carbon emissions and mitigation in Churchill, Canada. In C. M. Hall & J. Saarinen (Eds.), Tourism and change in polar regions: Climate, environment and experience (pp. 89–103). Routledge.

Dawson, J., Johnston, M. E., & Stewart, E. J. (2014). Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. Ocean & Coastal Management, 89, 88–99. https://doi.org/10.1016/j.ocecoaman.2013.12.005

Dawson, J., Cook, A., Holloway, J., & Copland, L. (2022). Analysis of changing levels of ice strengthening (ice class) among vessels operating in the Canadian arctic over the past 30 Years. ARCTIC. doi:10.14430/arctic75553

D'Souza, J., Dawson, J., & Groulx, M. (2021). Last chance tourism: A decade review of a case study on Churchill, Manitoba's polar bear viewing industry. Journal of Sustainable Tourism. https://doi.org/10.1080/09669582.2021.1910828

Du, Lei & Goerlandt, Floris & Kujala, Pentti (2020). Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from

AIS data. Reliability Engineering and System Safety, Elsevier, vol. 200.

Lemelin, H., Dawson, J., Stewart, E. J., Maher, P., & Lueck, M. (2010). Last-chance tourism: The boom, doom, and gloom of visiting vanishing destinations. Current Issues in Tourism, 13(5), 477-493

Haas, C., & Howell, S. E. (2015). Ice thickness in the northwest passage. Geophysical Research Letters, 42(18), 7673-7680. doi:10.1002/2015gl065704

Halliday, W. D., Insley, S. J., Hilliard, R. C., De Jong, T., & Pine, M. K. (2017). Potential impacts of shipping noise on marine mammals in the Western Canadian Arctic. Marine Pollution Bulletin, 123(1-2), 73-82. doi:10.1016/j.marpolbul.2017.09.027

Halliday, W., Pine, M., Citta, J., Harwood, L., Hauser, D., Hilliard, R., . . . Insley, S. (2021). Potential exposure of beluga and bowhead whales to underwater noise from ship traffic in the Beaufort and Chukchi Seas. Ocean & Coastal Management, 204, 105473. doi:10.1016/j.ocecoaman.2020.105473

Hanninen, M., Kujala, P., (2014). Bayesian network modeling of Port State Control inspection findings and ship accident involvement. Expert Syst. Appl. 41, 1632e1646. http://dx.doi.org/10.1016/j.eswa.2013.08.060.

Hassel, M., Asbjørnslett, B.E., Hole, L.P., (2011). Underreporting of maritime accidents to vessel accident databases. J. Accid. Anal. Prevent. 4 (6), 2053–2063.

Howell, S. E., Babb, D. G., Landy, J. C., & Brady, M. (2022). Multi-year sea ice conditions in the northwest passage: 1968–2020. Atmosphere-Ocean, 1-15. doi:10.1080/07055900.2022.2136061

IALA. (2012). IWRAP MKII Wiki. International Association of Marine Aids to Navigation and Lighthouse Authorities.

IALA. (2014) SAMSON Wiki. International Association of Marine Aids to Navigation and Lighthouse Authorities.

Löptien, U., & Axell, L. (2014). Ice and AIS: Ship speed data and sea ice forecasts in the Baltic Sea. The Cryosphere, 8(6), 2409-2418. doi:10.5194/tc-8-2409-2014

Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st Century trans-arctic shipping routes. Geophysical Research Letters, 43(18), 9720-9728. doi:10.1002/2016gl069315

Notz, D., & Stroeve, J. (2018). The trajectory towards a seasonally ice-free Arctic Ocean. Current Climate Change Reports, 4(4), 407-416. doi:10.1007/s40641-018-0113-2

Overland, J. E., & Wang, M. (2013). When will the summer arctic be nearly sea ice free? Geophysical Research Letters, 40(10), 2097-2101. doi:10.1002/grl.50316

Pizzolato, L., S. E. L. Howell, C. Derksen, J. Dawson, and L. Copland (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012, Clim. Change, 123, 161– 173, doi:10.1007/s10584-013-1038-3.

Psarros, G., Skjong, R., Eide, M.S. (2010). Under-reporting of maritime accidents. Accid.Anal. Prev. 42, 619–625.

Shelmerdine, R. L. (2015). Teasing out the detail: How our understanding of marine AIS data can better inform industries, developments, and planning. Marine Policy, 54, 17-25. doi:10.1016/j.marpol.2014.12.010

Schultz, M., & Bourne, S. (2019). Using automatic identification system (AIS) data to assess collision and grounding risk in U.S. coastal ports. doi:10.21079/11681/33343

Screen, J. A., & Williamson, D. (2017). Ice-free Arctic at 1.5 °C? Nature Climate Change, 7(4), 230-231. doi:10.1038/nclimate3248

Smith, L. C., & Stephenson, S. R. (2013). New Trans-Arctic shipping routes navigable by Midcentury. Proceedings of the National Academy of Sciences, 110(13). doi:10.1073/pnas.1214212110

Sormunen, O., Hanninen, M. and Kujala, P. (2016). Marine Traffic, Accidents, and Underreporting in the Baltic Sea. Zeszyty Naukowe, 46(118), 163–177

Stephenson, S. R., Smith, L. C., & Agnew, J. A. (2011). Divergent long-term trajectories of human access to the Arctic. Nature Climate Change, 1(3), 156-160. doi:10.1038/nclimate1120

Transport Canada. (2022). Appendix A: Marine Navigation Risk Accident (MNRA) Models. Emergency Towing Risk Assessment (ETRA); Methodology document.

Van Iperen, E. (2015). Classifying ship encounters to monitor traffic safety on the North Sea from AIS Data. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 9(1), 51-58. doi:10.12716/1001.09.01.06

Zhang, W., Goerlandt, F., Montewka, J., & Kujala, P. (2015). A method for detecting possible near Miss Ship Collisions from AIS Data. Ocean Engineering, 107, 60-69. doi:10.1016/j.oceaneng.2015.07.046

Appendix

Exploratory data analysis for variables considered in chapter 3.

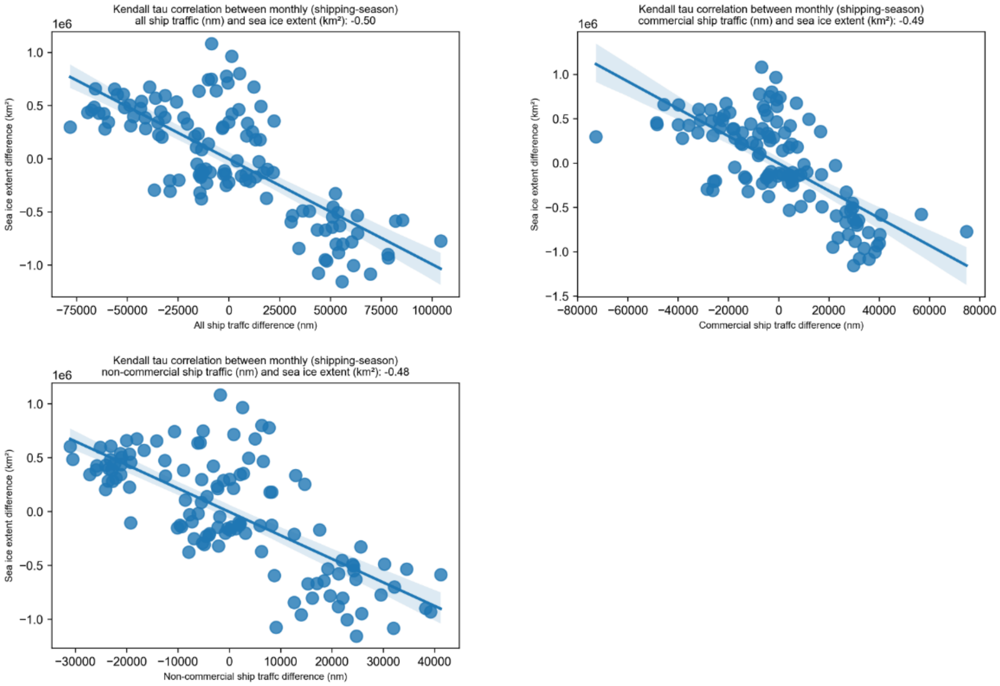


Figure A.1: Correlation plots between detrended monthly ship traffic and monthly sea-ice extent during the shipping-season from 1990-2019 (chapter 3).

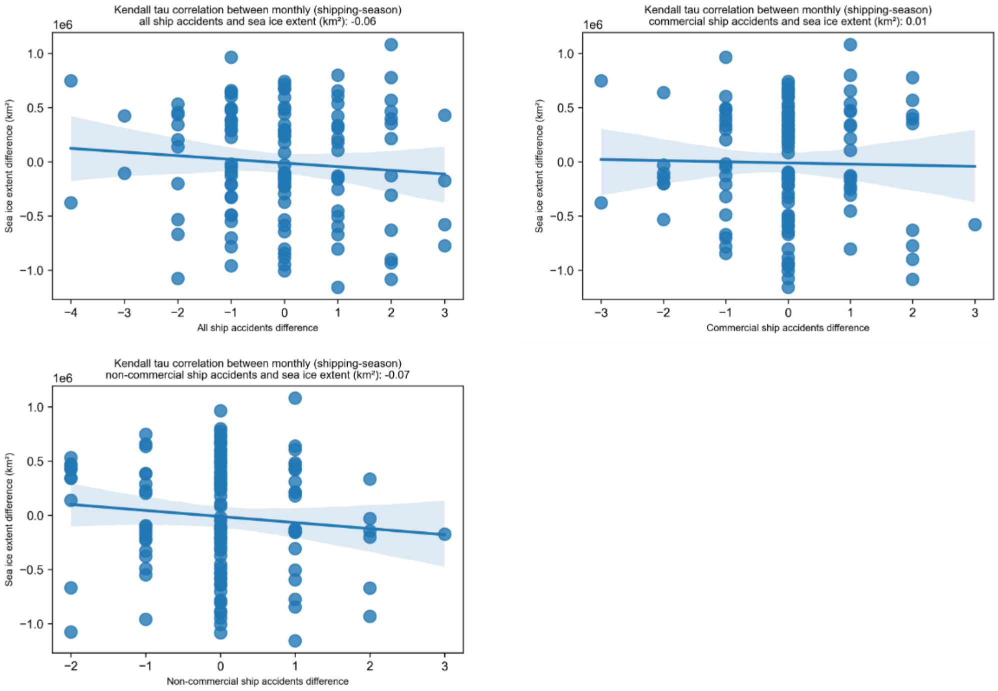


Figure A.2: Correlation plots between detrended monthly ship accidents and monthly sea-ice extent during the shipping-season from 1990-2019 (chapter 3).

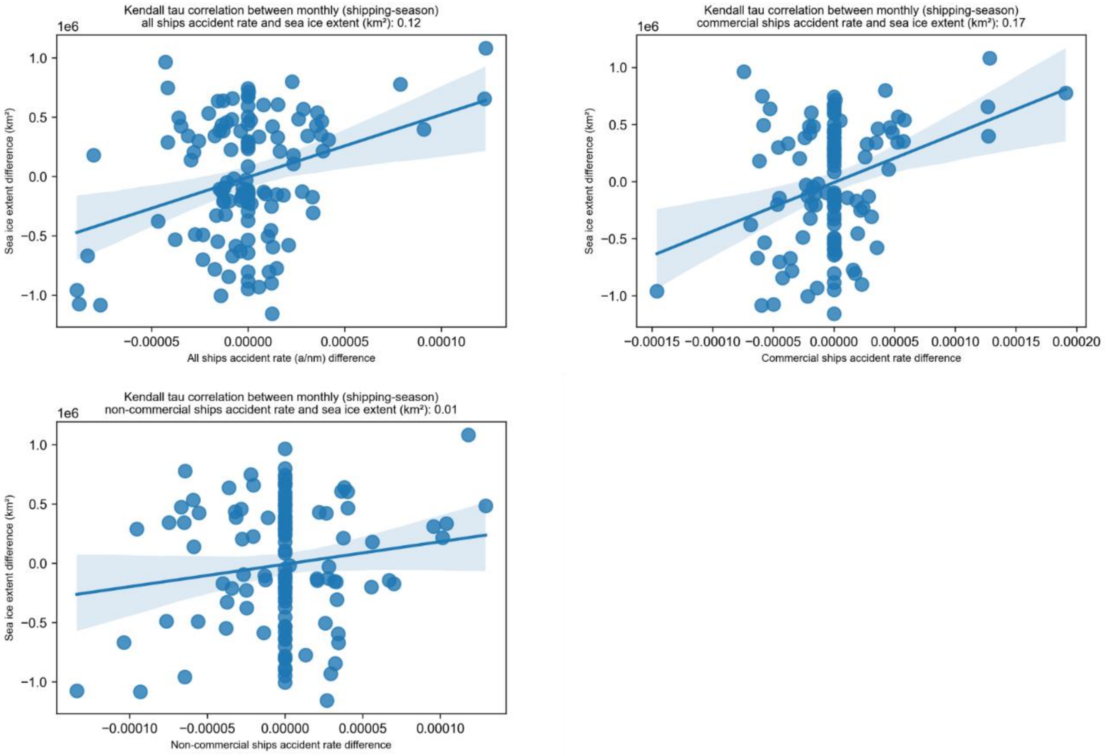


Figure A.3: Correlation plots between detrended monthly ship accident rates and monthly sea-ice extent during the shipping-season from 1990-2019 (chapter 3).

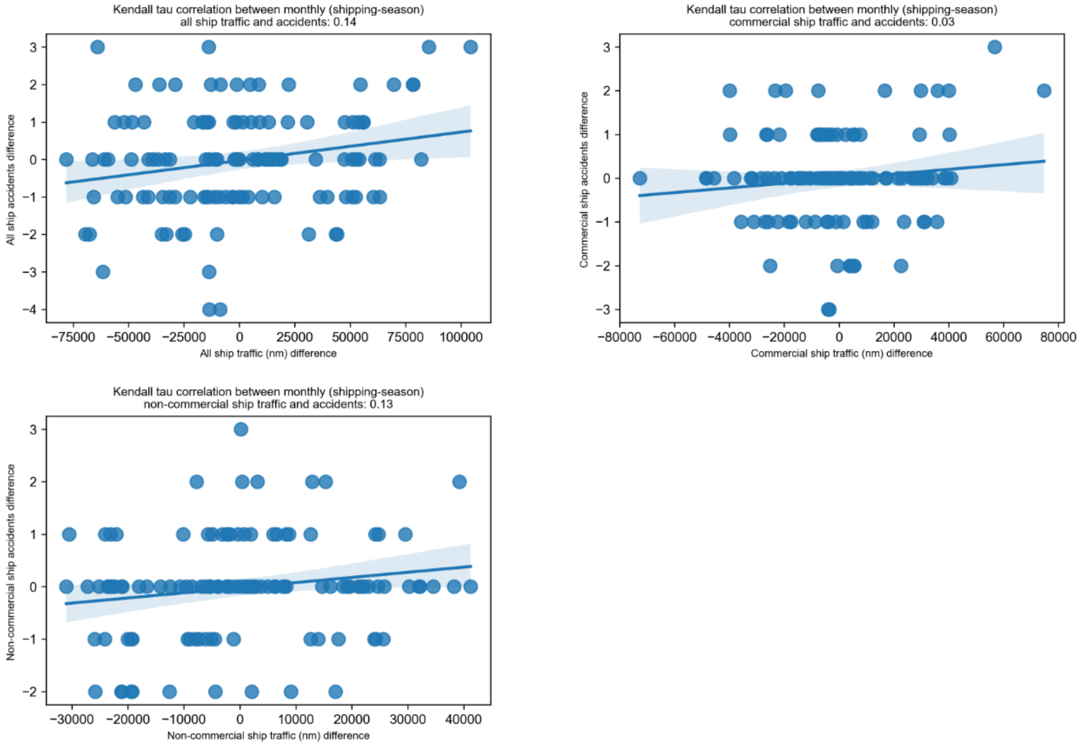


Figure A.4: Correlation plots between detrended monthly ship traffic and monthly accidents during the shipping-season from 1990-2019 (chapter 3).

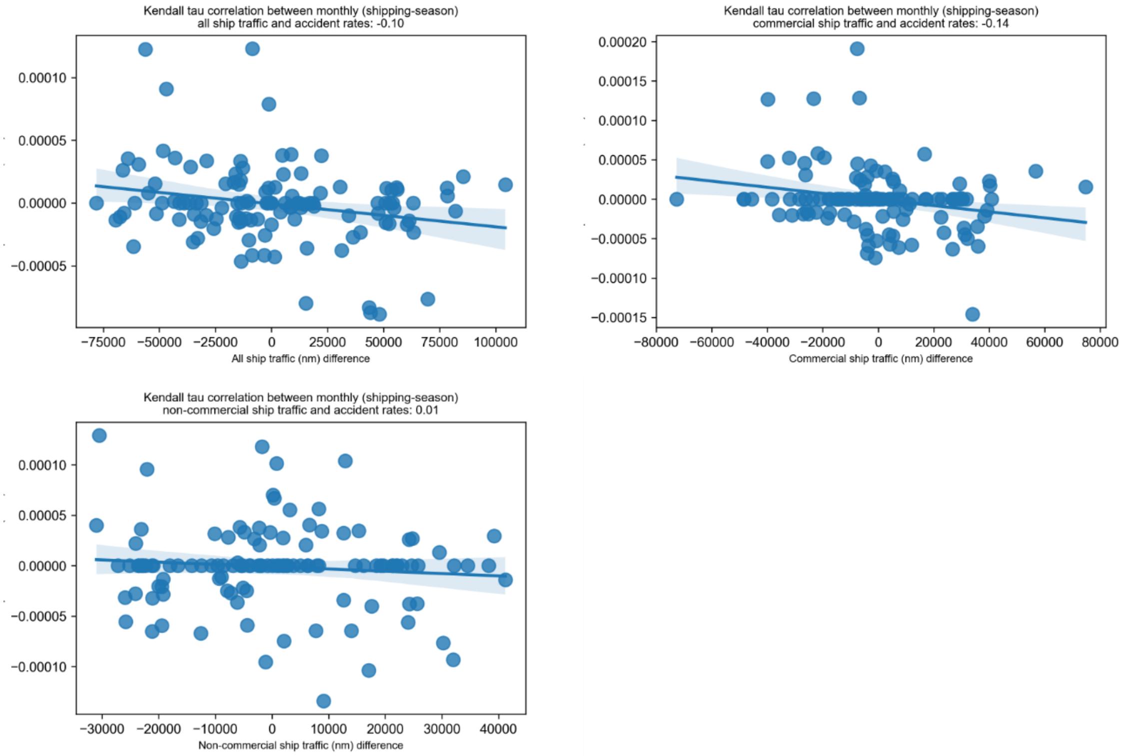


Figure A.5: Correlation plots between detrended monthly ship traffic and monthly accident rates during the shipping-season from 1990-2019 (chapter 3).

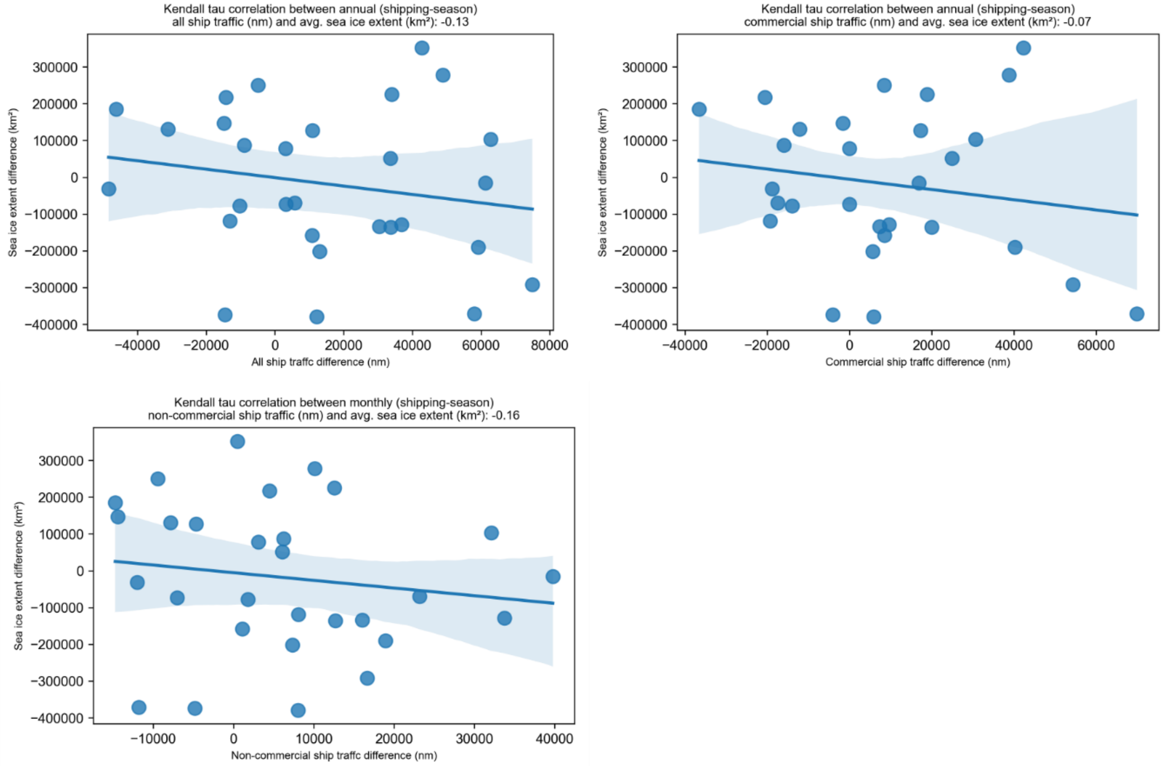


Figure A.6: Correlation plots between detrended annual ship traffic and annual average sea ice extent during the shipping-season from 1990-2019 (chapter 3).

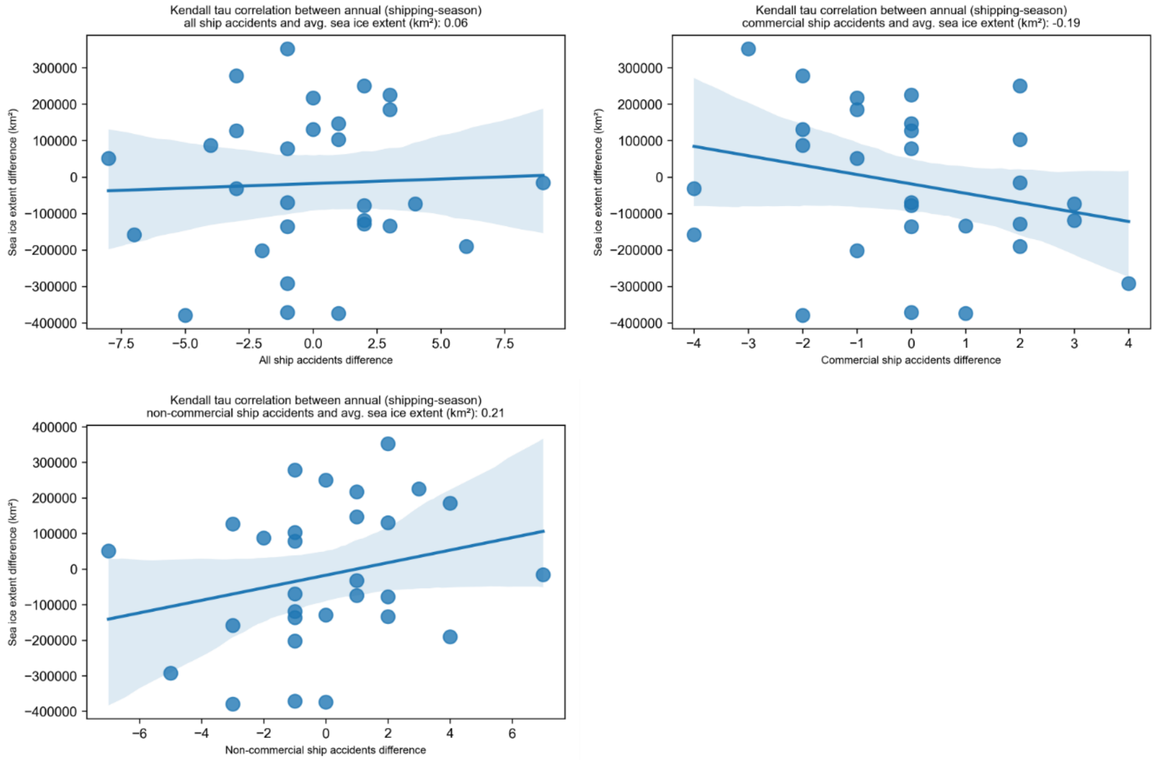


Figure A.7: Correlation plots between detrended annual ship accidents and annual average sea ice extent during the shipping-season from 1990-2019 (chapter 3).

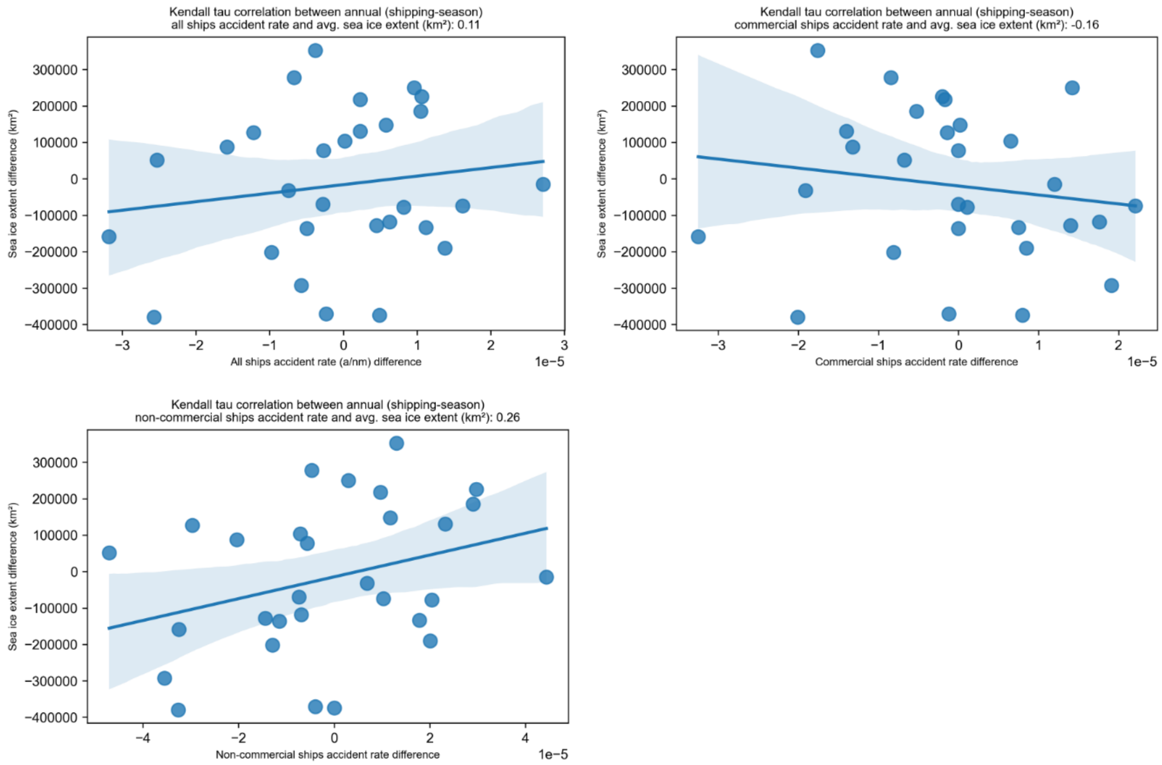


Figure A.8: Correlation plots between detrended annual ship accident rates and annual average sea ice extent during the shipping-season from 1990-2019 (chapter 3).

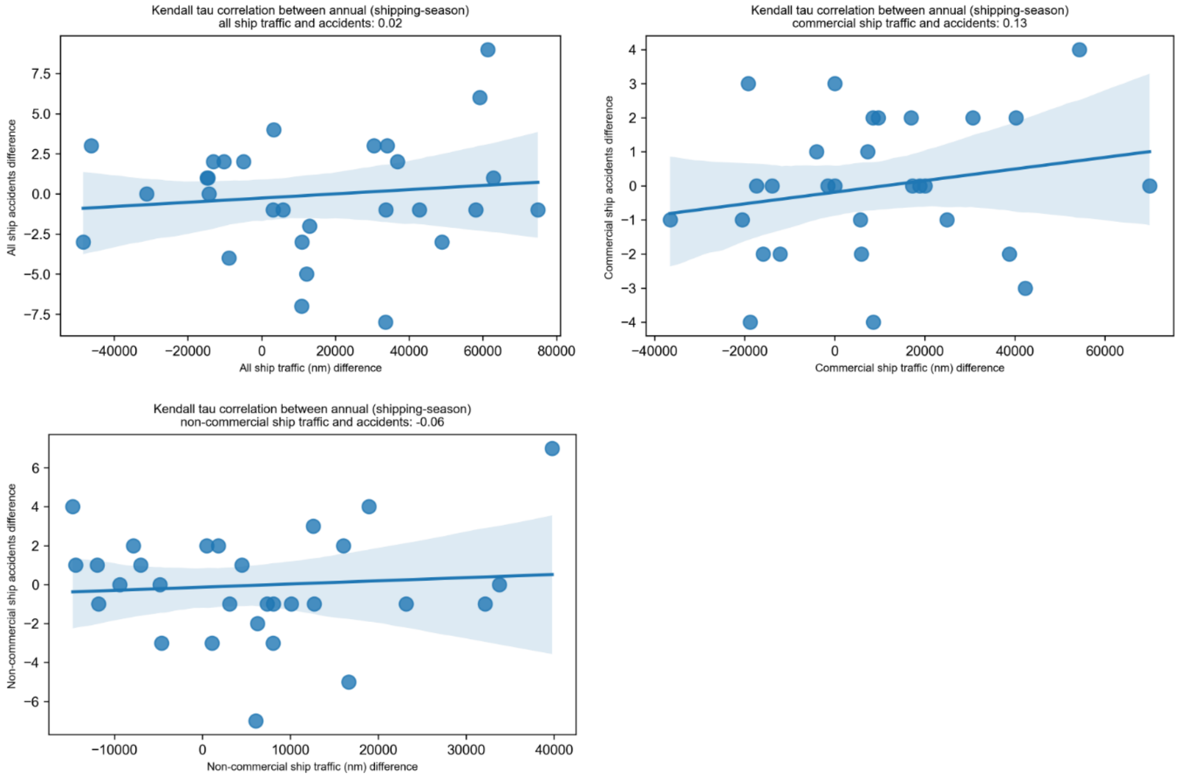


Figure A.9: Correlation plots between detrended annual ship traffic and annual ship accidents during the shipping-season from 1990-2019 (chapter 3).

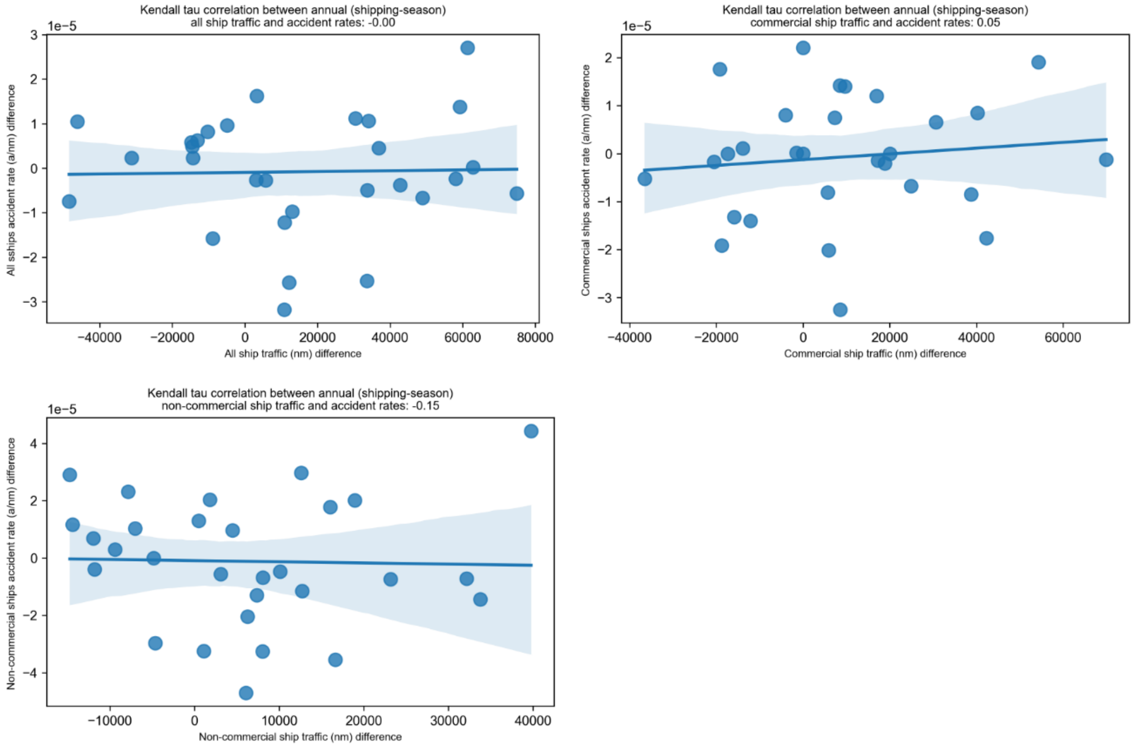


Figure A.10: Correlation plots between detrended annual ship traffic and annual ship accident rates during the shipping-season from 1990-2019 (chapter 3).

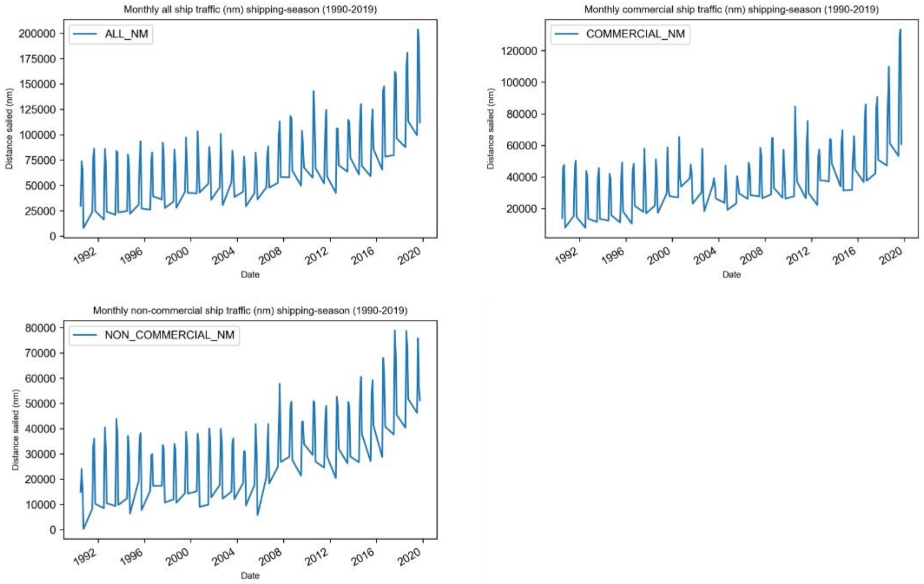


Figure A.11: Monthly time-series for monthly ship traffic during shipping-season from 1990 to 2019 (chapter 3).

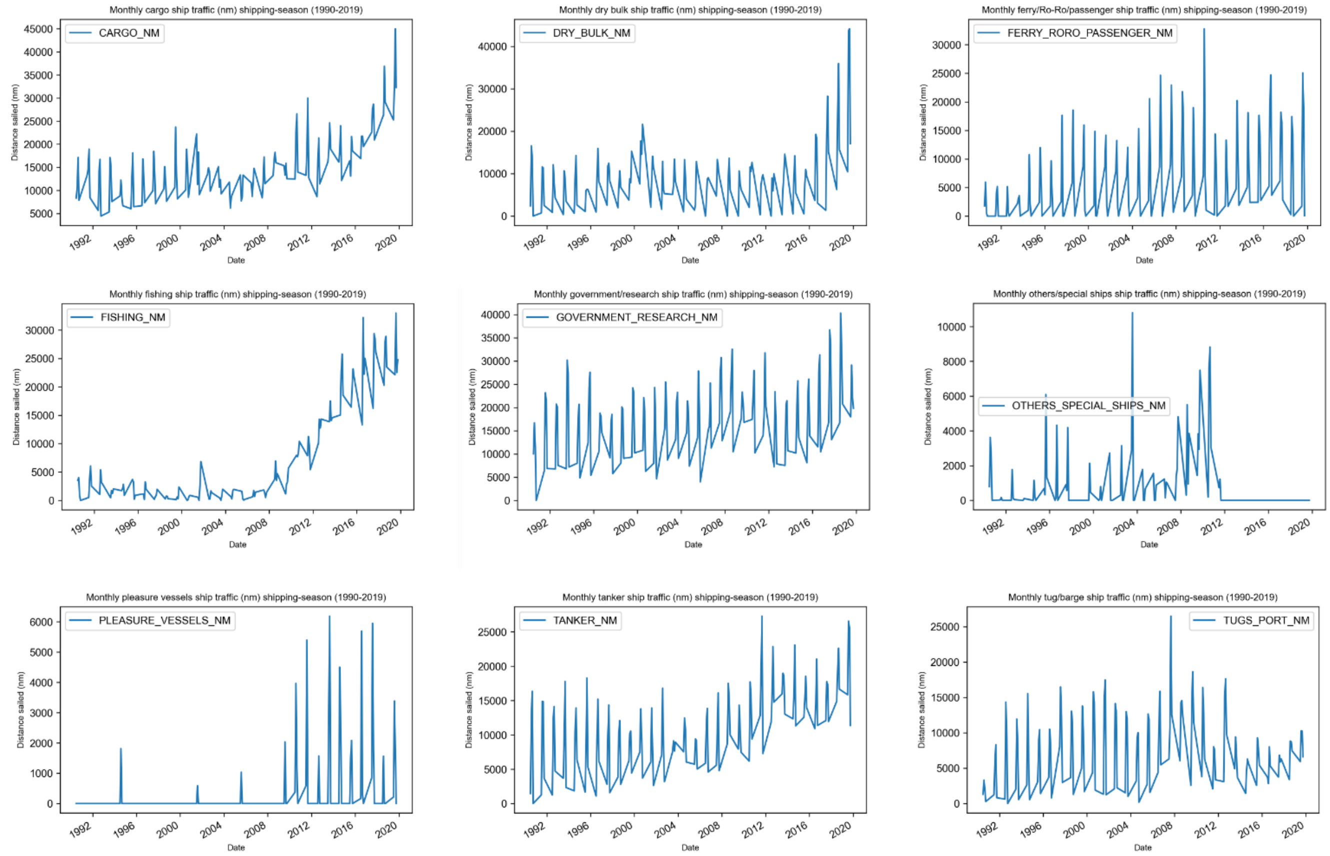


Figure A.12: Monthly time-series for monthly ship traffic during shipping-season from 1990 to 2019, by ship type (chapter 3).

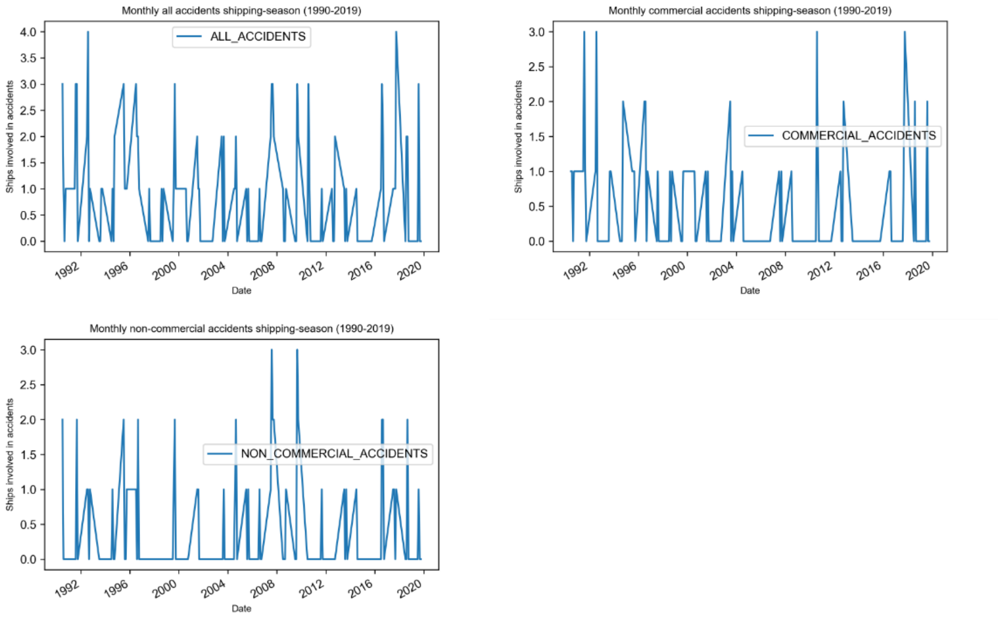


Figure A.13: Monthly time-series for monthly ship accidents during shipping-season from 1990 to 2019 (chapter 3).

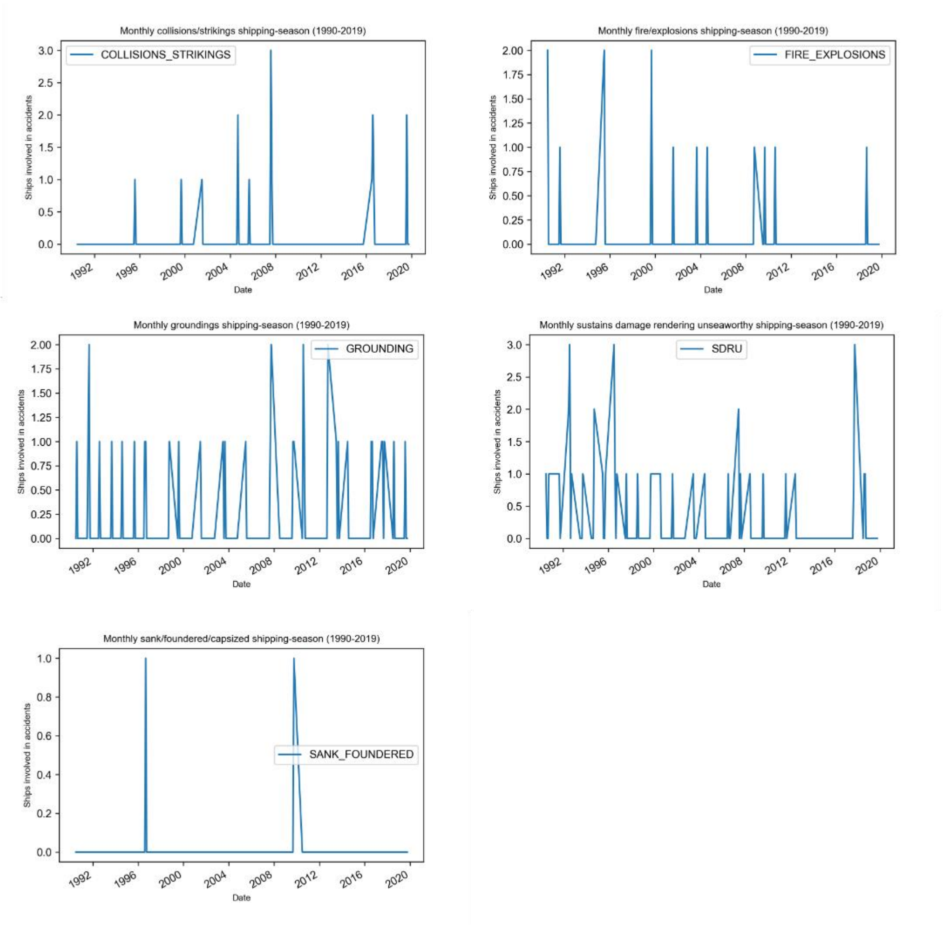


Figure A.14: Monthly time-series for monthly ship accidents during shipping-season from 1990 to 2019, by accident type (chapter 3).

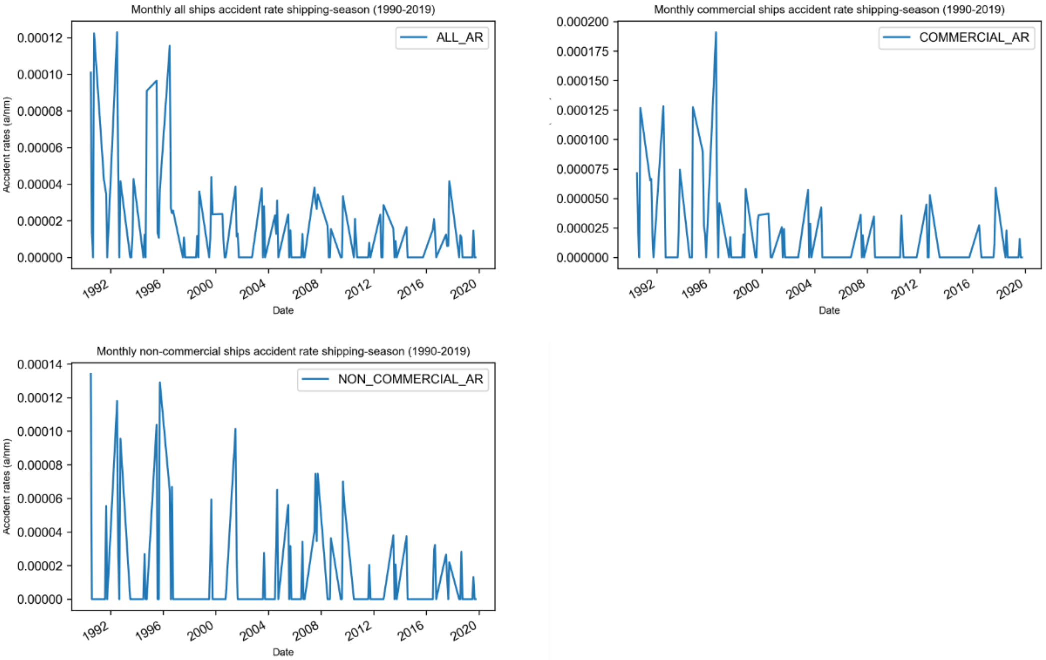


Figure A.15: Monthly time-series for monthly ship accident rates during shipping-season from 1990 to 2019 (chapter 3).

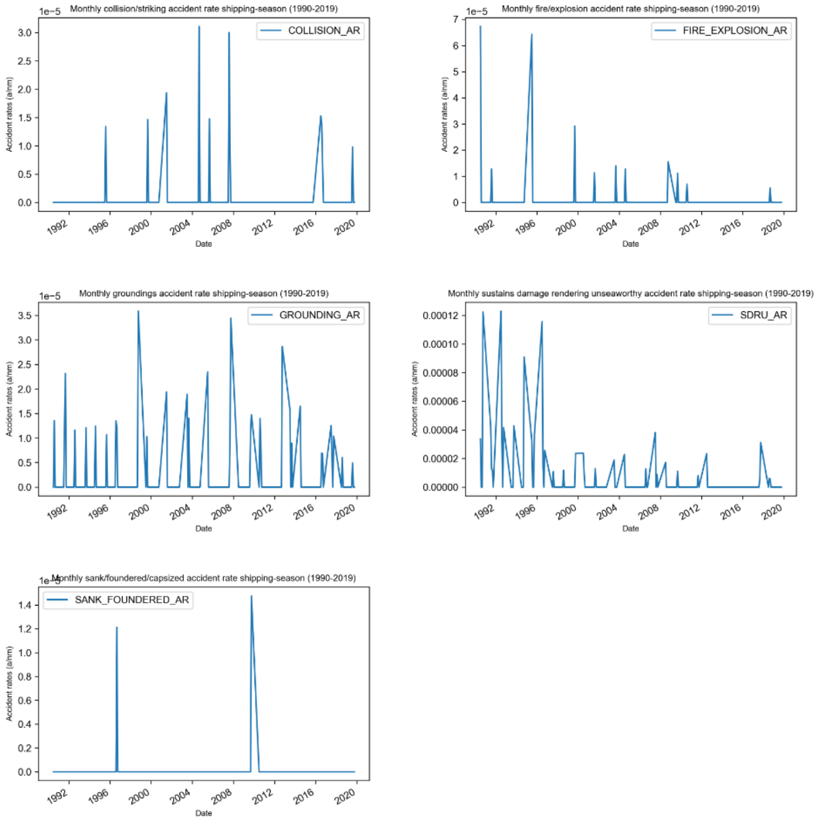


Figure A.16: Monthly time-series for monthly ship accident rates during shipping-season from 1990 to 2019, by accident type (chapter 3).

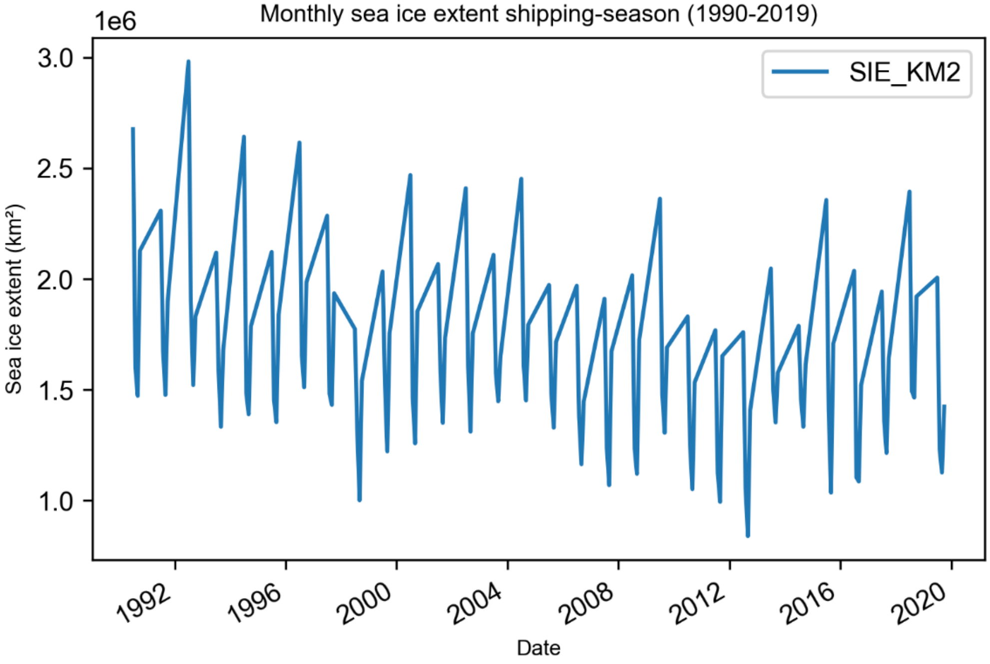


Figure A.17: Monthly time-series for monthly sea ice extent during shipping-season from 1990 to 2019 (chapter 3).

Figure A.18: Annual time-series for ship traffic during shipping-season from 1990 to 2019 (chapter 3).

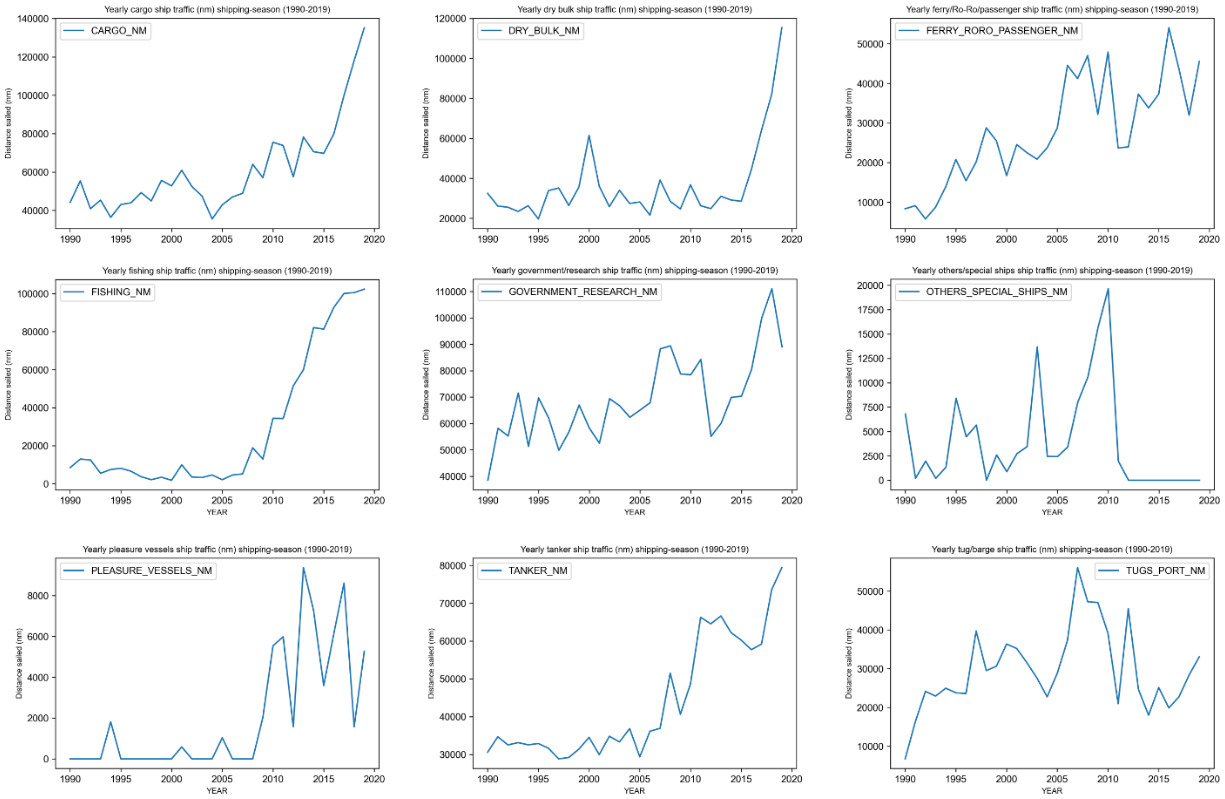


Figure A.19: Annual time-series for ship traffic during shipping-season from 1990 to 2019, by ship type (chapter 3).

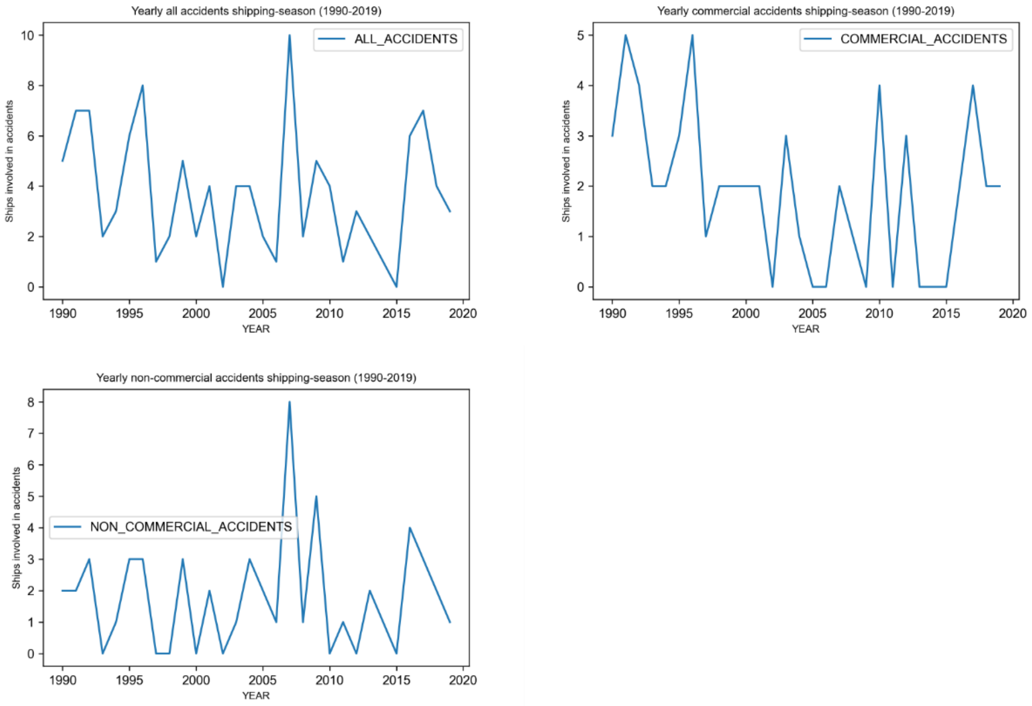
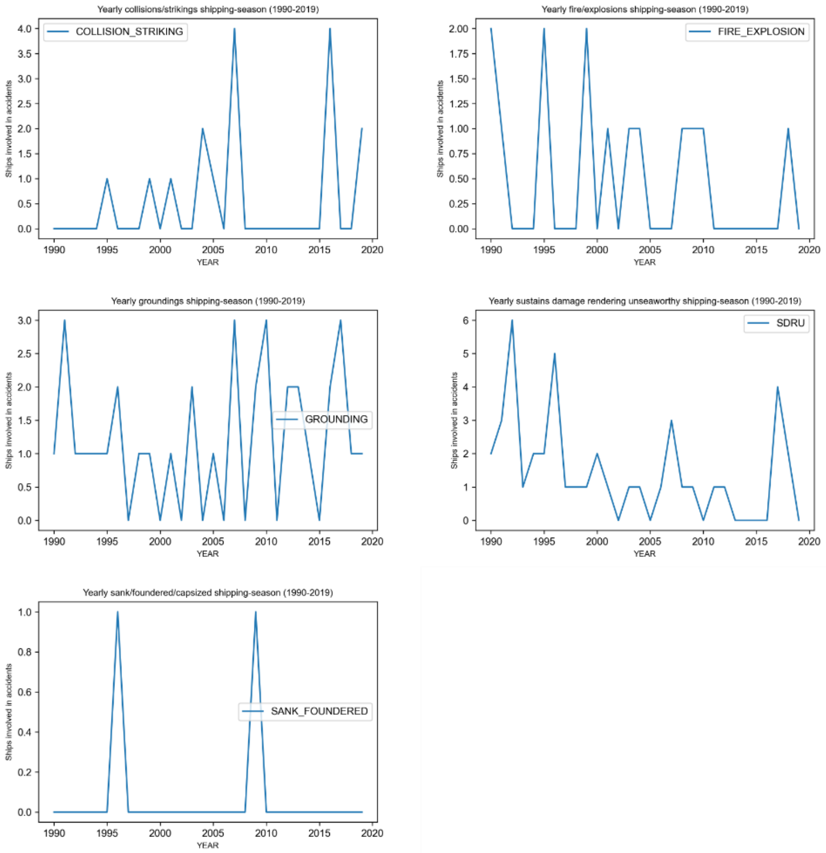


Figure A.20: Annual time-series for ship accidents during shipping-season from 1990 to 2019 (chapter 3).


Yearly collisions/strikings shipping-season (1990-2019)

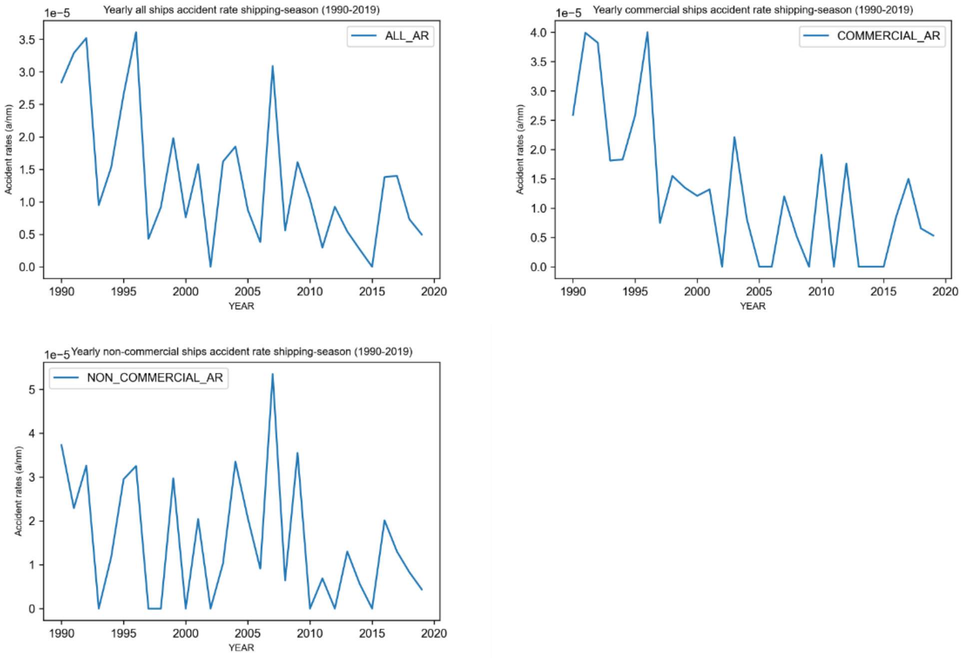
Yearly fire/explosions shipping-season (1990-2019)

Yearly groundings shipping-season (1990-2019)

Yearly sustains damage rendering unseaworthy shipping-season (1990-2019)

Yearly sank/foundered/capsized shipping-season (1990-2019)

Figure A.21: Annual time-series for ship accidents during shipping-season from 1990 to 2019, by accident type (chapter 3).


Yearly all ships accident rate shipping-season (1990-2019)

Yearly commercial ships accident rate shipping-season (1990-2019)

Yearly non-commercial ships accident rate shipping-season (1990-2019)

Figure A.22: Annual time-series for ship accident rates during shipping-season from 1990 to 2019 (chapter 3).

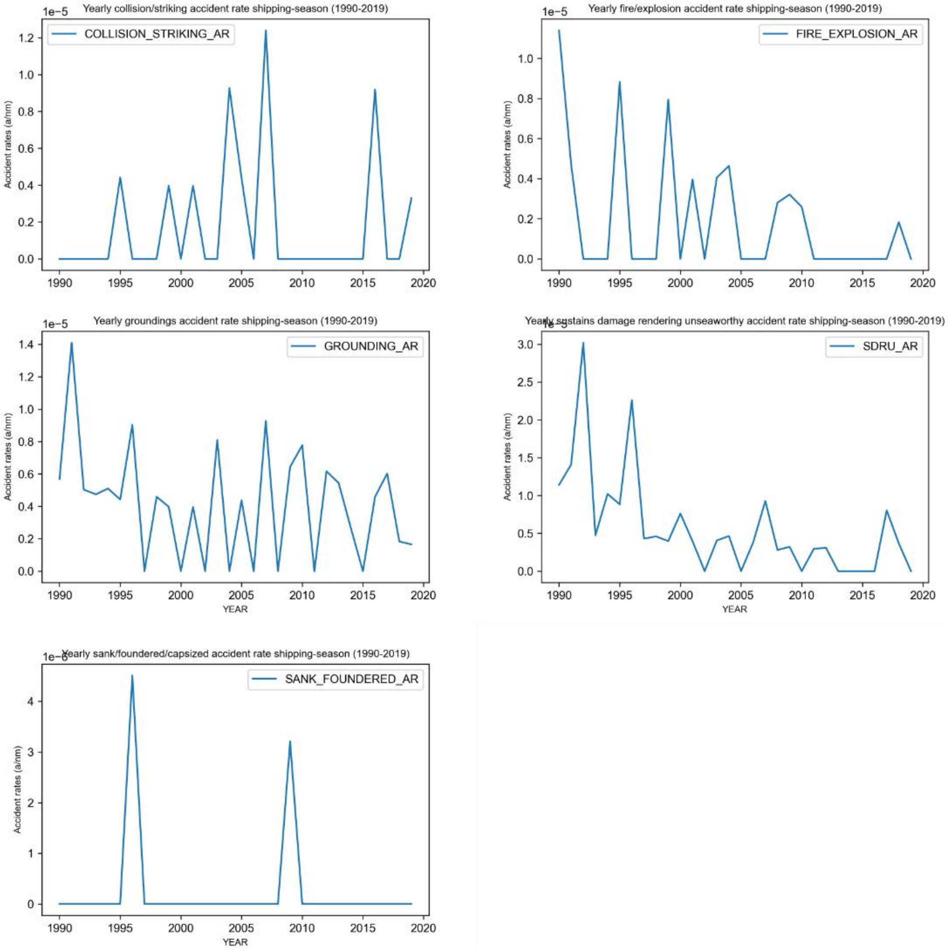


Figure A.23: Annual time-series for ship accident rates during shipping-season from 1990 to 2019, by accident type (chapter 3).

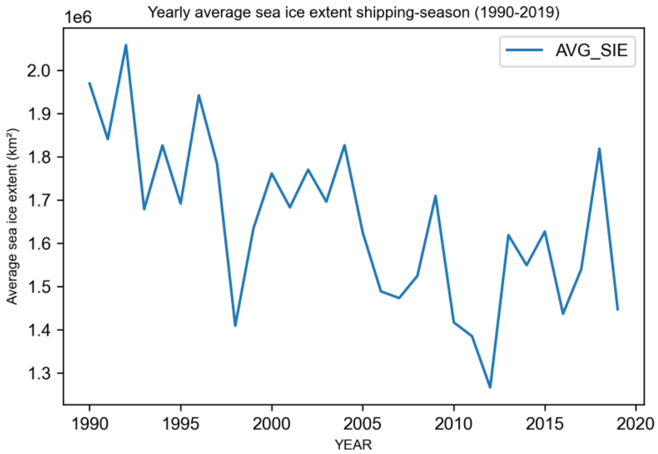


Figure A.24: Annual time-series for average monthly sea ice extent during shipping-season from 1990 to 2019 (chapter 3).