A Comprehensive Content and Risk Analysis of Maritime Shipping Operations in Arctic Canada

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Abstract

Arctic Canada has seen significant ecological changes since the 1990s, leading to sea ice melt, increased temperatures, and increased accessibility to the Northwest Passage. The increased accessibility to the Northwest Passage has allowed for vessels to easily access maritime routes that were not previously accessible. Changes to the Arctic landscape has led to the beginning of open water shipping seasons in Arctic waters, attracting international audiences for trade, tourism, fisheries, and other economic activity. This new passageway increases options for companies to reduce costs in shipping, while also facilitating new and emerging hazards and risks for operational vessels. Comprehensive risk analysis and full assessments need to be completed to aid policy- and decision-makers to support and manage the increasing maritime traffic in Canadian Arctic waters. To fill this knowledge gap, the overarching aim of this master's level research was to identify and preliminarily evaluate a comprehensive list of hazards (impact drivers) and risks (future impacts) for Maritime ship operations within Arctic Canada and to complete a preliminary assessment of identified maritime shipping hazards and risks throughout Arctic Canada.

Hazards and risks were identified using several text-based sources, including social media, grey literature, and peer reviewed journal articles, in order to conduct a comprehensive content analysis to identify the perspectives and trends emerging among the online community. Natural language processing methods were then used, such as word frequencies, word correlation, and topic modelling to identify key phrases, terminology, and thematic groups. This allowed for the creation of an inventory of relevant hazard and risk themes and categories that could be used as a strong basis for informing a risk analysis. Emerging themes included: sea ice, navigability issues, geopolitical concerns, and operational challenges, among others.

Following the identification of hazard and risk factors, a 'failure modes, effects, and criticality analysis' (FMECA) approach was used, along with a consequence-probability matrix, as means of performing a preliminary risk analysis. The method enables the collection of information regarding hazard and risk descriptors, consequence, probability, control mechanisms, impacts, and data quality information, to establish a validated risk rating score. Risk rating scores are calculated using consequences and probability scores to determine average risk ratings for individual hazards and risks and at the sector-based category level. A total of 154 variables were inventoried: 55 hazards were identified and 99 risks were noted that influence maritime ship operations in Arctic Canada. Five variables were classified as ‘VERY HIGH’: three hazards (hydrocarbon releases, transportation of dangerous goods, and multi-year sea ice) and two risks (community member displacement and socioeconomic impacts on indigenous peoples). Five thematic groups were seen as priority risk ratings, two of which identified with “HIGH” data quality indexes (Sea Ice, Environmental). A total of 35 hazards and 36 risks are recommended for further investigation, being classified with a ‘VERY HIGH’ or ‘HIGH’ data quality score. Results of this research supports a preliminary attempt at a comprehensive risk analysis that can be used in the future to conduct a full risk assessment.

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Chapter 1: Introduction

1.1 Problem Statement

Climate warming in the Arctic is occurring at three to four times the rate of the global average (Rantanen et al., 2022; IPCC, 2022; Government of Canada, 2021) and has led to extensive reductions in sea ice (Copland et al., 2021; Haas & Howell, 2015; Stewart et al., 2013). These changes in sea ice conditions are expected to increase the shipping season length for commercial and non-commercial vessels that serve and operate in the Canadian Arctic (Boylan, 2021; Dawson et al., 2018). Vessel activity in Arctic Canada has already increased by 75% (Dawson et al., 2018; Arctic Council, 2021; PAME, 2009) since about 1990. The observed increases in vessel traffic are rarely statistically correlated to reductions in sea ice extent. However, significance has been increasing over time (see Pizzaloto et al., 2016), meaning that climate change alone is not the only factor affecting maritime shipping activity. Other factors driving shipping trends in Arctic Canada include socioeconomic factors, such as commodity prices, economic and global trends, geopolitics, infrastructure availability, and others (Rantanen et al., 2022; Boylan, 2021; Dawson et al., 2019). In addition to creating opportunities for maritime shipping, climate change will facilitate a series of direct hazards (i.e., climate impact drivers) (IPCC, 2022; IPCC, 2019) that could lead to several different risks (i.e., future impacts) for ship operators in Arctic Canada.

Shipping operations in Arctic waters are subject to a variety of hazards that lead to diverse risks that are multidimensional, complex, and, in some cases, cumulative and cascading (IPCC, 2022). A variety of available definitions and processes that define hazards (i.e., climate impact drivers) and risks (i.e., future adverse effects) exist. This study uses definitional terms derived from the Intergovernmental Panel on Climate Change (IPCC), as they are widely accepted among the scientific community (IPCC, 2022). According to the IPCC, the definition of a hazard is "the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources." (IPCC, 2022). A risk is distinctly different from a hazard according to the IPCC, as a risk is defined as:

> “The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social, and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.” (IPCC, 2022).

In direct response to this complex content, this thesis-based research analysis will go beyond the examination of an individual or thematic group hazard and subsequent risk that may impact the operational capacity of a vessel in Arctic Canada by 1) engaging in a comprehensive inventory of the range of potential hazards and potential risk factors, and 2) developing methodological applications for assessing the levels of risk that may occur under current and future warming regimes. This research expands on previously completed work which identified and assessed independent or alike hazards and risks. For example, some studies singularly focus on sea ice presence (Chen et al., 2021; Haas & Howell, 2015; Stewart et al., 2013), underwater noise pollution (Lancaster et al., 2021; Würsig & Koski, 2021; Gross, 2018), increased human error due to lacking crew experiences (Comer et al., 2017; Johnston et al., 2017; Kum & Sahin, 2015), or tourism impacts on local communities (Johnston et al., 2017; Haas & Howell, 2015; Dawson et al., 2011). These studies have identified relevant and valuable baseline data, including occurrence probability, hazard severity, and direct/indirect impacts regarding hazard and risk exposure that can be used collectively to reveal a more comprehensive and integrated understanding of the cumulation of potential shipping risks in Arctic Canada resulting from a range of climate change hazards.

1.2 Research Aim and Objectives

The overarching aim of this master's thesis research is to identify and evaluate the range of hazards (i.e., climate impact drivers) and potential risk variables (i.e., potential future impacts considered to be negative) emerging from ship operations in the Northwest Passage (NWP). Identifying and assessing (a) hazards and (b) risks will aid in standardizing polar maritime risk assessment processes that could later be explicitly employed for shipping in northern environments and possibly replicated in other geographic regions worldwide. This approach will include diverse hazards and risks, building on existing studies that have often focused on singular variables as the primary (sometimes only) factor that is assumed to influence shipping (i.e., environment, unsafe acts, other). The interdisciplinary approach allows for a greater understanding of how Arctic shipping hazards are connected, how they influence each other, and how they influence (accentuate or limit) overall operational risks. The specific research objectives include to:

I. Create a comprehensive inventory of potential (a) hazards and (b) risks that affect shipping operations along the NWP via individual and thematic groups;
II. Classify and synthesize information of all individual (a) hazards and (b) risks into thematic groups using the outputs from objective I; and
III. Based on identified categories emerging from objective II, establish a risk rating score via a consequence-probability matrix for individual and thematic groups. Additional hazard and risk information will be collected to support risk scores such as 1) causes, consequences (direct and indirect), 2) current controls, and 3) data quality information.

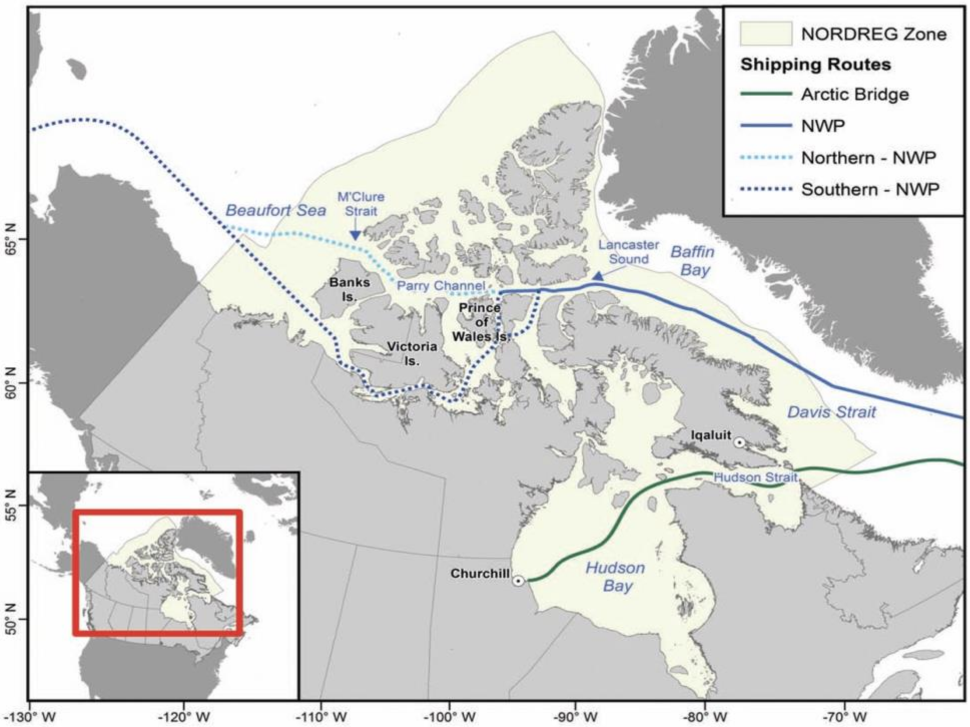
The overarching approach that will be taken in this thesis-based research project involves completing a comprehensive risk analysis, which is the precursor to a full risk assessment. A risk analysis focuses on identifying comprehensive hazards and resulting risks, in this case, along the NWP. A risk assessment, which could be completed in future research activities, involves a more rigorous and time-consuming exercise (Arctic Council, 2020; Mousavi et al., 2017) that is impractical to complete during a master's level study. The completion of a full risk assessment will be based on this completed risk analysis as a proposed Ph.D. level study that will begin upon completing this master's research (January 2024). The research planned in this master's-based risk analysis is vital in identifying hazards and subsequent risks, and determining data quantity, quality, probability of occurrence, hazard severity, and associated causes/consequences. These metrics will become essential in determining which hazards and risks influence each other and what quantitative analyses are feasible and possible in a future risk assessment.

1.3 Study Area

To address the objectives of this thesis-based research, the geographic focus is on Arctic Canada and, more specifically, the Northwest Passages (NWP) (Figure 1). The NWP is situated among the Canadian Arctic Archipelago that connects the Arctic, Atlantic, and Pacific Oceans. This area covers roughly 1.4 million square kilometres of the ocean (The Canadian Encyclopaedia, 2006). The NWP includes multiple route options, often referred to as the southern and northern routes (Figure 1). The NWP is considered a dynamic region due to its sheer size, allowing for many routes to be utilized to travel east or west. The first known Europeans to explore the Northwest Passage region were Martin Frobisher (1576), John Davis

(1585), William Baffin (1616), and Robert Bylot (1616) (Headland, 2022). The first successful voyage through the entirety of the NWP was by Roald Amundsen from 1903 to 1906 (Headland, 2022). Since then, there have been just over 350 voyages through the NWP (200 west, 151 east) (Headland, 2022).

Figure 1. Map of the Northwest Passage with labelled routes and NORDREG zone (Dawson et al., 2018).



The ongoing changes in sea ice conditions and technological advancements in vessel design and navigational tools have increased speculation regarding the feasibility of opening the NWP as an option for global trade (Meredith et al., 2019). The NWP could save up to 7,000 kilometres in distance compared to traditional maritime trade routes, such as using the Panama Canal when travelling from New York, USA to Yokohama, Japan (Somanathan et al., 2009; Somanathan et al., 2007). As sea ice concentration perpetually declines, operating seasons lengthen, and vessels can utilize the NWP for extended periods (Boylan, 2021). Presently, over 90% of vessels currently use the southern route of the NWP (Dawson et al., 2018). The southern route is favoured, beginning north of Baffin Island through the Lancaster Sound, south into Prince Regent Inlet, west into the Bellot Strait, and south adjacent to mainland Canada, through the Franklin and Victoria Straits. The route travels west adjacent to mainland Canada and Victoria Island towards the Beaufort Sea (Dawson et al., 2018). Additional routes that use the Barrow Strait and Peel Sound are considered alternate routes due to historical navigational difficulties (Dawson et al., 2018). The northern NWP route utilizes the M'Clure Strait and Parry Channel (Dawson et al., 2018). The northern route is estimated to become ice-free during operating seasons by the end of the 21st century, creating an additional route that is considered more cost-effective, though more remote (Dawson et al., 2018).

1.4 Literature Review

1.4.1 Understanding Risk Analysis and Risk Assessment

1.4.1.1 Defining Hazards and Risks

There are various definitions for hazards and risks coming from organizations such as the International Maritime Organization (IMO), the Intergovernmental Panel on Climate Change (IPCC) and the International Organization for Standardization (ISO) (IPCC, 2022; IMO, 2018; ISO, 2009). While there are some similarities among the definitions, there is substantial variation in definitional terms leading to confusion among risk management professionals and academics. Specifically, confusion exists between the terms hazard, impact, and risk with some believing these terms to some extent synonymous while others present clear and explicit differentiation. The lack of agreement on definitions for these terms has led academics and practitioners to struggle with the use of risk vocabularies when managing risks. The IPCC definitions of hazard, impact, and risk have been selected for this study, as it was determined that these definitions clearly delineate differences between the terms and are easy to understand and to apply in risk-based studies. The basic differences between the terms are as follows. Hazards are ‘climate impact drivers’, such as warming temperature or changing wind patterns, that have created an observable impact (current) or that may lead to a risk (future). According to the IPCC, a risk is typically a possible natural or human-made system that is a result of an interaction of climate-related hazards (IPCC, 2022). An example of a risk would be vessel capsizing, where high wind speeds influence the balance of a vessel. Other relevant terms used within this risk analysis include: vulnerability, exposure, and sensitivity, whereby ‘vulnerability’ is a function of a system’s ‘exposure’ to a ‘hazard’ and ‘sensitivity’ to a ‘hazard’ (IPCC 2021). Table 1 outlines key terminology that supports our understanding of the key concepts in this thesis. As noted, these definitions were established by the IPCC and the most recent versions of these concepts are used - see IPCC Annual Report 6 – Working Group II report (IPCC, 2022). To view a full version of the terms of reference, please see Appendix 1.

Table 1. List of key definitions taken from the AR6 IPCC glossary (IPCC, 2022).

Term (Source)	**Definition**
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.
Impact	The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.
Risk	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.
Sensitivity	The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

1.4.1.2 Defining and Differentiating between Risk Analysis and Risk Assessment

In 1948, the United Nations created the IMO, which began in 1958 to create standards for maritime shipping practices, including processes to assess and mitigate large-scale risks (IMO, 2019). This governing body facilitates cooperation among governments through regulations and practices that encourage the highest possible standards for shipping. The IMO has five central committees (including the Maritime Safety Committee (MSC)) (IMO, 2019). Key regulation topics include, but are not limited to, the Polar Code, the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code), Safe Mooring, and Formal Safety Assessments (IMO, 2018; IMO, n.d.). The usage of Formal Safety Assessments (FSAs) is important within environment, health, and safety where hazard and risk identification are used as means for strengthening and recommending policies to eliminate or mitigate risk (IMO, 2018). FSAs also follow near-identical assessment processes compared to the ISO standards which provide guidelines regarding consultation, data acquisition, and analysis (IMO, 2018). Formal Safety Assessments were adopted and implemented by IMO in 2002 as a response to the Piper Alpha catastrophe, which killed 167 people (IMO, n.d.). The IMO's regulations identify methods, frameworks, and principles for conducting FSAs regarding maritime shipping and was last modified in 2018 (IMO, 2018). The Polar Code was created in 2014 during the MSC's 94th session and became law in January 2017 (IMO, 2020). The Polar Code includes mandatory requirements surrounding safety (parts I-A), pollution prevention (parts II-A), and provisions for both sections (parts I-B and II-B) (IMO, 2020). A mandatory certificate for all vessels operating in Polar waters classifies ships into three (3) categories; (A) operational in multi- and first-year ice, (B) operational in first-year ice waters, and (C) operational in open water conditions (IMO, 2020). This regulation also requires vessel routing/reporting due to increased voyages through Arctic waters, mandatory training, and pollution regulation of heavy oils (IMO, 2020).

The Arctic Council (AC) Emergency Prevention, Preparedness, and Response Working Group (AC-EPPRWG) established a risk analysis and assessment common approach framework with the primary scope of analyzing Arctic marine environments (Arctic Council, 2020). The guideline follows a six-step process; (1) scope, context, and criteria, (2) risk identification, (3) risk analysis, (4) risk evaluation, (5) risk treatment; and (6) reporting (Arctic Council, 2020). The risk analysis framework uses two categories in defining risks (ship traffic and the environment), and requires observing each risk's likelihood, severity, and consequences before the risk assessment (Arctic Council, 2020). Hazard and risk identification is typically completed with a risk analysis, where both processes aid each other in providing data and complementing outputs regarding probability of occurrence, consequence, and controls (Arctic Council, 2020; ISO, 2009). A risk analysis process acts as a precursor to a more in depth risk assessment, providing input to assess risks that are subject to risk treatment upon further examination (Arctic Council, 2020; ISO, 2009). The AC-EPPRWG identified ten (10) Arctic risk-influencing factors for a risk analysis, including ice, topside icing, low temperatures, extended darkness, high latitude, remoteness, crew experience, lack of emergency equipment, severe weather, and the environment (Arctic Council, 2020).

In contrast to a risk analysis, a formal risk assessment provides a thorough examination of priority hazards and risks that examine the relationships between one another (Arctic Council, 2020; ISO, 2009). The outcome of a risk assessment is to determine which risks should be prioritized for risk treatment; typically visualized through risks categorized as intolerable, 'as low as reasonably possible' (ALARP), and negligible (ISO, 2009). The ALARP term is classified as a medium-level risk, using costs and benefits to determine whether a risk has been reduced or mitigated to decrease adverse consequences (ISO, 2009). An exemplary study conducted by Mousavi et al. (2017) highlights five critical steps within the risk assessment process: (1) risk and hazard identification, (2) risk analysis, (3) risk assessment), (4) risk treatment, and (5) reporting. This study used the risk assessment framework to improve vessel operations and decrease risk exposure (Mousavi et al., 2017). The research identified critical threats and processes that caused risk occurrence and assessed these metrics to provide recommendations for risk mitigation that is ALARP (Mousavi et al., 2017).

Previously completed research focused on specific Arctic shipping hazards and risks within one or two sector(s) or shipping process(es). Since previous research efforts have not vocalized the Arctic as a key priority, this has led to limited baseline data available and collection. This lack of evidence was a suspected cause for limited research opportunities to complete risk analyses and assessments to occur at the individual and sector level, being unable to examine all comprehensive hazards and risks using a singular risk analysis or assessment. Previous research has also revealed environmental and economic risks associated with Arctic shipping practices under Polar Code regulations (Bartenstein, 2019; Ghosh and Rubly, 2015). While operational costs and permit fees have been identified, many uncertainties remain regarding insurance pricing and estimation due to the vast unknowns (Ghosh and Rubly, 2015; Somanathan et al., 2009; Somanathan et al., 2007). Environmental concerns notably rise due to rapid changes in the natural environment and vessel activity within Arctic Canada (Bartenstein, 2019; Ghosh and Rubly, 2015).

Various international organizations such as the AC, IMO, and the International Organization of Standardization (ISO) have adopted and supported a framework that requires the identification of hazards, assessment of risks, determination of controls, and effective establishment of recommendations (Arctic Council, 2020; IMO, 2018; ISO, 2009). Various studies have identified and assessed specific hazards and risks, but have yet to produce a comprehensive evaluation of the wide range of plausible hazards. Given the complex nature of Arctic shipping, both risk identification (via assessment of hazards) and risk analysis seem an appropriate next step for more comprehensively understanding shipping sector challenges.

1.4.1.2 Specific Methods for Risk Analysis Techniques of Arctic Shipping

The AC, IMO, and ISO have established and recommended several structured analytical techniques (SATs) for risk analyses and assessments (Appendix 2) (Arctic Council, 2020; IMO, 2018; ISO, 2009). The suggested SATs use qualitative and quantitative data that can be used to complete the analysis while also considering subject matter expert opinions in situations of data deficiency (IMO, 2018; ISO, 2009).

The preliminary hazard analysis (PHA) is a simple means for identifying hazards and hazardous situations that can cause relative harm through a system, activity, and/or vessel (ISO, 2009). A study by Fu et al. (2021) used this method to review peer-reviewed articles and identify similarities of hazards and risks from 2000 to 2019 within the Arctic shipping context. The study identified the top 10 emerging risks from the reviewed articles, and expert judgment was the main analytical technique used due to sparse data availability (Fu et al., 2021).

The use of risk contribution tree (RCT) has illustrated risks among various hazards identified through categories and subcategories (IMO, 2018). RCTs are typically used in conjunction with fault and event tree diagrams for mapping each risk's severity and association with other known risks and hazards (IMO, 2018). Fault and event trees observe a specific risk category or event scenario using a strict YES/NO logic gate to determine risk conditions and consequences (ISO, 2009). See Mousavi et al. (2017) for an example of this method. These methods were deemed out of the scope for this research due to their limitations regarding the inability to assess risks comprehensively.

The Bayesian network uses probability to illustrate the likelihood of hazard occurrence, and it models dependencies and hazard relationships through the use of a cause-and-effect model, highlighting problematic relationships that heighten negative impacts (IMO, 2018, ISO, 2009). The Bayesian network is typically used when analyzing the relationship of one or two thematic groups or processes, noting the relationships among hazards and risks (ISO, 2009). An example of the Bayesian network was examined by Qian et al. (2020), who used the method when modelling the natural environment risks of arctic shipping practices. High quantities of data enhance the model's predictive performance, decrease the uncertainty of environmental risks, and correlate this with year-over-year and monthly analyses (Qian et al., 2020). This method was also used by Afenyo et al. (2019) to estimate the consequence of oil spills and the relationship to socioeconomic impacts on Arctic communities.

A bow tie analysis (BTA) is used to describe and analyze pathways of risk sources (causes and hazards) and prevention controls that result in an event (risks) occurring (ISO, 2009). The analysis then observes the mitigation and recovery controls to identify the consequences to the event (risks) occurrence (ISO, 2009). This metric is similar to a fault tree analysis, because it identifies and analyses specific causes and consequences of an event (ISO, 2009). However, this method focuses on the barriers between causes and the event risk and between the risk and the consequences. Aziz et al. (2019) used this method to identify operational risks for marine vessels, specifically five near miss incidents scenarios.

Consequence-probability matrices use and combine qualitative or semi-quantitative data that have identified the level of consequence and probability, being placed in a matrix to creating a risk rating score (ISO, 2009). The matrix uses pre-defined terms and bins to rank the level of consequence and probability of a hazard and risk to develop a standardized risk rating score (ISO, 2009). Due to the simplicity and easy use of this methodology, multiple sources such as Aziz et al. (2019) and Shanshan Fu et al. (2023) have used this method for previous Arctic shipping risk assessment within an individual sector of risk scenarios.

Various tools and methods have been used to successfully analyze hazards and risks in Arctic shipping. Each Arctic shipping risk analysis phase will require different structured analytical techniques to avoid biases. It is also necessary to use more than one SAT during each portion of the risk assessment process, where SATs serve specific functions to the risk assessment process and can aid specific aspects. Assessing comprehensive risk will require using multiple SATs systematically, complementing each other. Research has enabled conclusions surrounding the complexity of Arctic vessel operations, where hazards influence and trigger each other throughout the network (Fu et al., 2021).

1.3.2 Hazards and Risks for Arctic Shipping Operations

Interest in the Arctic for the purpose of maritime trade has existed for centuries with many colonial powers speculating on the economic possibility of shorter routes linking the Pacific and Atlantic Oceans (Somanathan et al., 2009; Somanathan et al., 2007). Climate change may allow for easier navigation through the NWP, because the diminishing sea ice has enabled a possible route (Boylan, 2021; Dawson et al, 2018; Pizzaloto et al., 2016). This can pose unprecedented risks during the beginning and end of the operational season, when hazards like iceberg presence are increasing (Boylan, 2021). All presently used routes typically have shallow waters, causing the water bodies to freeze quickly during winter, which poses a high degree of uncertainty. In response to ongoing uncertainty about the economic viability and physical risk of transiting the NWP, there is a need to conduct a risk analysis prior to a formalized risk assessment to determine priority hazard and risk variables, including but not limited to sea ice change.

The Arctic environment is often described as remote and pristine due to landscape features being untouched by human activity. The Arctic's remoteness exhibits undesirable conditions for humans and remains untarnished, though it has increased fascination within the science community and tourism industries. The Arctic is home to fragile wildlife and a unique ecosystem that was underutilized within the marine industry until the beginning of the 21st Century (Government of Canada, n.d.). Increased activity by a variety of vessel types has caused the environment to be disrupted by humans, creating numerous impacts (Dawson et al., 2018). However, there are limited legislative reporting requirements for the polar regions, and researchers argue the importance of conserving the Arctic, as it is the last place that remains unpolluted by excessive ship-source underwater noise (Lancaster et al., 2021; Gross, 2018; Moore et al., 2012).

Risk analysis and assessment play a critical role in disaster management to prevent environmental contamination such as the Exxon Valdez crude oil spill occurring in March 1989 (US-EPA, 2022). Approximately 11 million gallons of crude oil spilled into the Bligh Reef in Prince William Sound, Alaska, causing detrimental impacts to migratory birds, marine species living in coastal areas, and local fishing operations (US-EPA, 2022). The United States Coast Guard mobilized a nationwide effort to clean the spill, where bioremediation technologies, burning, and mechanical clean-up methods were used for remediation (US-EPA, 2022). With assistance from the National Oceanic and Atmospheric Association (NOAA), the team provided weather forecasts to ensure the clean-up method was the most appropriate for the weather (US-EPA, 2022). This example clearly demonstrates the underlying complexities regarding disaster and risk management in such remote, pristine, and ecologically sensitive areas, and presents a significant desire for thorough risk assessment to be completed prior to operations.

Table 2. List of Risk Influencing Factors (RIFs) with publications exemplifying hazards and risks that are implemented by Arctic Council (Arctic Council, 2020).

Risk Influencing Factors (RIFs)	Arctic Council's RIFs Description	Example of Hazards	Example of Risks	Example References
Environment	The environment with respect to sensitivity to harmful substances and other environmental impacts and its need for longer restoration.	Air pollution; Depletion of natural resources; Operational discharge of pollutants; Vessel-induced underwater noise	Deterioration of ecological habitat	Wang et al., 2022; Kamal & Kutay, 2021; Lancaster et al., 2021; Würsig & Koski, 2021; Zhang et al., 2020; Goldsmit et al., 2019; Baksh et al., 2018; Gross, 2018; Halliday et al., 2017
Extended periods of darkness or daylight	Extended periods of darkness or daylight as it may affect navigation and human performance.	Low sunlight		Berge et al., 2015; Barber et al., 2010
High latitude	High latitude, as it affects navigation systems, communication systems and the quality of ice imagery information.	Magnetic interference	Limited enforcement capabilities; Reliability of communication devices; Reduced quality of available information	Lancaster et al., 2021; Sheehan et al., 2021; Würsig & Koski, 2021
Ice	Ice may affect hull structure, stability characteristics, machinery systems, navigation, the outdoors working environment, maintenance and emergency, preparedness tasks and malfunction of safety equipment and systems.	First-year sea ice presence; Iceberg presence; Multi-year sea ice presence; Sea ice presence	Impact damage to vessel; Vessel machinery malfunctions; Increased navigational obstacles	Chen et al., 2021; Copland et al., 2021; Haas & Howell, 2015; Serreze & Stroeve, 2015; Stewart et al., 2013
Low Temperature	Low temperature may affect the working environment and human performance, maintenance and emergency preparedness tasks, material properties and equipment efficiency, survival time, and performance of safety equipment and systems.	Low air temperatures		Sheehan et al., 2021; Haas & Howell, 2015
Severe weather conditions	Rapidly changing and severe weather conditions, with the potential for escalation of incidents.	Extreme cold; Low visibility; Low air temperatures		Sheehan et al., 2021; Haas & Howell, 2015
Topside icing	Topside icing, with potential reduction of stability and equipment functionality.	Changing sea conditions; Extreme cold	Limited equipment functionality; Ship instability; Vessel capsizing	Sheehan et al., 2021; Haas & Howell, 2015

Note: this review will be used as a basis for the risk analysis proposed in this thesis

Table 2 outlines the intricacies of hazards and risks within maritime ship operations in the Arctic using the Arctic Council's risk influencing factors (RIFs) (Arctic Council, 2020). Table 2 utilized RIFs to initially understand and identify comprehensive hazards and risks in Arctic shipping. This was later converted into a thorough table when the failure modes, effects, and criticality analysis (FMECA) were completed. Please see Appendix 7 and 8 for a complete list of hazards and risks observed within this study.

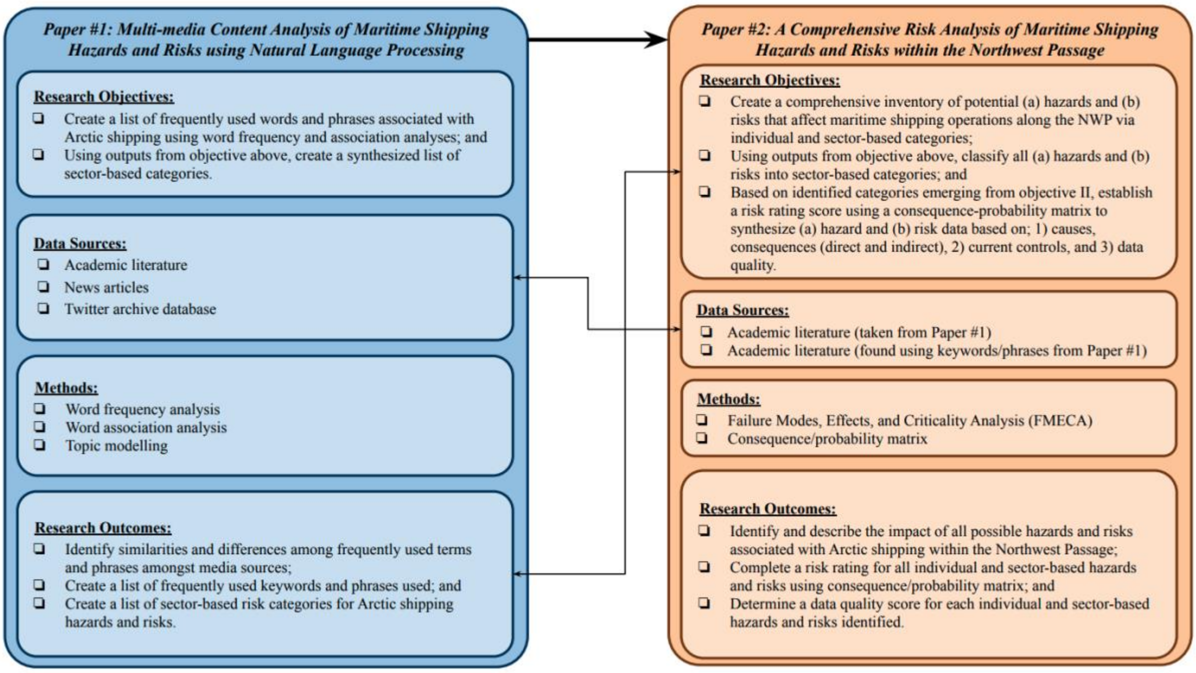
Various regulations, guidelines, and analytical techniques from international to local levels have been developed to support identifying hazards, assessing risks, and implementing mitigation measures to combat the highest threats related to Arctic shipping. Previously completed literature advocates for establishing dynamic risk models, historical analysis, and assessing possible human/organizational errors during shipping operations (Kamal & Kutay, 2021; van Hoof et al., 2020). Environmental Impact Assessments are also studied to account for various comprehensive risks, though strongly advocating for a dynamic process to suit the complexities of the project scope (van Hoof et al., 2020). A study by Zhou (2022) established a comprehensive risk assessment framework for navigation risks within the South China Sea regarding SAR capabilities (Zhou, 2022; Wang et al., 2022). A similar study also examined the societal impacts and risk acceptance regarding cargo international shipping risks in the form of injuries and fatalities using spatial information (Wang et al., 2022; Hu et al., 2007). Creating a comprehensive framework to assess the hazards and risks from vessel operations in the NWP is necessary. Identifying the highest threats will allow policymakers to target and mitigate high risks to conserve the uniqueness of the Arctic ecosystem through an evidence-based approach.

1.4 Organization of the thesis

The structure of this Master of Science thesis follows an article-based format, including two scientific papers that respond to the four research questions that were developed in this thesis research (see s*ection 1.2*). The overarching approach in this thesis-based research project, involved the completion of a comprehensive risk analysis, which is the precursor to a full risk assessment. A risk analysis focuses on identifying comprehensive hazards and resulting risks, in this case, along the NWP. A risk assessment, which could be completed in future research activities, involves a more rigorous and much more time-consuming exercise (Arctic Council, 2020; Mousavi et al., 2017) that is impossible to complete in the duration of a Master level study.

Chapter 2 (article 1) utilizes various forms of media, such as news articles, social media, and academic publications, to identify key terms and phrases associated with Arctic shipping hazards and risks within the Northwest Passage (NWP). Subsequently, these terms and phrases will guide the creation of thematic groups to categorize hazards and risks via sector when measuring and assessing risks, similar to risk-influencing factors noted by Arctic Council (Arctic Council, 2020). *Chapter 3* (article 2), a comprehensive risk analysis, was conducted using a Failure Modes, Effects, and Criticality Analysis (FMECA) along with a consequence/probability matrix to gather hazard and risk information from academic publications and assess them based on consequence and probability. This paper aims to provide recommendations regarding risk rating among hazards and risks that require further valuation through a future risk assessment. *Chapter 4* concludes the thesis, addressing the outcomes of the research objectives by providing a list of (a) hazards and (b) risks and their corresponding information such as data quality scores, controls, causes, and consequences. This chapter also addresses the main study limitations, examining the thesis' professional contributions, and areas of future work. Figure 2 identifies the relationships and organizations among both publications via a conceptual framework.

Figure 2. Detailed conceptual framework of this research.



Based on the completion of this risk analysis is proposed as a PhD level study that will begin after successfully completing this master's research that involves the undertaking of a full risk assessment (potentially in January 2024). The research that is planned in this master's-based risk analysis is key in not only identifying hazards and subsequent risks, but also in determining data quantity, quality, probability of occurrence, severity, and associated causes/consequences. These metrics will become essential in determining which hazards and risks influence each other, and what quantitative analyses are both feasible and possible in the future risk assessment, thoroughly assessing exposure, vulnerability, and severity using the IPCC's three-pronged approach.

1.5 References cited in Chapter 1

Agard, J., and Schipper, E. (2018). Intergovernmental Panel on Climate Change (IPCC) AR5-Annex II - Glossary. IPCC Working Group II - AR5 Report. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf

Akbayirli, K., and Tuna, O. (2022). How Do Practitioners View Arctic Shipping Routes? A Cognitive Appraisal Approach. *Transportation Research Part D: Transport and Environment*, 110, 103432. https://doi.org/10.1016/j.trd.2022.103432

Arctic Council. (2020). *Guideline for Arctic Marine Risk Assessment.* Arctic Council. Retrieved January 2023, from https://eppr.dnvgl.com/

Arctic Council. (n.d.). Addressing arctic pollution. Arctic Council. Retrieved April 2023, from https://arctic-council.org/explore/topics/pollutants/

Baksh, A.-A., Abbassi, R., Garaniya, V., and Khan, F. (2018). Marine Transportation Risk Assessment using bayesian network: Application to arctic waters. *Ocean Engineering*, 159, 422–436. https://doi.org/10.1016/j.oceaneng.2018.04.024

Barber, D. G., Asplin, M. G., Gratton, Y., Lukovich, J. V., Galley, R. J., Raddatz, R. L., and Leitch, D. (2010). The International Polar Year (IPY) Circumpolar Flaw lead (CFL) system study: Overview and the physical system. *Atmosphere-Ocean*, 48(4), 225–243. https://doi.org/10.3137/oc317.2010

Berge, J., Renaud, P. E., Darnis, G., Cottier, F., Last, K., Gabrielsen, T. M., Johnsen, G., Seuthe, L., Weslawski, J. M., Leu, E., Moline, M., Nahrgang, J., Søreide, J. E., Varpe, Ø., Lønne, O. J., Daase, M., and Falk-Petersen, S. (2015). In the dark: A review of ecosystem processes during the Arctic Polar Night. *Progress in Oceanography*, 139, 258–271. https://doi.org/10.1016/j.pocean.2015.08.005

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

The Canadian Encyclopedia. (2006). Arctic Archipelago. Retrieved March 2023, from https://www.thecanadianencyclopedia.ca/en/article/arctic-archipelago

Chen, J.-L., Kang, S.-C., Guo, J.-M., Xu, M., and Zhang, Z.-M. (2021). Variation of sea ice and perspectives of the Northwest Passage in the Arctic Ocean. *Advances in Climate Change Research*, 12(4), 447–455. https://doi.org/10.1016/j.accre.2021.02.002

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017). Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025. Washington DC, *International Council on Clean Transportation*. DOI: http://dx.doi.org/10.25607/OBP-1733

Conachey, R., & Montgomery, R. (2005, October). Development of machinery survey requirements based on reliability-centered maintenance. In SNAME Maritime Convention. OnePetro.

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

Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., and Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. *ARCTIC*, 71(1). https://doi.org/10.14430/arctic4698

Dawson, J., Stewart, E. J., Johnston, M. E., and Lemieux, C. J. (2016). Identifying and evaluating adaptation strategies for Cruise Tourism in Arctic Canada. *Journal of Sustainable Tourism*, 24(10), 1425–1441. https://doi.org/10.1080/09669582.2015.1125358

Dawson, J., Pizzolato, L., Howell, S., Copland, L., & Johnston,M. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. *Arctic*, 71. 15-26. https://doi.org/10.14430/arctic4698

Dawson, J., Johnston, M., Stewart, E., Lemieux, C., Lemelin, R., Maher, P., & Grimwood, B. (2011). Ethical considerations of last chance tourism. *Journal of Ecotourism*, 10(3), 250–265. https://doi.org/10.1080/14724049.2011.617449

Daya, A. A., & Lazakis, I. (2023). Developing an advanced reliability analysis framework for Marine Systems Operations and Maintenance. Ocean Engineering, 272, 113766. https://doi.org/10.1016/j.oceaneng.2023.113766

Dyrcz, C. (2017). Safety of navigation in the Arctic. *Scientific Journal of Polish Naval Academy*, 211(4), 129–146. https://doi.org/10.5604/01.3001.0010.6742

Filipiak, D., Węcel, K., Stróżyna, M., Michalak, M., & Abramowicz, W. (2020). Extracting Maritime Traffic Networks from AIS data using evolutionary algorithm. *Business and Information Systems Engineering*, 62(5), 435–450. https://doi.org/10.1007/s12599-020-00661-0

Fu, S., Goerlandt, F., & Xi, Y. (2021). Arctic Shipping Risk Management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents. *Safety Science*, 139, 105254. https://doi.org/10.1016/j.ssci.2021.105254

Ghosh, S., & Rubly, C. (2015). The emergence of Arctic shipping: Issues, threats, costs, and risk-mitigating strategies of the Polar Code. A*ustralian Journal of Maritime & Ocean Affairs*, 7(3), 171–182. https://doi.org/10.1080/18366503.2015.1093695

Goldsmit, J., McKindsey, C., Archambault, P., and Howland, K. L. (2019). Ecological risk assessment of predicted marine invasions in the Canadian Arctic. *PLOS ONE*, 14(2). https://doi.org/10.1371/journal.pone.0211815

Government of Canada. (2022, June 6). Shipping in the Arctic. Crown-Indigenous Relations and Northern Affairs Canada. Retrieved from https://www.rcaanc-cirnac.gc.ca/eng/1648145733596/1648145784817

Gross, M. (2018). Arctic shipping threatens wildlife. *Current Biology*, 28(15). https://doi.org/10.1016/j.cub.2018.07.053
Haas, C., and Howell, S. E. (2015). Ice thickness in the northwest passage. *Geophysical Research Letters*, 42(18), 7673–7680. https://doi.org/10.1002/2015gl065704

Halliday, W. D., Le Baron, N., Citta, J. J., Dawson, J., Doniol-Valcroze, T., Ferguson, M., Ferguson, S. H., Fortune, S., Harwood, L. A., Heide-Jørgensen, M. P., Lea, E. V., Quakenbush, L., Young, B. G., Yurkowski, D., and Insley, S. J. (2022). Overlap between bowhead whales (balaena mysticetus) and vessel traffic in the North American arctic and implications for conservation and management. *Biological Conservation*, 276, 109820. https://doi.org/10.1016/j.biocon.2022.109820

Halliday, W. D., Insley, S. J., Hilliard, R. C., de Jong, T., and 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. https://doi.org/10.1016/j.marpolbul.2017.09.027

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

Headland, R. (2022, December 8). Transits of the Northwest Passage to the End of 2022 Navigation Season. *Polar Information Sheets*. Retrieved March 2023, from https://www.spri.cam.ac.uk/resources/infosheets/northwestpassage.pdf

Hu, S., Fang, Q., Xia, H., and Xi, Y. (2007). Formal safety assessment based on relative risks model in ship navigation. *Reliability Engineering and System Safety*, 92(3), 369–377. https://doi.org/10.1016/j.ress.2006.04.011

International Maritime Organization (IMO). (2020). *International Code for Ships Operating in Polar Waters (Polar Code)*. International Maritime Organization. Retrieved February 2023, from https://www.imo.org/en/OurWork/Safety/Pages/polar-code.aspx

International Maritime Organization (IMO). (2019). *History of IMO*. International Maritime Organization. Retrieved March 2023, from https://www.imo.org/en/About/HistoryOfIMO/Pages/Default.aspx

International Maritime Organization (IMO). (2018, April 9). R*EVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA)*. International Maritime Organization (IMO). Retrieved February 2023, from https://www.imo.org/en/OurWork/Circulars/Pages/default.aspx

International Maritime Organization (IMO). (n.d.). *Formal Safety Assessment (FSA)*. International Maritime Organization. Retrieved March 2023, from https://www.imo.org/en/OurWork/Safety/Pages/FormalSafetyAssessment.aspx

International Organization for Standardization (ISO). (2018). Risk Management - Guidelines (ISO 31010:2009). Retrieved from: https://shahrdevelopment.ir/wp-content/uploads/2020/03/ISO-31000.pdf

International Organization for Standardization (ISO). (2009a). Risk Management - Vocabulary (ISO Guide 73:2009). Retrieved from: https://www.iso.org/obp/ui/#iso:std:iso:guide:73:ed-1:v1:en:term

International Organization for Standardization (ISO). (2009b). Risk Management - Risk Assessment Techniques (IEC/FDIS 31010:2009). Retrieved from: https://bambangkesit.files.wordpress.com/2015/12/iso-31010_risk-management-risk-assessment-techniques.pdf

Johnston, M., Dawson, J., De Souza, E., and Stewart, E. J. (2016). Management challenges for the fastest growing marine shipping sector in Arctic Canada: Pleasure crafts. *Polar Record*, 53(1), 67–78. https://doi.org/10.1017/s0032247416000565

Johnston, M. E., Dawson, J., and Maher, P. T. (2017). Strategic development challenges in marine tourism in Nunavut. *Resources*, 6(3), 25. https://doi.org/10.3390/resources6030025

Kamal, B., and Kutay, Ş. (2021). Assessment of causal mechanism of ship bunkering oil pollution. *Ocean and Coastal Management*, 215, 105939. https://doi.org/10.1016/j.ocecoaman.2021.105939

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

Lancaster, M. L., Winsor, P., and Dumbrille, A. (2021). Underwater noise from shipping: A special case for the Arctic. *Sustainability in the Maritime Domain*, 271–289. https://doi.org/10.1007/978-3-030-69325-1_14

Lasserre, F. (2014). Case studies of Shipping along Arctic routes. Analysis and profitability perspectives for the container sector. Transportation Research A 66, 144-161

Lemieux, C.J., Thompson, J., Dawson, J., and Shuster, R. (2013). Natural resource manager perceptions of agency performance on climate change. *Journal of Environmental Management* 114: 178-189. DOI: 10.1016/j.jenvman.2012.09.014

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M.M.C. , Ottersen, G., Pritchard, H., and Schuur, E. (2019). Polar Regions. *In: 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, pp. 203-320. https://doi.org/10.1017/9781009157964.005.

Moore, S., Reeves, R., Southall, B., Ragen, T. J., Suydam, R., and Clark, C. (2012). A new framework for assessing the effects of anthropogenic sound on marine mammals in a rapidly changing Arctic. *BioScience,* 62(3), 289–295. https://doi.org/10.1525/bio.2012.62.3.10

Mousavi, M., Ghazi, I., and Omaraee, B. (2017). Risk assessment in the Maritime Industry. *Engineering, Technology & Applied Science Research*, 7(1), 1377–1381. https://doi.org/10.48084/etasr.836

Pashkevich, A., Dawson, J., and Stewart, E. J. (2015). Governance of expedition cruise ship tourism in the Arctic: A comparison of the Canadian and Russian Arctic. *Tourism in Marine Environments*, 10(3), 225–240. https://doi.org/10.3727/154427315x14181438892883

Peeters, W., and Peng, Z. (2015). An Approach Towards Global Standardization of the Risk Matrix. Journal of Space Safety Engineering, 2(1), 31–38. https://doi.org/10.1016/s2468-8967(16)30037-4

Pizzolato, L., Howell, S. E., Dawson, J., Laliberté, F., and Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophysical Research Letters*, 43(23). https://doi.org/10.1002/2016gl071489

Protection of the Arctic Marine Environment (PAME). (2009). Arctic Marine Shipping Assessment 2009 Report. Arctic Council, April 2009, second printing. Retrieved from: https://pame.is/images/03_Projects/AMSA/AMSA_2009_report/AMSA_2009_Report_2nd_print.pdf

Qian, H., Zhang, R., and Zhang, Y. (2020). Dynamic Risk Assessment of natural environment based on dynamic Bayesian network for key nodes of the Arctic Northwest Passage. *Ocean Engineering*, 203, 107205. https://doi.org/10.1016/j.oceaneng.2020.107205

Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth and Environment*, 3(1). https://doi.org/10.1038/s43247-022-00498-3

Sand, M., Berntsen, T. K., Seland, Ø., and Kristjánsson, J. E. (2013). Arctic surface temperature change to emissions of black carbon within Arctic or Midlatitudes. *Journal of Geophysical Research: Atmospheres*, 118(14), 7788–7798. https://doi.org/10.1002/jgrd.50613

Schoeman, R. P., Patterson-Abrolat, C., and Plön, S. (2020). A global review of vessel collisions with Marine Animals. *Frontiers in Marine Science,* 7. https://doi.org/10.3389/fmars.2020.00292

Serreze, M. C., and Stroeve, J. (2015). Arctic sea ice trends, variability and implications for seasonal ice forecasting. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 373(2045), 20140159. https://doi.org/10.1098/rsta.2014.0159

Sheehan, R., Dalaklis, D., Christodoulou, A., Drewniak, M., Raneri, P., and Dalaklis, A. (2021). The Northwest Passage in the Arctic: A brief assessment of the relevant Marine Transportation System and current availability of search and rescue services. *Logistics*, 5(2), 23. https://doi.org/10.3390/logistics5020023

Somanathan, S., Flynn, P. C., and Szymanski, J. K. (2007). Feasibility of a sea route through the Canadian Arctic. *Maritime Economics & Logistics*, 9(4), 324–334. https://doi.org/10.1057/palgrave.mel.9100185

Somanathan, S., Flynn, P., and Szymanski, J. (2009). The northwest passage: A simulation. *Transportation Research Part A: Policy and Practice*, 43(2), 127–135. https://doi.org/10.1016/j.tra.2008.08.001

Stewart, E. J., Dawson, J., Howell, S. E. L., Johnston, M. E., Pearce, T., and 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. https://doi.org/10.1080/1088937x.2012.705352

Transport Canada. (2022). National Framework for Assessing the Cumulative Effects of Marine Shipping. 72 p. https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf

United States Environmental Protection Agency (US-EPA). (2022, November 29). Exxon Valdez Spill Profile. United States Environmental Protection Agency (US-EPA). Retrieved from https://www.epa.gov/emergency-response/exxon-valdez-spill-profile

van Hoof, L., van den Burg, S. W. K., Banach, J. L., Röckmann, C., and Goossen, M. (2020). Can multi-use of the sea be safe? A framework for risk assessment of multi-use at sea. *Ocean and Coastal Management*, 184, 105030. https://doi.org/10.1016/j.ocecoaman.2019.105030

van Luijk N, Carter NA, Dawson J, Song G, Parker C, et al. (2021) At the front lines of increased shipping and climate change: Inuit perspectives on Canadian Arctic sovereignty and security. Arctic Yearbook 2021. https://arcticyearbook.com/images/yearbook/2021/Scholarly-Papers/6_AY2021_Luijk_Dawson.pdf

Wang, J., Zhou, Y., Zhang, S., Zhuang, L., Shi, L., Chen, J., and Hu, D. (2022). Societal Risk Acceptance Criteria of the global general cargo ships. *Ocean Engineering*, 261, 112162. https://doi.org/10.1016/j.oceaneng.2022.112162

Wunderling, N., Willeit, M., Donges, J. F., and Winkelmann, R. (2020). Global warming due to loss of large ice masses and Arctic Summer Sea ice. *Nature Communications*, 11(1). https://doi.org/10.1038/s41467-020-18934-3

Würsig, B., and Koski, W. R. (2021). Natural and potentially disturbed behavior of Bowhead Whales. *The Bowhead Whale*, 339–363. https://doi.org/10.1016/b978-0-12-818969-6.00023-6

Zhang, C., Zhang, D., Zhang, M., Lang, X., and Mao, W. (2020). An integrated risk assessment model for safe arctic navigation. *Transportation Research Part A: Policy and Practice*, 142, 101–114. https://doi.org/10.1016/j.tra.2020.10.017

Zhou, X. (2022). A comprehensive framework for assessing navigation risk and deploying maritime emergency resources in the South China Sea. *Ocean Engineering*, 248, 110797. https://doi.org/10.1016/j.oceaneng.2022.110797

Chapter 2: Content Analysis of Arctic Maritime Shipping Hazards and Risks using Natural Language Processing (NLP)

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2.1 Abstract

For over a century, the Northwest Passage, which is a maritime trade route through the Canadian Arctic Archipelago connecting the Atlantic and Pacific Oceans has captured the imagination of global powers. There has been decades-long speculation of how climate change and sea ice reduction present opportunities and risks related to using the Northwest Passage. To better understand the range of hazard and risk perspectives associated with increased accessibility of the Northwest Passage, natural language processing methods were employed to evaluate perspectives from news articles, peer-reviewed journal publications, and social media data. Word frequency and correlation analyses were used to create lists of the top 25 keywords and phrases based on each data source. Frequently used words were distributed among ten thematic groups affiliated with Arctic shipping terminology (i.e., environmental, sea ice, political, navigational, and others). Overall, the most frequently identified terms used throughout all sources were 'sea,' 'ice,' 'sea ice,' and 'route(s).' Hazards identified from word frequency analysis included multi-year sea ice, first-year sea ice, inadequate route planning, extreme weather, sea ice melt, and sea ice concentration (among others). Frequently identified terminology led to the development of sector and individual hazards, primarily from the following subject areas: navigational, environmental, sea ice, and political thematic groupings. Results from this study can be used to inform future risk analyses and assessments based on an evidence-based evaluation of hazard and risk factors.

Keywords: Arctic shipping, content analysis, natural language processing, Northwest Passage, risk analysis, risk identification, word frequency, word association.

2.2 Introduction

The Arctic has been highlighted recently as a 'hot topic' in a cold environment (Chen et al., 2021). It is a region that is experiencing significant ecological changes (e.g., sea ice decline, permafrost melting), which has resulted in increased accessibility of the Canadian Northwest Passage (NWP) for shipping (Copland et al., 2021; Stephenson & Smith, 2015) and substantial increases in vessel activity since the 1990s (Dawson et al. 2018; Copland et al., 2021; Haas & Howell, 2015). Increased vessel activity poses significant risks and hazards to all operators, the environment, and communities (Chen et al., 2021; Dawson et al., 2015; Chricop, 2009). These changes in accessibility have caused global concern regarding environmental issues (Chen & Liu, 2022; Chen et al., 2021), geopolitical conflicts (Bennett et al., 2020), navigational risks (Chen & Liu, 2022; Copland et al., 2021; Kum & Sahin, 2015), and sociocultural issues (Zhu et al., 2023; van Luijk et al., 2021; Olsen et al., 2018; Johnston et al., 2017).

The remoteness of the Arctic environment allows for marine mammal and seabird species such as Beluga Whales (*Delphinapterus leucas*), Narwhals (*Monodon monoceros*), Ringed Seals (*Pusa hispida*), as well as seabirds, to thrive (Hauser et al., 2018). The ongoing presence of sea ice has historically influenced the sense of remoteness for most (if not all) months of the year (Chen & Liu, 2022; Haas & Howell, 2015). Local Inuit communities utilize the presence of sea ice to travel throughout the Arctic Archipelago for hunting and gathering purposes (Bennett et al., 2020; Olsen et al., 2018). The historically low rates of vessel activity pre-1990 have allowed these northern communities and species to live with negligible impacts from the anthropocentric activity of vessels (Olsen et al., 2018). As a result, this has also limited exposure to underwater noise, heavy fuel oil combustion, and other forms of air/water pollution resulting from vessel activity (Hauser et al., 2018; Comer et al., 2017). Northern Inuit communities are now significantly impacted by these rapid changes to their lands (Olsen et al., 2018), altering the accessibility for maritime traffic throughout the Arctic (Dawson et al., 2022;

Olsen et al., 2018). These communities face challenges relating to, but not limited to, fishing and hunting seasons and a decreased sense of community and agency due to a lack of support (Bennett et al., 2020; Dawson et al., 2015; Johnston et al., 2017). The relationships and connectedness with local northern and Indigenous communities are also meaningful, because these communities use Arctic species as a primary food source and the species have attained cultural significance (Bennett et al., 2020; Olsen et al., 2018).

From 1968 to 2015, sea ice extent decreased at a rate of 16%-20% per decade due to consistent global warming, opening the NWP to complete ice-free conditions during warmer months (Copland et al., 2021). This decrease in sea ice has sparked the involvement of global markets to examine the feasibility of utilizing the NWP in future years, while observing increased vessel activity due to fishing operations, tourism, personal voyages using pleasure crafts, and bulk carrier use (Dawson et al., 2022; Dawson & Halliday, 2021). As previous research findings have shown a change in perception towards the NWP, the global market requires confirmation through formal content analysis and risk assessment to confirm whether various media sources can act as a means for identifying hazards and risks regarding complex issues.

The scholarly literature contains few studies that use natural language processing (NLP) to further understand how Arctic shipping impacts humans in natural environments. For example, a study by Akbayirli and Tuna (2022) used a similar methodology to analyze user sentiment, identifying social media users' perspectives on shipping routes and highlighting positive perspectives on arctic shipping. Zhang et al. (2019) took a similar approach to identifying possible environmental hazards before a full risk assessment, using NLP to find relationships between keywords associated with navigational risks in the Arctic. Fu et al. (2021) furthered the previous research by completing an in-depth analysis of publications mentioning Arctic shipping hazards and risks. Fu et al. (2021) conducted descriptive, keyword, and word association analyses to identify trends within journals that published content explicitly relating to identifying and assessing Arctic shipping hazards and risks (Fu et al., 2021). A combination of the articles noted above will be utilized and expanded upon to understand comprehensive hazards and risks of Arctic shipping processes.

NLP can create opportunities to identify linkages between frequently used terms and phrases to formulate thematic groups that aid future steps within the more extensive risk assessment process (Fu et al., 2021; Dawson et al., 2020; Zhang et al., 2019). Specifically, within hazard and risk identification, this analysis is typically completed through subject matter expert (SME) questionnaires and consultations (Kum & Sahin, 2015). Studies such as that by Kum and Sahin (2015) have used SMEs to identify the severity and probability of likely operational hazards and risks in Arctic shipping operations. Obtaining agreement among SMEs determined the most pertinent hazards and risks throughout Arctic shipping practices (Kum & Sahin, 2015). This analysis was followed by a defuzzification process, a metric used to enhance the reliability of the results when interviewing or consulting large quantities of industry experts (Kum & Sahin, 2015). Although SME consultations are seen to identify operational risks effectively, they typically overlook community perspectives or challenges within this process (IMO, 2018; Kum & Sahin, 2015). Evaluating and incorporating the perspective through the additional use of open-source media could enable a more robust list of risks associated with increased shipping within Arctic Canada.

2.3 Methodology

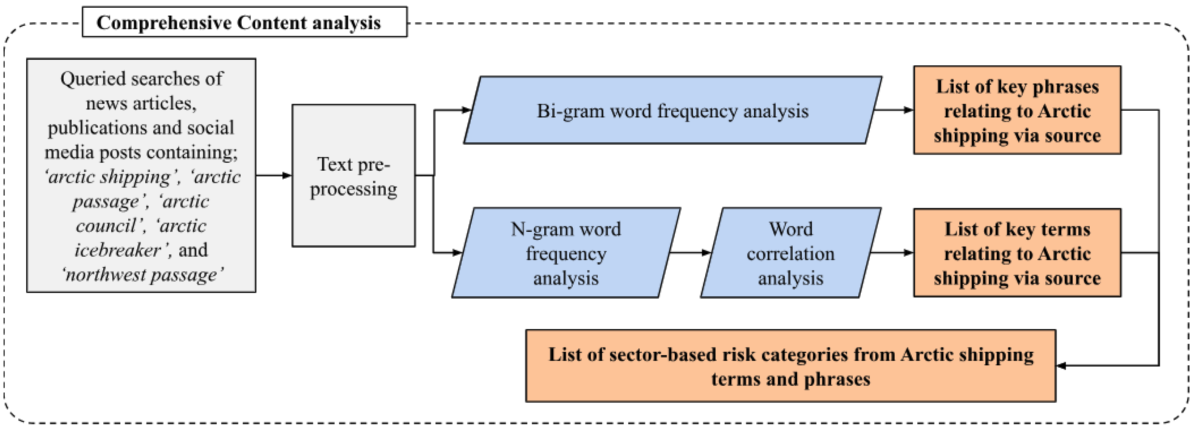
In this study, text from social media, scholarly publications, and news articles was collected, cleaned, and analyzed using R Studio NLP packages such as 'dplyr,' 'tidytext', and 'widyr.' Once cleaned, the text's word frequency and correlation analyses identified reoccurring terminology and phrases that described key thematic groups of terms within the text. This knowledge gap was addressed through a comparative analysis of the relationships between community and scientific/professional perspectives. Comparing key terms and phrases among each data source indicated whether there were different forms of discussion surrounding Arctic shipping processes. These frequently used terms and phrases created the basis of thematic groups among Arctic shipping-related processes. The results from this study were recommended for use as a method for comprehensive hazard and risk topic identification and information gathering for any complex process. Identifying these key terms, phrases, and essential thematic groups allows for a lower likelihood that hazards or risks will be missed in future risk assessment process steps. Testing this hazard and risk identification method also enabled researchers to understand the similarities and differences among various media, allowing researchers to utilize an alternate method to SME consultations, which may be unattainable in complex circumstances.

This initial content analysis was considered an integral means of risk identification, acting as a precursor to a much longer risk assessment process. Establishing key terminology and thematic groups has aided future steps of the risk assessment process, primarily the risk analysis and assessment, providing a metric to group similar risks together. Grouping similar hazards and risks allowed research to continue, as some risk metrics lack quality data.

A study by Akbayirli and Tuna (2022) used posts from LinkedIn and X (formerly known as 'Twitter') to identify user sentiment and emotions relating to the Arctic shipping industry. This study allowed researchers to use NLP methods to understand content about the Arctic shipping industry more broadly (Akbayirli & Tuna, 2022). With this study's success in understanding key trends and discussions via examining user sentiment and word frequency, a similar approach was deemed appropriate to identify hazards and risks (Akbayirli & Tuna, 2022). Another study completed by Dawson et al. (2020) examined keyword terminology use and connections throughout published IPCC reports, specifically related to global economic trade – including maritime Arctic shipping (Dawson et al., 2020). The research used a combination of word frequency and word co-occurrence analyses to determine trending topics and high-priority discussions recommended for investigations in climate change, trade, and transport (Dawson et al., 2020). Since all data collected is qualitative, both previous studies prove the effectiveness of natural language processing and are deemed successful in finding comprehensive keyword trends without compromising data reliability.

Natural language processing (NLP) is an automated practice that utilizes various pieces of written text (such as terms, phrases, and sentences) to understand structure and trends within any language (Khyani & B S, 2021). This tool analyzes various forms of written media when performing data cleaning and analytic functions (Khyani & B S, 2021). Processes such as text summarization, word association, word frequency, emotion detection, and sentiment analyses were NLP functions used to understand users' thoughts, opinions, and perspectives (Khyani & B S, 2021). Therefore, a content analysis was deemed the most appropriate measure for identifying hazards and risks. Figure 3 illustrates the research process, identifying processes, methods, and research objectives used to achieve the objectives of this study. Details are provided for each step below.

Figure 3. Research process map highlighting the processes used (light grey rectangles), methods (blue parallelograms), and research objectives (orange rectangles) used to complete this study.



2.3.1 Arctic Shipping Content Analysis Using Natural Language Processing

For this study, data was obtained through multiple forms of media such as social media (i.e., "X," formerly known as Twitter), news articles, and peer-reviewed publications in the form of a content analysis. These sources effectively illustrated the concerns of various stakeholders with diverse views, perspectives, and values. Collecting conversations from a variety of sources allows the for an increased understanding regarding the language and topics discussed in both an informal and formal setting. This will reduce the likelihood of missing unidentified hazards and risks that were previously missed during observations within formal and professional conversations. Analyzing the data sources as a content analysis has summarized similar perspectives, trending topics, and frequently used terminology. The analysis ensured separation among each categorized data source to highlight the similarities/discrepancies between formal and informal dialogue when discussing Arctic shipping-related hazards and risks.

English-language queries were used to extract and obtain data from the three sources listed above. A total of 12 queries related to the scope of the research did collect data observations, but were not utilized due to a lack of data availability. To be deemed a query with sufficient data, data was collected from the data range of 2007 – 2022 in hopes of capturing any changes in media perception or coverage of Arctic shipping. All data observations via each query underwent random sampling to ensure relevancy. This process included collecting five data observations from each query and each data source to ensure that 80% of each random sample was related to Arctic shipping.

News articles and academic publications were systematically chosen using these search queries within open-source information search engines. On average, five data observations were collected for each year for both news articles and publications between 2007 and 2022, a total of 273 data observations. News articles were increasingly difficult to find during earlier years, as publishing on online platforms was not as popular pre-2012. The entirety of each news article observation was used within the textual analysis. Publication data was also difficult to find pre-2015, likely due to limited baseline data availability and different research interests. Publication data was reduced due to the extensive text size and would not be able to fit within a singular cell. Publications followed various styles and structures and were unable to be broken down as a result. As publication observations were collected among many disciplines, the abstracts remained the consistent and were chosen as a result for the textual analysis.

For social media data collection, a minimum of 358 data observations were collected to satisfy this threshold (minimum two observations per month). This sum requirement was essential to ensure each query could examine a holistic discussion of Arctic shipping issues. Social media data was collected among all regions that have expressed international interest regarding Arctic shipping through the Arctic Council. Data from all Arctic Council member (8) and observer (13) states was collected as a result. To ensure a holistic representation of membered and observer states, it was required that all member states must produce a data observation for each query used. A maximum of two observer states were allowed to produce zero search results. As this is a preliminary study, this threshold requires further examination to determine its statistical significance.

A total of five queries were used: ‘arctic council’, ‘arctic passage’, ‘arctic icebreaker’, ‘arctic shipping’, and ‘northwest passage’. These selected queries collected 4802 unique data observations (200 news articles, 100 publications, and 4502 social media). Please see Appendix 3 for a year-by-year breakdown of the observations collected. This empirical study is the first to attempt to identify hazards and risk variables using various media outlets. A future study is recommended to create a baseline regarding statistical significance of social media, news article, and academic publication data observations for risk identification.

Another limitation regarding the use of older publications, news articles, and social media relates to the data quality and validity of the information presented. Pre-2012 data sources have a higher probability of being deemed obsolete, where newer or amended versions of data sources can possibly have updated information that is considered more reliable regarding hazards and risks. Table 3 highlights the frequency counts of the three data sources using publisher names and countries of origin. To note, X's privacy policy protects user-level data and was best suited to list all data observations regarding tweet usage via country of origin rather than user ID to protect user confidentiality.

Table 3. Frequency Count of Unique Publisher Names and Country of Origin via Source.

Source Name Frequency Counts						
	News Articles (100)		**Publications (200)**		**Social Media (4502)**	
Rank	*Publisher Name*	*Count*	*Journal Name*	*Count*	*Country of Origin*	*Count*
1	Arctic	5	CBC News	27	United States	1961
2	Marine Policy	5	Nunatsiaq News	18	Canada	1104
3	Maritime Policy & Management	4	Global News	13	Great Britain	466
4	Polar Record	4	High North News	13	Denmark	202
5	Transportation research. Part A: Policy and practice	4	The Globe and Mail	11	Norway	181
6	Geophysical Research Letters	3	Eos	8	Finland	118
7	Maritime Transport and Regional Sustainability	3	Bellona	6	Sweden	73
8	Transportation Research Part D: Transport and Environment	3	Macleans	6	France	60
9	Atmospheric Chemistry and Physics	2	Toronto Star	6	Iceland	59
10	Global Environmental Change	2	Canadian National Observer	5	Germany	47
11	Journal of Maritime Law and Commerce	2	Eye on the Arctic	5	Russia	41
12	Marine Pollution Bulletin	2	Marine Insight	5	India	40
13	Nature Climate Change	2	The Arctic Institute	5	Spain	33
14	Ocean Development & International Law	2	Freight Waves	4	Italy	30
15	Polar Geography	2	Bloomberg	3	Netherlands	28

16	The International Journal of Marine and Coastal Law	2	The Barents Observer	3	Switzerland	25
17	WMU Journal of Maritime Affairs	2	KYUK	2	Poland	15
18	FEMS Microbiology Ecology	1	Naval News	2	Japan	7
19	Advances in Climate Change Research	1	Phys.org	2	Singapore	7
20	Alaska Journal of Commerce	1	The Independent Barents Observer	2	China	4
21	American Review of Canadian Studies	1	The Wall Street Journal	2	South Korea	1
22	Anthropocene	1	The Washington Post	2		
23	Applied Sciences	1	Anadolu Agency	1		
24	Arabian Journal of Geosciences	1	Arctic Today	1		
25	Arctic Marine Governance	1	Axios	1		
26	Asian Geographer	1	Baird Maritime	1		
27	ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering	1	Brown Political Review	1		
28	Atmosphere-Ocean	1	Business Insider	1		
29	Australian Journal of Maritime & Ocean Affairs	1	Climate Change News	1		
30	Biological Sciences	1	CNN	1		
31	Coastal Management	1	Cruise Industry News	1		
32	Cogent Social Sciences	1	Defense News	1		
33	Cold Regions Science and Technology	1	Electronics Weekly	1		
34	Earth, Atmospheric, and Planetary Sciences	1	Energy Intelligence	1		
35	Earth's Future	1	Financial Post	1		
36	Environmental Research Letters	1	GRID News	1		
37	Environmental Security in the Arctic Ocean	1	Hakai Magazine	1		
38	FACETS	1	Houston Marine & Energy Insurance Conference	1		
39	International Affairs	1	Iceland Review	1		
40	International Council on Clean Transportation	1	Innovation News Network	1		
41	International Journal of e-Navigation and Maritime Economy	1	Jordan News	1		

42	International Journal on Marine Navigation and Safety of Sea Transportation	1	KNBA	1	
43	International Journal; Toronto	1	MercoPress.	1	
44	Journal of Cleaner Production	1	MLI	1	
45	Journal of Glaciology	1	National Post	1	
46	Journal of Maritime Engineering & Technology	1	Nature	1	
47	Journal of The Arctic Institute of North America	1	Nikkei Asia	1	
48	Logistics	1	Pulizer Center	1	
49	Maritime Economics & Logistics	1	Quartz	1	
50	National Research Council Canada	1	Radio Canada International	1	
51	Northern Review	1	Reuters	1	
52	Ocean and Coastal Law Journal	1	Sail-World Cruising	1	
53	Ocean and Coastal Management	1	Saltwire	1	
54	Ocean Engineering	1	Seatrade Cruise News	1	
55	Polar Research	1	Statista	1	
56	Public Library of Science (PLoS) ONE	1	Sustainability Times	1	
57	Quaternary Science Reviews	1	TASS	1	
58	Reliability Engineering & System Safety	1	The Asahi Shimbun	1	
59	Risk Analysis	1	The Cradle	1	
60	Russian Arctic	1	The Energy Mix	1	
61	Safety Science	1	The Maritime Executive	1	
62	Sustainability	1	The Moscow Times	1	
63	The Beaver: Exploring Canada's History	1	The Watchers	1	
64	The Polar Journal	1	Today@Wayne	1	
65	The Yearbook of Polar Law Online	1	US Naval Institute News	1	
66	TransNav	1	Vancouver Observer	1	
67	Transport Policy	1	Vice	1	
68	Water	1	Voa News	1	
69			WBUR	1	
70			Wisconsin State Journal	1	
71			YaleEnvironment360	1	
72			YiCai Global	1	

2.3.1.1 Text Pre-processing

Natural language processing was used to examine frequently used terms and phrases and has been used for this study to examine terms relating to maritime shipping operations within the Arctic. Data observations were collected into a Microsoft Excel document in an identical format among all sources and manipulated using R Studio. Data observations were pre-processed through the tm package using the 'corpus' function (Huang et al., 2021; Feinerer & Hornik, 2020). This function standardized all text by removing punctuation, special characters, numeric values, whitespace (i.e., additional spaces), and stopwords (Huang et al., 2021; Feinerer & Hornik, 2020). Stopwords are filler terminology that provide no meaning to the observation text, such as the words ‘the,' or ‘and’ (Huang et al., 2021; Feinerer & Hornik, 2020). Stopwords were removed to ensure the analysis identified and counted frequently used significant terms that depicted the Arctic shipping processes' context.

Machine learning techniques such as stemming and lemmatization were considered for this analysis, though they were excluded. Stemming would reduce words or tokens to their base word as a means of shortening the terms and normalizing sentences (i.e., 'caus' is a root for terms such as 'causing', 'causation', 'causes') (Khyani & B S, 2021). Similarly, lemmatization is a process that groups words or tokens with a similar lemma in its vocabulary form, allowing grouping to a root word rather than stem (i.e., 'well,' better,' and 'fine' are lemmas to 'good') (Khyani & B S, 2021). Both processes were excluded from the analysis due to possible manipulation of individual term meaning, which could create confusion and inconsistencies when analyzing key phrases and word correlation.

2.3.1.1 Word Frequency Calculations

A word frequency analysis was completed once all data sets were pre-processed. A word frequency analysis in the form of n-gram (single word frequency) and bi-gram (multi-word frequency) were used to identify trends in participant behaviours (Zhang, 2018). The analyses allowed researchers to strengthen their understanding by identifying key terminology used in formal and informal conversations (Zhang, 2018). This foundational knowledge is essential when analyzing conversations using word correlation, all within the premise of identifying key terminology regarding Arctic shipping risks and hazards. Upon the completion of calculating the distributing words used within Arctic shipping-related text, a n-gram analysis was completed. Using n-gram analysis helps identify strings of words (known as a 'token') within a data observation (Brzic et al., 2023). A similar methodology was utilized to identify topic areas and terms surrounding deception in datasets for climate change and COVID-19 (Brzic et al., 2023). Before creating word frequency diagrams, data observations for each source required text pre-processing to ensure all data was formatted the same way and that identical matching was excluded. Text tokenization is completed through extensive data observations, typically in paragraphs or sentences, and strips each observation to a digestible amount for analysis (Mullen et al., 2018). Given the suggested scope of research, each data observation should be tokenized to the word level. Tokenization was calculated using the 'unnest_tokens' function within the 'tidytext' package (Mullen et al., 2018; Silge & Robinson, 2016). When tokenization was completed, the 'dplyr' and 'tidytext' packages were used to process, count, and quantify the number of unique words used by each data source (Wickham et al., 2022; Wickham et al., 2019; Silge & Robinson, 2016). Before plotting the data, all search terms (i.e., 'arctic shipping,'…) were removed from the analysis to prevent data from becoming skewed.

Using a bi-gram analysis, the above methodology was replicated in a similar format to calculate the top phrases used. The 'unnest_tokens' function was used again in greater detail, setting the 'n' value to 2, examining a pair of two consecutive words used within a data observation (Wickham et al., 2019; Silge & Robinson, 2016). Of note, stopwords were excluded prior to pairing to ensure the study examined words that were of significance to Arctic shipping. The top 10 most frequent values were collected from each data source. They were displayed using a bar chart, highlighting the most frequently used terms to describe Arctic shipping related tweets, articles, and publications. Akbayirli and Tuna (2022) used a similar method to analyze social media data. Akbayirli and Tuna's study identified countries that were mentioned the most frequently and mentioned other countries within the same social media observations using a word cloud for data visualization (Akbayirli & Tuna, 2022).

2.3.1.2 Word Correlation Calculations

Once the most frequently used terms and phrases were determined, these terms were further examined using word correlation. Word correlation is a form of analysis to determine the proportion of similarly used words occurring before or after the term (Wickham et al., 2022; Robinson, 2020; Silge & Robinson, 2016). This type of analysis allows researchers to understand key themes and subjects within a given topic. To complete this analysis, the 'dplyr,' 'tidytext,' and 'widyr' packages are used together. The tokenization processes used the 'unnest_tokens' to separate larger text into individual words (Silge & Robinson, 2016). Stopwords were removed using the 'filter(!word %in% custom_stop_words$word)' function. The function 'pairwise_cor' was used to examine the correlation between the unique terms identified within the observation count of each word. Finally, terms were filtered and grouped using the 'filter(item1 %in% c(""))' and 'group_by' functions to limit the search results by the selected term (Wickham et al., 2022; Robinson, 2020; Silge & Robinson, 2016). The top 10-

word correlation results were exported into an excel spreadsheet for data visualization. A final comparison was initiated among other frequently used terms to identify similarities or differences among alike or duplicate terms. This determined whether popular terms were merely as a result of co-incidence or beginning to indicate a deeper meaning throughout the text.

2.3.1.3 Thematic Group Topic Modelling

As a final analysis, the frequent terms, phrases, and correlated terms were used to identify thematic groups. Thematic groups aided in determining appropriate grouping and classification among frequently used words and phrases from previous analyses. Groups were created based on the similarities among associated words of frequently used terms and phrases. A similar analysis was completed to determine key thematic groups surrounding misleading questionnaire data (Brzic et al., 2023). The study identified two thematic groups using word frequency analysis: COVID-19 and climate change-related deceptive information (Brzic et al., 2023). Future uses of thematic groups can include utilizing this research as part of a risk analysis or assessment, acting to congregate hazards and risks alike.

2.4 Results

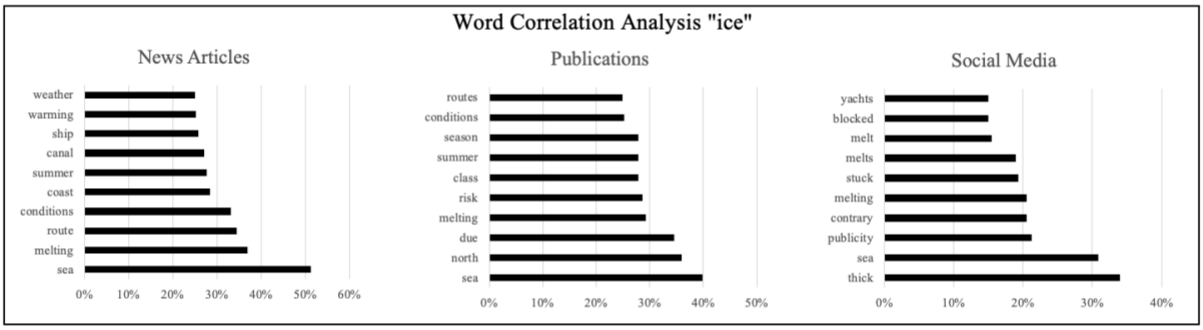
In this manuscript, we investigated three distinct data sources (news articles, peer-reviewed journal article publications, and social media datasets) to identify trends in individual word frequency, bi-gram frequency, and word correlation. Table 4 highlights the 20 most frequently used terms by data source.

Table 4. N-gram Word Frequency Analysis via Source.

Word Frequency: N-Gram						
	News Articles		**Publications**		**Social Media**	
Rank	*Term*	*Value*	*Term*	*Value*	*Term*	*Value*
1	ice	943	ice	175	ice	415
2	sea	689	sea	118	sea	249
3	canada	644	ships	71	canada	215
4	ships	485	risk	69	ship	192
5	route	480	route	64	climate	188
6	russia	467	environmental	63	russia	166
7	ship	382	routes	60	north	159
8	northern	375	marine	58	inuit	155
9	canadian	368	potential	56	oil	143
10	north	364	climate	54	change	142
11	coast	331	model	52	china	136
12	climate	324	emissions	51	time	136
13	oil	319	ship	46	arcticcouncil	135
14	waters	295	results	44	route	127
15	international	283	oil	43	cruise	116
16	vessels	278	global	41	found	111
17	years	277	paper	41	routes	108
18	polar	264	region	40	meeting	107
19	region	261	navigation	39	ocean	107
20	year	261	canadian	38	expedition	105

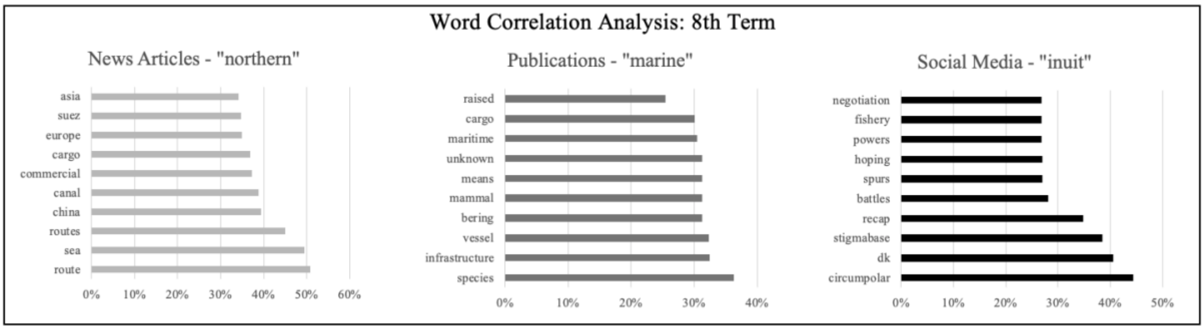
The results from Table 4 enabled the development of word correlation charts. Word correlation visualized this process through the creation of a percentage value, determining the quotient through dividing the associated word summed value by the total quantity of associated terms. This was expressed using a percentage of times each correlated term was used with the selected word. Any term that came before or after the selected word counted as an ‘association’. Figure 4 identifies the 10 highest correlated terms that are associated with most frequently used term (‘ice’) among all data sources.

Figure 4. Word Correlation Analysis using the Most Frequent Term among All Sources; "ice".



To determine word correlation distribution among data sources, terms of different meanings were selected to understand the distribution patterns and textual context expressed. The eighth most correlated word was selected for analysis as these terms were the first to express distinct differences among terminology, creating easier identification of patterns. The distinct differences in terms allowed for a broader examination among possible hazard and risk variables. Displaying the interaction between different terminology allows researchers to begin examining the similarities among sectors that are varied. These terms were the most frequently used terms that were located in different thematic groupings. Figure 5 illustrates the correlation between the eighth most frequently used n-gram terms ('northern,' 'marine,' and 'Inuit') among each source.

Figure 5. Word Correlation Analysis using the 8th Most Frequent Terms among Sources.



Using n-gram word frequency analysis in Table 4 enabled the completion a word frequency assessment of bi-gram terms. Word correlation distribution charts were created for the top 10 frequently used n-gram terms via source. These distribution charts are included in Appendix 4. To further understand and validate perspectives regarding Arctic shipping concerns seen within the n-gram analyses, a bi-gram frequency analysis was completed to understand key phrases used among sources. Table 5 illustrates and identifies the 20 most frequently used two-word phrases in each data source.

Table 5. Bi-gram word frequency Analysis via Source.

Word Frequency: Bi-gram						
	News Articles		**Publications**		**Social Media**	
Rank	*Term*	*Value*	*Term*	*Value*	*Term*	*Value*
1	northwest passage	419	arctic shipping	74	northwest passage	1732
2	arctic shipping	261	sea ice	68	arctic council	539
3	sea ice	250	northwest passage	65	arctic shipping	321
4	sea route	235	canadian arctic	28	climate change	120
5	coast guard	223	climate change	25	sea ice	88
6	northern sea	219	arctic sea	24	shipping routes	86
7	arctic council	206	arctic ocean	23	arctic ocean	72
8	climate change	198	sea route	23	years doomed	71
9	arctic waters	121	northern sea	22	doomed northwest	69
10	arctic ocean	119	arctic marine	18	passage attempt	68
11	black carbon	112	arctic waters	16	passage ipa	68
12	heavy fuel	102	black carbon	16	ship found	67
13	fuel oil	94	global warming	16	found arctic	66
14	united states	91	arctic council	15	arctic years	65
15	story continues	79	polar code	14	stan rogers	63
16	canadian arctic	72	shipping arctic	14	shipping lanes	61
17	canadian coast	66	shipping routes	14	shipping arctic	60
18	continues advertisement	65	ice conditions	13	drinking northwest	57
19	shipping routes	61	arctic region	12	memphis zoo	52
20	arctic sea	60	sea routes	11	arctic ice	49

Word association analyses were not completed for bi-gram analyses due to the inability to recognize numerous words for tokenization. Based on results from n-gram and bi-gram frequency charts via source, terms and phrases were placed into thematic groups based on the representation after analyzing individual term word association. The selected thematic groups were created based on identifying larger scale patterns amongst the data more broadly. Table 6 identifies a ranked distribution of thematic groups via all sources of frequent words and phrases used.

Table 6. Thematic group topic modelling ranked by most frequently used n-gram and bi-gram words.

Thematic Group	Term Count	N-gram Terms	Bi-gram Terms
		Thematic Group Topic Modelling	
Political	**33**	canada, canadian, ships, ship, risk, route, oil, climate, change, russia, china, northern, north, potential, environmental, marine, inuit, coast, arcticcouncil, results, waters, international, polar, navigation, region, global, vessels	arctic council, polar code, north america, united states, imo arctic, canadian arctic
Navigational	**33**	ship, ships, risk, route, routes, climate, russia, china, northern, north, marine, environmental, inuit, oil, cruise, time, model, arcticcouncil, waters, navigation, region, global, vessels, expedition	northwest passage, arctic shipping, sea route, nw passage, shipping lanes, shipping routes, shipping arctic, ms simon, hmcs labrador
Environmental	**29**	ice, sea, ship, risk, climate, change, russia, north, environmental, marine, inuit, oil, potential, coast, model, results, waters, polar, ocean, global	arctic ocean, arctic waters, northern sea, arctic sea, arctic circle, climate change, global warming, north pole, arctic marine
Assessment	**16**	ships, ship, risk, route, routes, climate, change, north, environmental, marine, oil, potential, model, emissions, results, paper	
Pollutants	**14**	ship, ships, route, climate, northern, oil, potential, emissions, results, waters,	black carbon, oil gas, fuel oil, heavy fuel
Economic	**13**	ships, routes, change, china, northern, environmental, inuit, oil, potential, cruise, coast, emissions, navigation	
Social	**13**	ships, ship, climate, change, north, cruise, environmental, marine, inuit, oil, coast, expedition	coast guard
Community	**11**	ships, ship, climate, change, north, environmental, marine, inuit, cruise, coast	inuit circumpolar
Sea Ice	**10**	ice, sea, routes, climate, coast, arcticcouncil,	sea ice, arctic ice, melting arctic, ice conditions
Technological	**7**	risk, climate, change, russia, northern, oil, emissions	

2.5 Discussion

2.5.1 Trending Conversations and Ideas

2.5.1.1 Sea Ice Concerns

Among all data sources, terms such as 'sea,' 'ice,' and 'sea ice' are the most frequently used words and phrases. Word frequency and association analysis indicate conversations targeting the topics of sea ice concentration, multi-year and first-year sea ice, sea ice melt, and ice conditions. This can be further validated throughout academic literature, which discusses the hazards associated with Arctic sea ice extent for vessels, specifically vessels lacking proper ice classification (Dawson et al., 2022; Dawson et al., 2017). Multi-year sea ice and high sea ice concentrations create harsh and intolerable conditions for navigating the NWP (Qian et al., 2020; Pizzolato et al., 2016). These conditions can be diminished or exacerbated through the environment and social climate of the region. Typically, the Arctic contains annual periods of extended darkness (Berge et al., 2015; Barber et al., 2010), extreme low temperatures (Chen et Liu, 2022), as well as occasional severe weather (Sheehan et al., 2021; Haas & Howell, 2015) and high wind speeds (Sheehan et al., 2021; Qian et al., 2020). As a result, the presence of sea ice is observed to be influenced by the Arctic environment, which, in turn, is highly likely to influence vessel behaviour (Fu et al., 2021; Pizzolato et al., 2016). The findings confirm and reiterate the extent to which sea ice hazards identified within academia are to be prioritized for ongoing and further assessment.

Sea ice also influences a wide range of additional sectors during Arctic vessel operations, such as navigation (Copland et al., 2021; Dawson et al., 2017; Pizzolato et al., 2016), economical (Somanathan et al., 2009; Somanathan et al., 2007), social (van Luijk et al., 2021; Olsen et al., 2018), environmental (Dawson et al., 2022; Qian et al., 2020; Lauta et al., 2018), community (van Luijk et al., 2021; Lauta et al., 2018), and political factors (Lancaster et al., 2021; Würsig & Koski, 2021; Gross, 2018). Due to the complexity of sea ice's influence on almost all other thematic groups, it is essential to holistically understand this critical factor when addressing the complex nature of Arctic shipping. Further understanding of these relationships among the thematic groups is recommended for future assessments.

2.5.1.2 Navigability Concerns

Among word frequency and correlation analysis, terms such as 'route,' 'routes,' 'sea route,' 'ship,' and 'ships' were all identified in numerous sources. These terms sparked discussions surrounding navigational options, comparing the Suez Canal, Northeast Passage, and the Panama Canal to one another (Lasserre, 2014; Somanathan et al., 2009; Somanathan et al., 2007). Academic publications currently mimic similar research, where Chen and Liu have enhanced and analyzed methodologies for quantifying and comparing the fuel efficiency and overall profitability of the NWP (Chen & Liu, 2022; Lasserre, 2014; Somanathan et al., 2009).

Operational factors such as transit speed (Lasserre, 2014; Corbett et al., 2009; Somanathan et al., 2009), load factors (Lasserre, 2014), fuel consumption (Lasserre, 2014; Somanathan et al., 2009), fuel costs (Lasserre, 2014; Corbett et al., 2009; Somanathan et al., 2009), and sea ice presence (Pizzolato et al., 2016; Haas & Howell, 2015; Somanathan et al, 2009) have been proven to influence route viability. Results of word correlation analysis have also identified similar areas of contention, specifically within word associations for 'ships'. The term correlated to words such as 'carriage,' 'navigability,' 'class,' 'speed', and 'gases.' From the uses of these terms, it can be preliminarily suggested that authors express similar views surrounding concerns over navigational risks. Navigational risks such as vessel average speeds, presence and carriage of dangerous materials (i.e., heavy fuel oils and cargo quantity), and vessel ice classification influence a vessel's vulnerability to emerging risks within the NWP. Further investigation is required to determine the causes, consequences, and current control mechanisms to limit possible navigational risks. A formalized risk analysis can validate these preliminary findings regarding the prioritization of navigational risks.

Other key observations in navigation-related terminology were 'traffic,' 'increased,' 'transport,' 'mining,' and 'discharge.' All terms were observed to be associated with the usage of 'ships'. This can be linked to previous findings of academics, where Arctic shipping vessel activity has increased upwards of 75% per region since 1990 (Copland et al., 2021; Pizzolato et al., 2016; Dawson et al., 2015). This increased vessel activity raises concerns regarding the positive and negative impacts from increased economic activity and development of the Canadian Northern economy (Chen et al., 2021; Mudryk et al., 2021; Lasserre, 2014). However, increased vessel traffic creates potential threats of ecological damage and community-level implications, including the loss of cultural lands, sense of remoteness, and air/water quality (Qian et al., 2020). Increased transportation within Arctic waters has proven to cause net-negative implications at the community level, observing increases in operational discharges of toxic substances (Comer et al., 2017) as well as increased underwater noise (Lancaster et al., 2021; Würsig & Koski, 2021; Hauser et al., 2018; Gross, 2018; Halliday et al., 2017). Previous publication findings complement the issues addressed in the word frequency and association analyses. A formalized risk analysis is recommended to confirm and validate results of this study to aid in the completion of a future risk assessment.

Increases in vessel activity apparent through this study and through previous literature, pose risks of vessel related accidents occurring more regularly. The term 'ships' was frequently associated with additional words such as 'accidents,' 'accelerating,' 'pollution,' and 'ice-covered.' Previous literature has examined the severity and likelihood of occurrence among various forms of vessel related accidents, such as groundings (Dawson et al., 2022; Fu et al., 2022; Zhang et al., 2020), iceberg collisions (Dawson et al., 2022; Zhang et al., 2020), vessel-vessel collisions (Dawson et al., 2022; Zhang et al., 2020), vessel capsizing (Wang et al., 2022), and vessel stuck in ice (Fu et al., 2018). Current literature states these possible activities' catastrophic severity on crew members, the environment, and implications to surrounding communities (Mudryk et al., 2021; van Luijk et al., 2021; Olsen et al., 2018). An overarching cause of an increase in the severity of these issues relates to the remoteness of these vessels to civilization and search and rescue services (Bennett et al., 2020; Olsen et al., 2018; Borch et al., 2016). The remoteness increases average response time and limits the ability to contain vessel accidents, causing exponential increases in risk severity. Academics have explained that the likelihood of these accidents posing catastrophic impacts is unlikely (Fu et al., 2018; Borch et al., 2016). Furthermore, preliminary findings suggest limitations surrounding search and rescue capacities, response times, vessel accidents, and vessel collisions as priority risks associated with navigating Arctic waters. Further confirmation using a combination of qualitative and quantitative data within a formalized risk analysis is required prior to the declaration of these risks.

2.5.1.3 Political and Regulatory Concerns

Arctic Canada has experienced ongoing decline in sea ice concentration since the 1990s, creating increasingly navigable portions of the NWP during warmer months (Copland et al., 2021; van Luijk et al., 2021). With the NWP becoming more navigable in recent and future years, this has sparked international economic interest regarding the utilization of this passage as a cost savings approach to present routes (Somanathan et al., 2009; Somanathan et al., 2007). Certain countries are against economic development and support further conservation to protect endemic species and limit anthropocentric impacts (Bennett et al., 2020; Halliday & Dawson, 2021). Terms such as 'international' indicated similar perspectives regarding the complex conflict of competing global interests through correlated terms such as 'difficult,' 'protection,' 'status,' 'ban,' and 'standards.' These terms echo concerns regarding the protection and the development of further standards and legislation to protect the Arctic. 'China' was also frequently used within the analysis, indicating contrasting perspectives. Terms such as 'utilization,' 'northernsearoute,' 'silk,' 'arcticnwpassage,' and 'attractive' appeared under word association. This highlights the competing global interests of countries such as China, where this country is looking at utilization and referring to this region as the 'Arctic silk road' for economic development and transportation (Akbayirli & Tuna, 2022; Bennett et al., 2020). Identifying the contrasting perspectives surrounding the Arctic through analysis of these terms provides an excellent example of the complex nature of this issue (van Luijk et al., 2021). The socio-political tensions surrounding policy development and implementation of Arctic shipping continue to evolve and are recommended to be examined within future assessments. A formalized risk analysis is recommended to validate the preliminary findings to confirm the severity and frequency of these select variables.

Sovereignty issues within the Canadian context are still apparent, for issues surrounding preceding land, lack of Inuit agency, and illegal dumping activities that occur frequently within Arctic Canada (Lancaster et al., 2021; Würsig & Koski, 2021). Shipping activities such as trespassing, transiting through ecologically sensitive areas, and increased shipping activity have increased stress on the Arctic ecosystem's thresholds (Lancaster et al., 2021; Würsig & Koski, 2021). With these thresholds accumulating additional stress, the presence of sovereignty concerns are identified to be linked with operational discharges into Arctic waters, creating extensive water and noise pollution that harms marine mammals and seabirds (Hauser et al., 2018; Halliday et al., 2017). Increased shipping presence has been noted to also increase pollution concentrations due to operational discharges, fostering risks of bioaccumulation, and impacting local Inuit communities in carrying out hunting for primary food source acquisition (van Luijk et al., 2021; Bennet et al., 2020; Hauser et al., 2018). Previous studies complement this research, where terms such as 'Canada' observe associations with words such as 'sovereignty,' 'law,' 'issues,' 'Inuit,' 'recede,' 'illegality,' and 'dumping.' The preliminary identification of these risks can be further validated through the collection of qualitative and quantitative data within a risk analysis to determine priority for future risk treatment. Similar perspectives exist regarding indigenous peoples' challenges to the lack of Inuit agency within their communities and constant territorial disputes regarding the status of the Canadian Northwest Passage at the national and international levels. The preliminary findings of this study recommended examining these hazards and risks further through analyses solely observing the indigenous peoples' concerns using a northern perspective (e.g., platforms such as 'Facebook', community reports).

2.5.2 Data Source Comparisons

Academic publications observe an even distribution among word association charts across the three selected data sources. News articles and social media data highlight more robust correlation rates among the top three associated terms. As a result, terms that have a high word association score are also likely to be correlated among the bi-gram analysis. It is inferred that the consistent verbiage used in social media and news articles relates to the readability of the text, given this data is posted within a public-facing platform. Common terminology that is digestible and easy to read allows other individuals to reply, interact, and express their opinions and views on the subject matter. Using terminology that is difficult to comprehend in the form of acronyms, scientific terms, and other industry jargon hinders the readability of the text. It can cause a lack of engagement with the subject matter if the audience cannot clearly understand the text. These findings are apparent in a study authored by Chapman (2022), where the findings suggest that current writing methods, specifically within academics, can cause 'moments of untranslatability,' furthering the barriers to decolonial knowledge (Chapman, 2022). Data observations that are unclear and difficult to interpret can misguide audiences to the appropriate textual meaning can also be linked to Baram-Tsabari et al. (2020), identifying that science-based publications are at the epicentre of the issue of untranslatability (Baram-Tsabari et al., 2022). The authors discuss how the use of irregular words and acronyms hinders the ability to become immersed in the realm of research alongside academics (Baram-Tsabari et al., 2022; Heidari et al., 2022). The findings from this study contrast these previous findings as exhibited in Figures 3 and 4, respectively. Further analysis is recommended to obtain statistical confidence.

2.6 Conclusion

Shipping within Arctic waters is a complex process that involves various hazard and risk variables that increase stress and damage within the natural environment (Qian et al., 2020; Pizzolato et al., 2016), local communities (Bennett et al., 2020; Olsen et al., 2019), and to vessel operators and crew (Fu et al., 2023; Halliday & Dawson, 2021; Qian et al., 2020). Key terms identified within word frequency and correlation analyses further validate the justification for utilizing multiple sources of media in completing a comprehensive content analysis to grasp diverse perspectives on the hazards and risks of Artic shipping activity. Ten unique thematic groups have emerged from word correlation and frequency diagrams, classifying Arctic shipping risks in the form of community, pollutants, sea ice, social, environmental, economic, assessment, navigational, political, and technological categories. Frequently used terminology and phrases identified within the study illustrate the complexity and intricacy of Arctic shipping processes through the multi-faceted impacts. Thematic groups such as sea ice, navigation, and political factors highlight the numerous and interconnected concerns these hazards and risks impose. Thematic groups and key terminology highlighting Arctic shipping concerns are recommended to be integrated in future steps of the risk assessment process. The 10 identified categories are recommended for use as broader umbrella of categories for individual hazards and risks to be affiliated with, allowing a future risk assessment to analyze hazard and risk trends at holistic or granular levels. Key terms and phrases highlighted are recommended to be used as search query terms for examining possible data sources, publications, and/or case studies for a future risk analysis and risk assessment.

Understanding the perspectives of Arctic shipping is complex in nature, requiring further analysis to understand the larger scope of the problem. The following list provides recommendations of topic areas that aid in filling this knowledge gap including: 1) a comparative study that analyzes online users' emotions, sentiments, and perceptions of the terms ‘hazard’ and ‘risk’ when discussing topics of risk assessment on social media platforms; 2) historical sentiment analysis that analyzes social media data to identify users’ thoughts, sentiments, and opinions related to the Arctic shipping industry; and 3) a historical content analysis that analyzes news articles to understand the ideas, sentiments, and perceptions shared regarding Arctic shipping between Arctic Council member versus observer states.

2.7 References cited in Chapter 2

Akbayirli, K., & Tuna, O. (2022). How do practitioners view arctic shipping routes? A cognitive appraisal approach. *Transportation Research Part D: Transport and Environment, 110, 103432*. https://doi.org/10.1016/j.trd.2022.103432

Baram-Tsabari, A., Wolfson, O., Yosef, R., Chapnik, N., Brill, A., & Segev, E. (2020). Jargon use in public understanding of science papers over three decades. *Public Understanding of Science, 29(6),* 644–654. https://doi.org/10.1177/0963662520940501

Barber, D. G., Asplin, M. G., Gratton, Y., Lukovich, J. V., Galley, R. J., Raddatz, R. L., & Leitch, D. (2010). The International Polar Year (IPY) Circumpolar Flaw lead (CFL) system study: Overview and the physical system. *Atmosphere-Ocean, 48(4),* 225–243. https://doi.org/10.3137/oc317.2010

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

Benoit, K., Muhr, D., & Watanabe, K. (2021). stopwords: Multilingual Stopword Lists. R package version 2.2. https://CRAN.R-project.org/package=stopwords

Berge, J., Renaud, P. E., Darnis, G., Cottier, F., Last, K., Gabrielsen, T. M., Johnsen, G., Seuthe, L., Weslawski, J. M., Leu, E., Moline, M., Nahrgang, J., Søreide, J. E., Varpe, Ø., Lønne, O. J., Daase, M., & Falk-Petersen, S. (2015). In the dark: A review of ecosystem processes during the Arctic Polar Night. *Progress in Oceanography, 139,* 258–271. https://doi.org/10.1016/j.pocean.2015.08.005

Borch, O., Andreassen, N., Marchenko, N., Ingimundarson, V., Gunnarsdóttir, H., Iudin, I., Petrov, S., Jakobsen, U., & Dali, B. (2016, October 7). Maritime activity in the high north : Current and estimated level up to 2025 : MARPART Project Report 1. *Nord Open Research Archive*. https://nordopen.nord.no/nord-xmlui/handle/11250/2413456

Brzic, B., Boticki, I., & Bagic Babac, M. (2023). Detecting deception using natural language processing and machine learning in datasets on COVID-19 and climate change. *Algorithms, 16(5),* 221. https://doi.org/10.3390/a16050221

Chapman, E. (2022). Revocalising Human geography: Decolonial language geographies beyond the nation-state. *Progress in Human Geography, 47(1),* 24–42. https://doi.org/10.1177/03091325221131852

Chen, P., & Liu, T. (2022). Environmental and economic analysis on sailing from Taiwan through Arctic passages. *Water, 14(13), 2099*. https://doi.org/10.3390/w14132099

Chen, J., Kang, S., Guo, J., Xu, M., & Zhang, Z. (2021). Variation of sea ice and perspectives of the Northwest Passage in the Arctic Ocean. *Advances in Climate Change Research, 12(4),* 447–455. https://doi.org/10.1016/j.accre.2021.02.002

Chircop, A. (2009). The growth of international shipping in the Arctic: Is a regulatory review timely? *The International Journal of Marine and Coastal Law, 24(2), 355–380*. https://doi.org/10.1163/157180809x421699

Christensen, M., Georgati, M., & Arsanjani, J. J. (2019). A risk-based approach for determining the future potential of commercial shipping in the Arctic. *Journal of Marine Engineering & Technology, 21(2),* 82–99. https://doi.org/10.1080/20464177.2019.1672419

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017). Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025. Washington DC, *International Council on Clean Transportation*. DOI: http://dx.doi.org/10.25607/OBP-1733

Conachey, R., & Montgomery, R. (2005, October). Development of machinery survey requirements based on reliability-centered maintenance. In SNAME Maritime Convention. OnePetro.

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

Corbett, J. J., Wang, H., & Winebrake, J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment, 14(8),* 593–598. https://doi.org/10.1016/j.trd.2009.08.005

Dawson, J., Holloway, J., Debortoli, N., & Gilmore, E. (2020). Treatment of international economic trade in Intergovernmental Panel on Climate Change (IPCC) reports. Current Climate Change Reports, 6(4), 155–165. https://doi.org/10.1007/s40641-020-00163-x

Dawson, J., Pizzolato, L., Howell, S., Copland, L., & Johnston, M. (2018). Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. *ARCTIC, 71(1)*. https://doi.org/10.14430/arctic4698

Dowle, M., & Srinivasan, A. (2021). data.table: Extension of `data.frame`. R package version 1.14.0. https://CRAN.R-project.org/package=data.table

Ebinger, C., & Zambetakis, E. (2009). The geopolitics of Arctic melt. *International Affairs, 85(6),* 1215–1232. https://doi.org/10.1111/j.1468-2346.2009.00858.x

Feinerer, I., & Hornik, H. (2020). tm: Text Mining Package. R package version 0.7-8. https://CRAN.R-project.org/package=tm

Fu, S., Goerlandt, F., & Xi, Y. (2021). Arctic Shipping Risk Management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents. *Safety Science, 139, 105254.* https://doi.org/10.1016/j.ssci.2021.105254

Fu, S., Zhang, D., Montewka, J., Zio, E., & Yan, X. (2018). A quantitative approach for risk assessment of a ship stuck in ice in Arctic Waters. *Safety Science, 107,* 145–154. https://doi.org/10.1016/j.ssci.2017.07.001

Gross, M. (2018). Arctic shipping threatens wildlife. *Current Biology, 28(15)*. https://doi.org/10.1016/j.cub.2018.07.053

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

Halliday, W., & Dawson, J. (2021). Ship-Source Noise Modeling from 2015-2018 in the Kitikmeot Region and Lancaster Sound (Northwest Passage), Nunavut. http://hdl.handle.net/10393/41926

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

Hauser, D., Laidre, K., & Stern, H. (2018). Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proceedings of the National Academy of Sciences, 115(29)*, 7617–7622. https://doi.org/10.1073/pnas.1803543115

Heidari, N., Sebastian Feser, M., Scholten, N., Schwippert, K., & Sprenger, S. (2022). Language in primary and Secondary Geography Education: A systematic literature review of empirical geography education research. *International Research in Geographical and Environmental Education, 32(3),* 234–251. https://doi.org/10.1080/10382046.2022.2154964

Huang, L., Perry, P., Nielsen, F., Porter, M., & Boulton, R., (2021, May 2). corpus: Text Corpus Analysis. ‘Corpus’. R package version 0.10.2. https://CRAN.R-project.org/package=corpus

Lancaster, M. L., Winsor, P., & Dumbrille, A. (2021). Underwater noise from shipping: A special case for the Arctic. *Sustainability in the Maritime Domain, 271–289.* https://doi.org/10.1007/978-3-030-69325-1_14

Johnston, M., Dawson, J., & Maher, P. (2017). Strategic development challenges in marine tourism in Nunavut. *Resources, 6(3),* 25. https://doi.org/10.3390/resources6030025

Khyani, D., & B S, S. (2021). An Interpretation of Lemmatization and Stemming in Natural Language Processing. *Journal of University of Shanghai for Science and Technology, 22(12)*. https://doi.org/1007-6735

Lasserre, F. (2014). Case studies of Shipping along Arctic routes. Analysis and profitability perspectives for the container sector. *Transportation Research A 66,* 144-161

Moore, S., Reeves, R., Southall, B., Ragen, T. J., Suydam, R., and Clark, C. (2012). A new framework for assessing the effects of anthropogenic sound on marine mammals in a rapidly changing Arctic. *BioScience, 62(3)*, 289–295. https://doi.org/10.1525/bio.2012.62.3.10

Mudryk, L., Dawson, J., Howell, S., Derksen, C., Zagon, T., & Brady, M. (2021). Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change, 11(8)*, 673–679. https://doi.org/10.1038/s41558-021-01087-6

Mullen, L., Benoit, K., Keyes, O., Selivanov, D., & Arnold, J. (2018). Fast, consistent tokenization of natural language text. *Journal of Open Source Software, 3(23),* 655. https://doi.org/10.21105/joss.00655

Müller, K., & Wickham, H. (2021). tibble: Simple Data Frames. R package version 3.1.6 https://CRAN.R-project.org/package=tibble

Olsen, J., Carter, N., & Dawson, J. (2019). Community perspectives on the environmental impacts of arctic shipping: Case studies from Russia, Norway, and Canada. *Cogent Social Sciences, 5(1*). https://doi.org/10.1080/23311886.2019.1609189

Ooms, J. (2021). writexl: Export Data Frames to Excel 'xlsx' Format. R package version 1.4.0. https://CRAN.R-project.org/package=writex

Pizzolato, L., Howell, S., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophysical Research Letters, 43(23)*. https://doi.org/10.1002/2016gl071489

Protection of the Arctic Marine Environment (PAME). (2009). Arctic Marine Shipping Assessment 2009 Report. Arctic Council, April 2009, second printing. Retrieved from: https://pame.is/images/03_Projects/AMSA/AMSA_2009_report/AMSA_2009_Report_2nd_print.pdf

Qian, H., Zhang, R., & Zhang, Y. (2020). Dynamic Risk Assessment of natural environment based on dynamic Bayesian network for key nodes of the Arctic Northwest Passage. *Ocean Engineering*, *203,* 107205. https://doi.org/10.1016/j.oceaneng.2020.107205

Robinson, D. (2020). widyr: Widen, Process, then Re-Tidy Data. R package version 0.1.3. https://CRAN.R-project.org/package=widyr

Sheehan, R., Dalaklis, D., Christodoulou, A., Drewniak, M., Raneri, P., & Dalaklis, A. (2021). The Northwest Passage in the Arctic: A brief assessment of the relevant Marine Transportation System and current availability of search and rescue services. *Logistics*, *5(2)*, 23. https://doi.org/10.3390/logistics5020023

Silge, J., & Robinson, D. (2016). Tidytext: Text mining and analysis using tidy data principles in R. *The Journal of Open Source Software, 1(3),* 37. https://doi.org/10.21105/joss.00037

Somanathan, S., Flynn, P., & Szymanski, J. (2009). The northwest passage: A simulation. *Transportation Research Part A: Policy and Practice*, *43(2)*, 127–135. https://doi.org/10.1016/j.tra.2008.08.001

Somanathan, S., Flynn, P. C., and Szymanski, J. K. (2007). Feasibility of a sea route through the Canadian Arctic. *Maritime Economics & Logistics*, *9(4)*, 324–334. https://doi.org/10.1057/palgrave.mel.9100185

Stephenson, S. R., & Smith, L. C. (2015). Influence of climate model variability on projected arctic shipping futures. *Earth's Future*, *3*(11), 331–343. https://doi.org/10.1002/2015ef000317

Stewart, E., Dawson, J., Howell, S., Johnston, M., Pearce, T., and 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. https://doi.org/10.1080/1088937x.2012.705352

van Luijk N, Carter NA, Dawson J, Song G, Parker C, et al. (2021) At the front lines of increased shipping and climate change: Inuit perspectives on Canadian Arctic sovereignty and security. *Arctic Yearbook 2021*. https://arcticyearbook.com/images/yearbook/2021/Scholarly-Papers/6_AY2021_Luijk_Dawson.pdf

Wickham, H., François, R., Henry, L., & Müller, K. (2022). dplyr: A Grammar of Data Manipulation. R package version 1.0.8. https://CRAN.R-project.org/package=dplyr

Wickham, H. (2021). dtplyr: Data Table Back-End for 'dplyr'. R package version 1.1.0. https://CRAN.R-project.org/package=dtplyr

Wickham, H. (2019). stringr: Simple, Consistent Wrappers for Common String Operations. R package version 1.4.0. https://CRAN.R-project.org/package=stringr

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, LD., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, TL., Miller, E., Bache, SM., Müller, K., Ooms, J., Robinson, D., Seidel, DP., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., & Yutani, H. (2019). "Welcome to the tidyverse." *Journal of Open Source Software, 4(43), 1686*. doi:10.21105/joss.01686.

Würsig, B., & Koski, W. (2021). Natural and potentially disturbed behavior of Bowhead Whales. *The Bowhead Whale, 339–363*. https://doi.org/10.1016/b978-0-12-818969-6.00023-6

Zhang, Z. (2018). Text Mining for Social and Behavioral Research Using R: A Case Study on Teaching Evaluation. Retrievable from https://books.psychstat.org/textmining.

Zhang, M., Zhang, D., Zhang, C., & Cao, W. (2020). Navigational risk factor analysis of Arctic shipping in ice-covered waters. *Maritime Transport and Regional Sustainability, 153–177*. https://doi.org/10.1016/b978-0-12-819134-7.00010-1

Zhou, X. (2022). A comprehensive framework for assessing navigation risk and deploying maritime emergency resources in the South China Sea. *Ocean Engineering, 248,* 110797. https://doi.org/10.1016/j.oceaneng.2022.110797

Zhu, S., Ng, A., Afenyo, M., Panahi, R., & Bell, M. (2023). Socio-economic impacts of shipping along the Northwest Passage: The cost to locals. *Marine Policy, 153, 105647*. https://doi.org/10.1016/j.marpol.2023.105647

Chapter 3: Comprehensive Risk Analysis of Maritime Shipping Hazards and Risks in Arctic Canada

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3.1 Abstract

The Canadian Arctic has experienced significant changes in climate and associated declines in sea ice conditions since the beginning of the 21st century. This has led to summer months having ice-free days throughout many sections of the Northwest Passage (NWP) and increased maritime shipping opportunities. If ongoing climate change patterns persist as expected, this will continue to increase accessibility of the NWP. Previous studies have examined the individual risks of maritime shipping operations through the NWP, though there has yet to be a study that examines hazards and risks in a comprehensive manner. To fill this gap, a wide range of academic sources were used to conduct a comprehensive content analysis of present-day risks related to maritime ship operations in Arctic Canada. Resulting from this effort was a list of potential hazards and risks which were then used to complete a Failure Modes, Effects, and Criticality Analysis (FMECA) and a Consequence-probability Matrix risk rating in order to determine possible data sources, data limitations, hazard/risk severity, frequency, control measures, and direct/indirect impacts. A total of 96 risks and 55 hazards were identified among 12 unique thematic groups. Results of the FMECA reveal that 26% of risks are assessed as 'VERY HIGH' or 'HIGH'. Among the 12 thematic groups, community-based risks were identified as exhibiting the highest average thematic group risk rating, with a moderate data quality analysis score classified as 'moderate agreement, moderate evidence'. The findings from this study could be used to complete a comprehensive risk assessment and to aid in investment and management decision-making for the Arctic shipping sector in Canada.

Keywords: Arctic shipping, consequence/probability matrix, content analysis, FMECA analysis, natural language processing, Northwest Passage, risk analysis, risk rating.

3.2 Introduction

The Canadian Arctic Archipelago, specifically the Northwest Passage (NWP), has undergone considerable physical and ecological changes since the beginning of the industrial revolution (IPCC, 2022; Mudryk et al., 2021). Changes in global temperatures have disproportionately caused a significant shift in sea ice melt and concentration (Qian et al., 2020; Pizzolato et al., 2016), increased pollutant ppm content (Jing et al., 2021; Comer et al., 2017), more frequent underwater noise (Halliday & Dawson, 2021; Halliday et al., 2017), frequent tourism (Johnston et al., 2017), and changes in the types and frequency of vessel operations within the Arctic (Fu et al., 2023; Copland et al., 2021; Pizzolato et al., 2016). These ecological changes have allowed for the NWP to become ice free during some months of the year and have gained international interest as a result (Mudryk et al., 2021; Pizzolato et al., 2016). Many Arctic Council observer countries such as South Korea, China, India, Singapore, and other nations have indicated global interests in determining the feasibility of using the NWP as a viable shipping corridor from increased research and discussions on social media (Akbayirli & Tuna, 2022; Bennett et al., 2020). As a result, the NWP appears to save approximately 7,000 kilometres compared to alternate routes such as the Panama and Suez Canal when travelling from New York, USA to Yokohama, Japan (Chen et al., 2021; Somanathan et al., 2009). The global attention about the NWP sparks many questions regarding the longevity of utilizing Arctic Canada as an international trade corridor, as it may impose and exacerbate economic, operational, environmental, indigenous, and community-focused risks (Chen et al., 2021; Qian et al., 2020; Olsen et al., 2019). Prior to internationalizing the NWP for economic use, risk analyses and assessments must be able to thoroughly and comprehensively identify all hazards and risks associated with Arctic shipping operations. These forms of analysis are essential to determine the worst-case outcome so policy- and decision-makers can plan accordingly to mitigate and/or protect communities from being exposed to severe hazards and risks.

There have been no previously completed comprehensive risk analyses or assessments examining a wide range of Arctic shipping hazards and risks (Fu et al., 2023; Afenyo et al., 2017; Mousavi et al., 2017). A lack of Arctic shipping risk assessments has been identified with the ongoing complexity of Arctic shipping processes and previous lack of data availability (Afenyo et al., 2017; Peeters & Peng, 2015). Previous risk assessments have been completed without the completion of a risk analysis and, as a result, do not adequately identify priority hazards and risks or data sources and/or limitations, thus resulting in various incongruities among selected data (Qian et al., 2020; Afenyo et al., 2017). The lack of previous research examining comprehensive hazards and risks (Qian et al., 2020; Afenyo et al., 2017) has created significant data limitations and fostered inconsistent approaches to implement when selecting hazards and risks for analysis (Afenyo et al., 2017; Mousavi et al., 2017). Analyses such as that by Fu et al. (2023) have calculated a risk identification, analysis, and assessment model among four navigation accident scenarios in Arctic environments. This approach included a consequence-probability matrix to effectively quantify the risks observed, and it classified the risks into subcategories; 'Unsafe act', Unsafe conditions', 'Navigational accidents', and 'Environmental conditions' (Fu et al., 2023).

Defining and reaching a consensus within the academic community regarding terminologies such as 'hazard' and 'risk' has been an ongoing issue (Peeters & Peng, 2015). Scientists use a variety of terms when completing risk analyses and assessments, which results in discrepancies in definitions used by professions. These discrepancies foster slightly different outcomes that increase the difficulty for replication and co-comparison among similar assessments (Peeters & Peng, 2015). This study will use the Intergovernmental Panel on Climate Change (IPCC) Working Group II's (WGII) definitions regarding hazards and risks which will allow precedence for industries to utilize this created methodology (IPCC, 2022). No previous study has used these definitions from the IPCC completely, which may ease the current problem of unsystematic uses for the definition of terms (Afenyo et al., 2017; Mousavi et al., 2017).

To address the knowledge gaps stated above, the objectives of this research are to comprehensively create an inventory potential (a) hazards and (b) risks regarding Arctic shipping operations in the NWP. Once the inventory has been created, a risk rating score will be calculated using consequence and probability of occurrence via each hazard or risk. An identical risk rating score will be applied for all identified thematic groups. Finally, information will be synthesized via individual hazard and risk, collecting risk rating scores, data quality scores, causes and consequences, and controls. Successfully addressing the identified research objectives above will create a risk analysis model that can be replicated for future uses surrounding other issues within Polar environments. This study will also create a systematic process to identify the highest risks of moderate or high data quality that require prioritization. Implementing a method that calculates data quality among sources is also essential in determining whether a source should be deemed appropriate for use within a more thorough risk assessment. The hazards and risks that are recommended for future analyses attributed from this study will be prioritized for inclusion within a thorough comprehensive risk assessment.

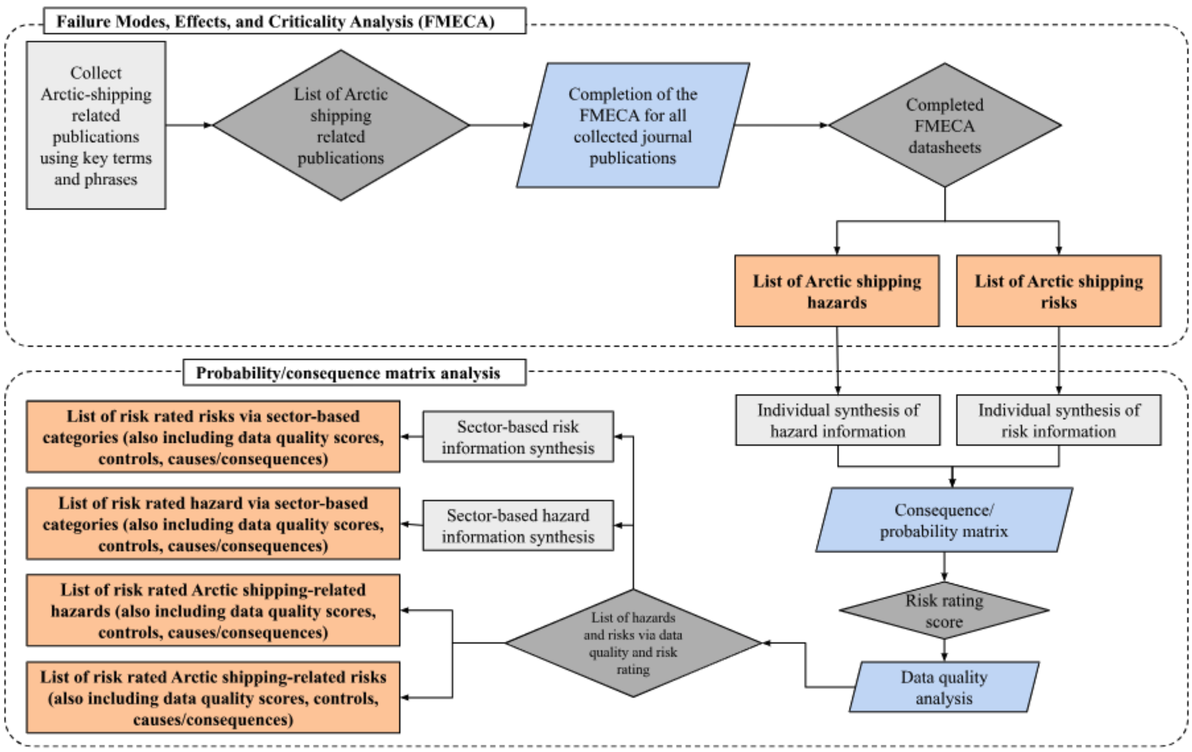
An ideal risk assessment is to be completed following a formalized risk analysis that identified hazards and risks that have sufficient data to fully assess. Current studies have typically been completed without a thorough risk analysis, limiting the opportunities to implement a comprehensive risk assessment in the future. Failing to perform a risk analysis limits the feasibility to further understand the relationships and key similarities/differences (i.e. severity, probability, and impacts) among individual risks and thematic group risk groups. Current literature has focused on identifying an individual risk(s) or sectors (primarily sea ice) to determine their corresponding impacts, though, failing to integrate sectors. As previous risk analyses have focused on one specific sector or individual (a) hazards and (b) risks, identifying sectors may create ease for assessing risks comprehensively. The grouping of alike hazards and risks can account for the lack of data availability among previously identified hazards and risks.

3.3 Methodology

To effectively inventory hazards and to provide a risk rating for hazards (impact drivers) and risks (future impacts) for maritime ship operations, a two-step process was employed. First, data regarding Arctic shipping-related publications was collected that discussed information specific to hazards and risks. A total of 94 peer-reviewed publications were selected for this study that examined a wide range of discipline and issues. Articles were chosen using search queries from open-source journal databases and search engines. To ensure the most accurate information, journals that were published more recently were prioritized over studies that were considered obsolete. Since there have been very few studies regarding Arctic shipping-specific risk assessment research, many research publications were collected from the years 2006 to 2023. All 100 articles were initially taken from Chapter 2 and were assessed based on the relevancy of identifying hazards and risks. Of this sample size, 68 were identified as relevant articles and examined further. The remaining 26 publications were found through frequently used terms and phrases from Chapter 2 as means of search queries. A list of all peer-reviewed publications can be observed in Appendix 5.

These peer-reviewed publications were utilized to complete a Failure Modes, Effects, and Criticality Analysis (FMECA). The FMECA identified hazards and risks, associated causes, consequences, controls, and data quality information. Second, the consequence/probability matrix synthesized consequence and probability metrics using the information collected by the FMECA by calculating and giving a risk rating to each hazard and risk. A risk rating score was calculated for all unique hazards and risks, grouping like hazards and risks together through the averaging of their consequence and probability scores, estimated data quality scores, and other synthesized information. Hazards and risks were assessed using the same risk rating equation as it was the most systematic method to address this complex process. Initially assessing all variables using the same equation establishes a baseline for priority sequence, allowing researchers to prioritize the most severe hazards and risks for further assessment. The premise of this study is to preliminarily identify and create risk rating scores for all individual hazards and risks. In subsequent assessment, it is recommended that different risk rating equations be used for risks and hazards, as the objectives will be to identify the linkages and similarities among hazards and risks alike. All thematic groups followed a similar synthesis process that combined hazards and risks to formulate an official risk rating and data quality scores for each category. Figure 6 highlights the methodological process this research has taken to achieve its designated research objectives.

Figure 6. Research process map highlighting the processes used (light grey rectangles), methods (blue parallelograms), key outputs (grey diamonds), and research objectives (orange rectangles) used to complete the research project.



3.3.1 Step 1: Risk Identification using academic literature to complete a Failure Modes, Effects, and Criticality Analysis (FMECA)

Using the results from step one, frequently used terms and phrases identified in *Chapter 2* were used as search query terms in search for Arctic shipping-related journal publications. If deemed relevant to the research scope, journal publications were downloaded for use within the FMECA analysis. The selected articles were used with previously collected articles from the comprehensive content analysis noted in *Chapter 2* to complete the risk identification process. Data sources included, but are not limited to, the following journals: Maritime Transport and Regional Sustainability, Marine Policy & Management, Polar Record, and Risk Analysis.

The Failure Modes, Effects, and Criticality Analysis (FMECA) was used to identify which systems, components, and processes examine potential avenues of failure, therefore determining the critical effects on the performance of the entire system (ISO, 2009). This analytical tool identified and deconstructed each hazard and risk at the individual level to further understand the complexity, similarities, and differences amongst them. Most FMECA analyses are completed as worksheets when collecting data regarding processes and systems to ensure a systematic and organized approach is followed (ISO, 2009). Please see Appendix 6 for an example FMECA data observation worksheet used to collect data observations. The FMECA analyses identified the operations that exhibit hazards/risks, level of consequence, probability of occurrence, present-day causes and consequences (both indirect and direct), as well as control measures that are presently in place or recommended at the individual hazard/risk level (ISO, 2009).

Given the scope of this research, the FMECA collected the following information: (i) data-specific information (i.e., data type, sources, and availability), (ii) hazard/risk-specific information (i.e., hazard/risk name, description, probability of occurrence, level of consequence, causes/consequences [in/direct]), and (iii) any control mechanisms in place. Daya and Lazakis' (2023) research further confirms the applicability of this method, collecting similar data using the FMECA analysis to thoroughly analyze system-level operations and maintenance on shipping vessels (Daya & Lazakis, 2023).

3.3.2 Step 2: Risk Analysis Utilizing a Consequence/Probability Matrix and Indicators Measuring Data Quality

Once hazards and risks have been identified using the FMECA analysis worksheets, data observations were synthesized using a consequence/probability matrix (ISO, 2009). The consequence/probability matrix combined qualitative or semi-quantitative data to calculate a risk rating score using levels of consequence and probability (ISO, 2009). This consequence/probability matrix is commonly used to rate all hazards and risks, and determines which variables need further examination and immediate treatment, typically acting as a screening process to identify the highest hazards and risks (ISO, 2009). Typically, probability and consequence are scored using five-by-five grid values ranging from 1 (low) through 5 (high) to calculate a risk score (ISO, 2009). A similar methodology is used by the Intergovernmental Panel for Climate Change (IPCC) within the assessment reports (AR) where these reports utilize a multi-colour method to illustrate risk significance, called the 'burning ambers' (Meredith et al., 2019). For the study, the calculation for the consequence/probability matrix was designed to fit the comprehensive variables, given the complexities of the research scope. This study utilized the IPCC's methodology of the burning ambers in illustrating the level of risk. Previous research by Conachey and Montgomery (2005) completed a risk analysis using a consequence/probability matrix to identify preliminary risks to the global marine industry (Conachey & Montgomery, 2005).

3.3.2.1 Risk Rating Calculations

To calculate the risk rating for each hazard and risk, a four (consequence) by five (probability) grid matrix was used for this study, following ISO guidelines (ISO, 2009). Previous research by Afenyo et al. (2017) used a consequence/probability matrix that required five bins for their probability scores. These bins were used to illustrate the significant differences in the probability of occurrence when assessing shipping accident reports (Afenyo et al., 2017). More bins were selected for probability after noting higher levels of differing results regarding probability than consequence. Prior to the discussion of the risk rating score calculation, both consequence and probability scores must be understood thoroughly to understand the decisions behind calculating the risk rating scores.

3.3.2.1.1 Consequence Calculation

The term 'consequence' is defined through the IPCC AR6 glossary as realized risks on human or natural systems where interactions of climate-related exposures, hazards (including weather and/or climate events), and vulnerability create risks (IPCC, 2018). Consequences are also called impacts or outcomes that can become adverse or beneficial (IPCC, 2018). The labelling for these bins is similar to the study conducted by Fu et al. (2023) that examined shipping-related accidents using an object-oriented Bayesian Network and a consequence/probability matrix. This research was used to inform the broader community regarding the risk of navigational accidents such as grounding, ship-ship, and ship-ice collisions (Fu et al., 2023). Table 7 highlights four consequence rating scores used, 'LOW,' 'MEDIUM,' 'HIGH,' and 'CATASTROPHIC' with corresponding values.

Table 7. Generalized consequence rating score descriptions adopted from Fu et al. (2023).

Consequence Index	Score	Description
CATASTROPHIC	10	Complete loss, causing irreversible damages and/or multiple casualties.
HIGH	7	Severe that causes long term damages and/or loss of life/serious injuries.
MEDIUM	4	Non-severe that causes short term damages and/or life serious injuries.
LOW	1	Localized damage that causes negligible damage and/or minor injuries.

As consequences are defined differently according to the thematic groups, Table 8 illustrates the distinctiveness of consequence ratings among various sectors. These sectors were chosen using the outcomes from the natural language processing word frequency and correlation results, grouping similar terms into ten thematic groups. These categories followed similar groupings for hazard and risk variables as per a study by Fu et al. (2023), where they grouped shipping-related risks based on different actions. In the event individual hazards and risks provided minimal evidence or low agreement, hazards and risks were grouped by thematic groups to merge data sets together and create stronger, holistic understandings of key and trending issues. Recommending sectors over individual risks for further investigation allows for leniency towards determining national and regional priorities for areas like research. This should ensure a thorough understanding of the broader scope of the thematic group's relationships among the chosen hazards and risks within the groups.

It was difficult to determine a comprehensive consequence score amongst the wide variety of themes that uses both qualitative and quantitative data to determine hazard and risk consequences. As a result, using thematic groups to group consequence definitions was the most-effective method to ensure all risks and hazards were adequately binned into specified consequence. Separating consequence scores into specific groups enabled a thorough assessment of each consequence's severity based on a thematic group, rather than one comprehensive definition. This removed the subjectivity when determining the appropriate bin for each individual hazard and risk.

Table 8. Consequence rating definitions based on thematic group.

Consequence Index	Assessment	Community	Economic	Environmental	Operational/Navigational
CATASTROPHIC	Extreme assessment errors, data gaps, and/or uncertainties	Irreversible damages, significant loss of culture and/or heritage creating unliveable conditions	Significant economic impacts/costs (valued over CAD 250,000)	Catastrophic environmental damage to an entire ecosystem and/or species population, required remediation and indefinite monitoring.	Catastrophic threat to operations, creating conditions that will impact the vessel's ability to complete a successful trip.
HIGH	Large assessment errors, data gaps, and/or uncertainties	Irreversible damages, significant loss of culture and/or heritage, liveable conditions still present.	Long-term economic impacts/costs (valued up to CAD 250,000)	Significant environmental damage requires long-term remediation and monitoring.	High threats posing long term impacts on the entire trip, causing increased difficulties or significant navigational delays.
MEDIUM	Moderate assessment errors, data gaps, and/or uncertainties	Long-term damages to culture and heritage. Mitigation and conservation plans are in place to reduce and revert harm.	Short-term economic impacts/uncertainty (valued up to CAD 25,000)	Large environmental damage that requires short-term remediation and monitoring, above ecological thresholds to recover naturally.	Moderate threat posing short-term impacts during sections of the trip, causing increased difficulties or moderate delays.
LOW	Small assessment errors, data gaps, and/or uncertainties	Short-term damages to culture and heritage. Mitigation plans are in place to reduce and revert harms.	Negligible economic impacts/uncertainty (valued up to CAD 1,000)	No or minor environmental damage, below ecological thresholds to recover naturally.	Negligible threat to operations causing an individual or small, short-term impact on normal operations.

Consequence Index	Political/Regulatory	Pollutants	Safety	Sea Ice	Technological
CATASTROPHIC	Polarizing or complex international interests/legislation among jurisdictions and/or completely unenforceable regulations.	1,000L uncontrolled release/spill or covering a protected area or critical habitat	Multiple fatalities	Complete sea ice presence, with majority multi-year and first-year sea ice present.	Entire device/system failure or errors
HIGH	Different or complex international interests/legislation among jurisdictions with challenging regulations regarding enforceability.	999-250L uncontrolled release/spill, any controlled release of substances	Single fatalities	High sea ice presence, with multi-year and first-year sea ice present.	Large-scale temporary outage/error: Moderate error or failure impacting the entire duration of the voyage.
MEDIUM	Similar international interests/legislation among jurisdictions and/or sufficient enforcement capabilities with few limitations.	250L-50L uncontrolled release/spill	Near miss and/or emergency services required	Moderate sea ice presence, first-year sea ice present.	Moderate errors or technology failure during sections of the voyage.
LOW	International interests/legislation among jurisdictions are cohesive and/or have high enforcement capabilities.	<50L uncontrolled release/spill	Single or multiple injuries	Low or no sea ice presence, first-year sea ice present.	Minor/short-term system error/glitch

3.3.2.1.2 Probability Calculation

Given the high variability among the probability scores within the dataset, five bins were chosen as a result. A probability score was given to each bin between the integers 1 (remote/lowest probability) and 5 (almost certain probability). It is assumed that the higher probability of a hazard or risk occurring would correlate to becoming a higher risk for maritime shipping operations. The terms used to describe probability were chosen from studies such as Conrow (2003) and Fu et al. (2023). These studies adequately articulated a methodology that allows for equally distributed categories for probability classification (Fu et al., 2023; Conrow, 2003). The term 'remote' was often referred to as a low probability within shipping risk assessments and was selected as a result (Fu et al., 2023). Table 9 depicts the probability ratings, scores, descriptions, and probability frequency per ship year (Fu et al., 2023; Afenyo et al., 2017).

Table 9. Probability Rating Score Descriptions as adopted from Fu et al. and Afenyo et al. (Fu et al., 2023; Afenyo et al., 2017).

Probability Index	Score	Description	Frequency (per year)
ALMOST CERTAIN	5	100-85% occurrence probability	Once a voyage
LIKELY	4	85-65% occurrence probability	Once a month
BETTER THAN EVEN	3	65-55% occurrence probability	Once a year
UNLIKELY	2	55-35% occurrence probability	Once every 5 years
REMOTE	1	35-0% occurrence probability	Once every ship lifetime (~20 years)

3.3.2.1.3 Risk Rating Score Calculation

To calculate the risk score for each individual hazard and risk, the values among all observed consequence scores applicable to the hazard or risk were averaged. The average for all probability scores applicable to the hazard or risk were also used to remain consistent across both metrics. Average values were prioritized over median values due to the varying degrees in data quantity among observed hazards and risks. To avoid any possibility of data being skewed due to inconsistent findings, the average was taken for both metrics. The calculation for this risk rating equation is the product between the averaged consequence and probability scores and is expressed within Equation 1 below.

Equation 1. Risk rating (RR) calculation.

$$Risk\ Rating\ (RR) = Consequence * Probability$$

Risk assessments are typically recommended to adhere to the IPCC three-pronged matrix approach, which requires assessing exposure, hazard(s), and vulnerability (IPCC, 2022). Since the objective of this research is to identify all hazards and risks relating to Arctic shipping, the IPCC three-pronged matrix was deemed too sophisticated at this time. The overarching aim of this analysis was to establish the existence of comprehensive hazards and risks relating to Arctic shipping. Given the scope of the research, a consequence/probability matrix was the most appropriate option for completing a comprehensive content and risk analysis. Numerous methods were available to calculate and assess risks through this matrix, specifically highlighting a higher consequence score than probability (Fu et al., (2023); Afenyo et al., (2017). The consequence of a hazard or risk occurring is more influential, specifically in Arctic environments and as such, was given values that were double the probability scores. This research used the guidelines set by the ISO to calculate the risk score, using a consequence/probability matrix by calculating the product of the consequence and probability scores (ISO, 2009). As seen within Appendix 2, the consequence-probability matrix was listed as 'Strongly Applicable' for both risk identification and risk analysis processes within all structured analytical techniques considered (IMO, 2018; ISO, 2009). The use of this method can be further justified, as it was also used within a recent study by Afenyo et al. (2017), which calculated Arctic shipping-related accidents using a five-by-five consequence/probability matrix (Afenyo et al., 2017). Hazard and risk scores use the matrix in Figure 7 to determine their risk rating at the individual hazard- and risk-level.

Figure 7. Risk matrix for calculating the level of risk as adopted from the consequence/probability matrix from ISO and IPCC guidelines (Meredith et al., 2019; Peeters & Peng, 2015; ISO, 2009).

PROBABILITY					
ALMOST CERTAIN	**5**	5	20	**35**	**50**
LIKELY	**4**	4	16	**28**	**40**
BETTER THAN EVEN	**3**	3	12	21	**30**
UNLIKELY	**2**	2	8	14	20
REMOTE	**1**	1	4	7	10
	Score	**1**	**4**	**7**	**10**
		LOW	MEDIUM	HIGH	CATASTROPHIC
		CONSEQUENCE			

Risk Ratings (RR)
- VERY HIGH
- HIGH
- MODERATE
- UNDETECTABLE

Once the risk rating score has been calculated, the quantitative scores were classified into a formalized risk rating category, as guided by IPCC's guidelines on risk assessment (IPCC, 2022). Hazards and risks were rated on a scale of 1 to 50 among four risk rating bins; 'VERY HIGH' (50-36), 'HIGH' (35-25), 'MODERATE' (24-10), and 'UNDETECTABLE' (9-1) (IPCC, 2022). The burning Amber's colour-coding scheme from the IPCC guidelines was used for consistency (Meredith et al., 2019). The risk rating score for the analysis was determined using Table 10. Once all individual risk scores were calculated, Table 10 highlights the risk rating scores, criteria ranges, and descriptions of each risk rating category.

Table 10. Cumulative risk rating (RR) score adopted from the IPCC guidelines (Meredith et al., 2019).

Risk Rating	Range	Description
VERY HIGH	50-36	A priority risk that is considered to create catastrophic long-term or indefinite damages. Control measures and monitoring are mandatory to eliminate or mitigate the identified hazards or risks to achieve as low as reasonably possible (ALARP) standards. Caution expressed after measures implemented.
HIGH	35-25	High risks inflict a high possibility of occurrence as well as consequence, creating medium to long term damages on the human or natural environments. High hazards and risks identified shall require specific management, control measures, and continuous monitoring practices to achieve ALARP standards. Caution expressed after measures implemented.
MODERATE	24-10	Moderate risks are manageable, though disrupt current systems in place periodically that create impacts that are close or at ecological thresholds. Once thresholds are reached, this can possibly cause short- or medium-term impacts to human or ecosystem dynamics. These hazards and risk present a higher degree of

		probability and severity that require specific management and control measures to achieve ALARP standards.
UNDETECTABLE	9-1	An undetectable risk is tolerable and does not exceed current ecological thresholds that inflict long term damages. Undetectable hazards and risks are seen as the lowest priority, requiring little or no use management practices.

To summarize, each hazard and risk score used the consequence-probability matrix to determine the risk score. Risk scores were calculated using the matrix from Figure 5 and Equation 1 (Risk Rating Equation) that determined the quantitative risk value. When a risk score was established, Table 10 was utilized to determine the risk rating. All risk rating scores were calculated among average values of each hazard or risk consequence and probability values. Once finalized, the study determined the data quality scores for hazards and risks observed.

3.3.2.2 Data Quality Calculations

This research measures data quality using two separate metrics; Level of Agreement and Evidence Scores as expressed in a percentage value between 0-100%. The sum of both Level of Agreement and Evidence Scores was calculated, then divided by 100, to receive a percentage score. The data quality equation is expressed below (Equation 2). These metrics were based on the IPCC's uncertainties guidance document, emphasizing the importance of determining the level of agreement and evidence among data scores (Mastrandrea et al., 2010).

Equation 2. Data Quality (DQ) calculation.

$$Data\ Quality\ (DQ)\ =\ \left(\frac{Level\ of\ Agreement\ (LoA)\ +\ Evidence\ Score\ (ES)}{100}\right)$$

To effectively calculate the data quality among the selected articles, seven unique (7) indicators were used to calculate the data quality score. There are two similar indicators that describe the different ways of understanding quantity of evidence among data observations (Amount (A) and Agreement Quantity (AQ)). The Amount (A) variable presents the proportion of hazards or risks observed among all data collected. Agreement Quantity (AQ) is a threshold-based metric that uses a set of two true/false functions. If three or more articles were observed, a score of 50% was given to the hazard or risk. If five or more observations observed, the conditions were satisfied, and the hazard or risk received a perfect score. Figure 8 illustrates the classification of indicators used and its associated weighting scheme.

Figure 8. Visual breakdown of data quality indicators and weightings.

Data Quality	Evidence Score (ES)				Level of Agreement (LoA)		
Indicator Name	Type (T)	Amount (A)	Consistency (C)	Quality (Q)	Agreement (Ag)	Distribution (D)	Agreement Quantity (AQ)
Weight	12.5	12.5	12.5	12.5	10	10	30
Highest Score	100						

Two types of data quality scores will be calculated, one representing overall data quality as expressed in five bins: 'VERY HIGH', 'HIGH', 'MODERATE', 'LOW', and 'VERY LOW'. These are further explained in Table 11. The other is granular based on the LoA and ES scores, both requiring three bins. Both methods have been adopted from the IPCC's uncertainties guidance document, demonstrating how to express data quality scores, and properly representing them in a qualitative manner (Mastrandrea et al., 2010).

Table 11. Data quality score descriptions adopted from the IPCC guidelines (Meredith et al., 2019).

Data Quality Index	Interval	Description
VERY HIGH	100% - 80%	Data confidence is acceptable with a maximum degree of certainty.
HIGH	79% - 60%	Data confidence is acceptable for use with certainty.
MODERATE	59% - 40%	Data must be used cautiously in situations where weighting options are available.
LOW	39% - 20%	More data is required before use in risk assessment.
VERY LOW	19% - 0%	Little to no data is available, and more data before assessment use.

Once the initial data quality score has been calculated and ratings are assigned, there was an additional rating scale for both Level of Agreement and Evidence Scores to increase granularity in data quality. The descriptors specifically used within Tables 11, 12, and 13 specify the requirements of the data quality. This study is the first to create a quantifiable data quality score that is utilized in a comprehensive manner. As a result, it was difficult to collect information regarding data quality among interdisciplinary sectors. The Level of Agreement data collected was interpreted by the authors by utilizing the differences in risk rating scores as well as the quantity of studies found. Evidence Score data were empirically based on the replicability of the study and collecting data regarding the study design though interpretation. Tables 12 and 13 highlight the granularity, providing researchers with a specific understanding of the strengths and shortcomings of the data observed for the Level of Agreement and Evidence.

Table 12. Level of Agreement (LoA) score descriptions adopted from the IPCC guidelines (Meredith et al., 2019).

Level of Agreement	Interval	Description
High agreement	50.00 - 33.34	High agreement indicates a substantial quantity of data has been collected to determine a definitive consensus, determining a moderate or high proportion of authors agree amongst the risk rating score.
Medium agreement	33.33 - 16.67	Medium agreement indicates one of two possibilities: 1. Substantial quantity of data has been collected, though a moderate or low proportion of authors agree amongst the risk rating score. 2. Insufficient data has been collected, though a moderate or high proportion of authors agree amongst the risk rating score.
Low agreement	16.66 - 0.00	Low agreement indicates insufficient data has been collected to determine a definitive consensus, identifying a moderate or low proportion of authors agree amongst the risk rating score.

Table 13. Evidence Score (ES) descriptions adopted from the IPCC guidelines (Meredith et al., 2019).

Evidence	Interval	Description
Robust evidence	50.00 - 33.34	Robust evidence is supported by a numerous and a diverse range of subject matter experts. The data is available for study replication and provides a high quality of data throughout. The evidence also includes a wide-range of research expressing consistent results.
Medium evidence	33.33 - 16.67	Medium evidence is supported by a numerous and a few subject matter experts. The data is typically available for study replication and provides a moderate data quality. The evidence also includes research expressing moderate variability among results.

Limited evidence	16.66 - 0.00	Limited evidence is supported by a singular or very few studies that do not include a diverse subject matter experts. The data is primarily unavailable for replication and provides a low data quality. The evidence does not express consistent results.

3.3.2.2.1 Level of Agreement Scores

First, the Level of Agreement (LoA) determined whether the observed publications were able to come to a consensus among each hazard or risk in a similar manner, while also considering the quantity of articles that examined similar hazards or risks. The Level of Agreement was the sum of the risk agreement (Ag), risk distribution (D), and Agreement Quantity (AQ) scores. The risk agreement and distribution scores were multiplied by a value of 10, and the quantity score was multiplied by a value of 30 to create a product value between 0 - 50. The AQ score was determined as higher priority among the risk agreement scores. The LoA was determined from the IPCC's uncertainties guidance document, which determined the importance of identifying whether sources have polarizing ranges and/or outcomes of high and low consequence (Mastrandrea et al., 2010). For clarification, the Level of Agreement (LoA) equation that was used can be expressed below.

Equation 3. Level of Agreement (LoA) calculation.

$$Level\ of\ Agreement\ (LoA) = (RA * 10) + (D * 10) + (AQ * 30$$

The Risk Agreement (RA) score was calculated by identifying the maximum risk rating value as classified under each individual hazard or risk, represented as a proportional value. The maximum proportion was selected from the four risk rating categories; 'VERY HIGH' (50-36), 'HIGH' (35-25), 'MODERATE' (24-10), and 'UNDETECTABLE' (9-1). As a hypothetical example, a shipping risk observed 5 occurrences, two were identified as 'MODERATE' (scores; 25, 25) and three 'HIGH' (scores; 28, 28, 30) risk ratings. Since most of the values were considered 'HIGH', the risk agreement score was 12 (See equation 4). Equation 4 below expresses the calculations for the risk agreement score.

Equation 4. Risk Agreement (RA) calculation.

$$[\ RA\ (6)\ =\ \left(\frac{maximum\ value\ (3)}{total\ observed\ value\ (5)}\right) *\ 10\ ]$$

The RA score was further examined using risk distribution (D) to determine whether the observed risk rating scores were significantly different than each other. Risk distribution calculated the total quantity of observations expressed that are two or more categories away from each other (i.e. VERY HIGH-MODERATE (VH-M), VERY HIGH-UNDETECTABLE (VH-U), and HIGH-UNDETECTABLE (H-U)). For every hazard or risk variable that observed one of the following risk distribution possibilities, the D score was reduced by 25% as a means of deciphering between hazard and risk variables with similar or the same risk rating scores and those with varied risk ratings. If a hazard or risk had a risk rating score among all categories, the score was noted an automatic zero. For example, fictional hazard Y had risk rating scores of 50 (VH), 40 (VH), 30 (H), and 8 (U). This indicates fictional hazard Y satisfied the requirements for two of three possible distribution outcomes (VH-U, H-U) and accrued an overall score of 5. Equation 5 illustrates this calculation for the risk distribution score.

Equation 5. Risk Distribution (D) calculation.

$$[\ D\ (5)\ =(1-\left(\frac{[VH-M\ (0)]+[VH-U(1)]+[H-U(1)]+[sum=3(0)]}{total\ observed\ value\ (4)}\right)) *\ 10\ ]$$

The Agreement Quantity (AQ) was expressed as a set of two 'TRUE' or 'FALSE' functions. To ensure satisfaction of the first function, each hazard or risk received a minimum of three data observations to score 50%. To receive a perfect score, each hazard or risk inventoried had to be observed for a minimum of 5 data observations. The only assumption was that each hazard or risk had met a threshold to establish a statistically significant consensus. As a threshold has not been formally established in previous research scopes, it was determined that the odd values of 3 and 5 articles were to be sufficient. Any hazard or risk that received a score of 5 or above would account for 22% of all hazards and risks observed. This would allow for prioritizing hazards and risks that are more frequently observed than others. Other odd threshold values such as ‘7’ and ‘3’, were initially considered. However, implementing the value of ‘3’ would increase the total number of hazards and risks, satisfying the AQ to 40% of the dataset, hence notably mentioning the moderately studied hazards and risks. Since the total quantity of articles observed was 94, requiring ‘7’ articles to satisfy the requirement would account for 7.4% of all data observed. This was deemed too high, given this is a newly introduced method. Using the fictional example for hazard Y, four data observations were observed, satisfying the 50% threshold requirement for the AQ, though this did not meet the requirements for a perfect score. Overall, hazard Y received an AQ score of 15.

3.3.2.2.2 Evidence Scores

The evidence score combined four equally weighted indicators: evidence type, amount, consistency, and quality. All indicators that makeup the evidence score were multiplied by a score of 12.5, making them equally weighted. The evidence score was expressed in equation 6:

Equation 6. Evidence Score (ES) calculation.

$$Evidence\ Score\ (ES) = (T * 12.5) + (A * 12.5) + (C * 12.5) + (Q * 12.5)$$

Evidence Type (T) refers to the quantity of methods used to examine each hazard or risk in theoretical, observational, or hybrid studies. It is assumed that diversifying the types of evidence collected from studies reduced uncertainties surrounding theoretical versus operational hazards/risks. This is represented as a proportion through finding the quotient that counted the unique evidence-type values per hazard/risk divided by all options.

Evidence Amount (A) was a proportion-based indicator that observed the total observational quantity collected on a given hazard or risk divided by all data observations. This indicator created a normalized score, following suit with other methods of analysis within the research. A shortcoming to this metric is that this metric will generally score low, as most hazards and risks identified occur less than 25% within the dataset, possibly increasing the difficulty to receive a 'VERY HIGH' data quality score.

Evidence Consistency (C) used the coefficient of variation, utilizing an approach that standardizes the variability between the standard deviation and the mean of each hazard or risk observed (Toeh et al., 2017). Since this assessed the variability among a dataset in the form of a ratio, it cannot be used as means to construct a confidence interval (Mastrandrea et al., 2010; Toeh et al., 2017). This limitation is not applicable to this study as calculating the confidence interval is not within the scope (Mastrandrea et al., 2010; Toeh et al., 2017). When calculating the C value, the following equation (7) as seen below was used:

Equation 7. Evidence Consistency (C) calculation.

$$Evidence\ Consistency\ (C)\ = \frac{\sigma}{\mu}$$

The σ represented the standard deviation among each hazard or risks and μ the mean of each individual hazard or risk. To calculate this indicator, each data observation's risk rating score was utilized to find the standard deviation and the mean for each hazard or risk. Once found, the consistency score found the difference between 1 and the coefficient of variation, as seen in equation 7. This numeric value highlighted the percentage of consistency between the values of 0 (not consistent) to 1 (consistent). This was able to be later simplified during indicator weighting within the analysis. The coefficient of variation was chosen as the ideal metric to determine evidence consistency due to its interdisciplinary use within the field of social and natural sciences (Toeh et al., 2017). A similar study used the coefficient of variation as a means to measure the amplitude of shipping practices, such as hulling, by utilizing this metric in an inversed manner (Mastrandrea et al., 2010).

The final indicator used to calculate the evidence score calculator was the evidence quality (Q). Q observed the data availability used to complete the study and whether the data was mentioned as deficient. The availability of the data was an essential metric used to understand whether data can be easily obtained for use in a subsequent study regarding risk analysis or assessment. A known limitation to this metric was that many data deficiencies are not typically noted and expressed in detail within journal publications, as it can diminish the strength of the authors argument. Though, both pieces of data collected are important in determining the overall quality regarding the observed evidence.

3.4 Results and Discussion

Among all identified Arctic shipping variables, 55 (35.7%) were inventoried as hazards, including 2 that were classified as 'VERY HIGH' (Transportation of dangerous goods, multi-year sea ice) and 24 that were classified as a 'HIGH' via risk rating scores. Table 14 is a subset of all hazards inventoried, listing hazards via RR that were classified with 'HIGH' or 'VERY HIGH' data quality scores. Among all identified variables, 99 (64.3%) were identified as risks, including 3 classified as 'VERY HIGH' (community member displacement, hydrocarbon releases, and socioeconomic impacts on indigenous peoples), and 37 with 'HIGH' risk rating scores. Table 15 is a subset of all risks inventoried, listing risks via RR that were classified with ‘HIGH’ or ‘VERY HIGH’ data quality scores. Table 16 identified 41.6% of all thematic groups with a ‘HIGH’ RR score. Among groups with a ‘HIGH’ RR, 40% (two of five themes) were classified with a data quality score of ‘HIGH’ or ‘VERY HIGH’. A recommendation is to further investigate the root causes and interrelationships among the thematic groups: ‘Community’, ‘Pollutants’, ‘Sea Ice’, and ‘Social’. Among inventoried variables, 46% listed were classified as having a ‘VERY HIGH’ or ‘HIGH’ data quality score.

A total of 24 hazards were classified with a ‘VERY HIGH’ or ‘HIGH’ data quality score (55 were identified among all hazards). Two hazard variables were classified as ‘VERY HIGH’ RR scores, both observed with high agreement among data quality scores. ‘Transportation of dangerous goods’ and ‘Multi-year sea ice’ were hazard variables with the largest scores. Data quality scores that classified 53 hazard variables with a ‘VERY HIGH’ (DQ score >80%) score which accounted for 5.45% amongst all hazard variables (12.5% among selected hazards in Table 14). Similarly, the proportion of hazard variables also classified with a ‘VERY HIGH’ RR score was 3.6% of all hazard data (8.3% among hazards in Table 14).

Table 14 identifies all hazards classified as a ‘VERY HIGH’ or ‘HIGH’ data quality risk, listing rating scores from greatest to least. The transportation of dangerous goods within Arctic shipping operations has proven significant, as it is the number one hazard in the analysis. This hazard has a risk rating of 41.36 and a data quality score of 72.5%, showing that this is a likely hazard with evidence to back this claim. The transportation of dangerous goods hazard can be validated through numerous studies: the Arctic Council’s Expert Group on Black Carbon and Methane (2021) and Bard (1999) highlighted the connections this hazard has within other processes like exploitation and exploration of natural oil and gas reserves. Hazardous materials such as heavy fuel oil, natural gas, ammonia, and other dangerous chemicals are noted within Vorkamp and Rigét (2014) and Messener (2020). These studies suggest that toxic chemicals such as black carbon create negative health impacts and higher risks for oil spills and ecological damages to occur (Messener, 2020; Bard; 1999).

Table 14. Comprehensive list of all hazards inventoried that are classified as 'VERY HIGH' and 'HIGH' data quality scores and organized via greatest to least using RR scores.

Thematic Group	Hazard Name	RR Index	RR Score	DQ Index	DQ Description	DQ Score
Operational	Transportation of dangerous goods	**VERY HIGH**	**41.36**	HIGH	High agreement, Medium evidence	72.5%
Sea Ice	Multi-year sea ice presence	**VERY HIGH**	**36.31**	VERY HIGH	High agreement, Robust evidence	80.5%
Pollutants	Air emissions (combustion)	**HIGH**	**35.54**	VERY HIGH	High agreement, Medium evidence	80.1%
Pollutants	HFO carriage and transport	**HIGH**	**35.00**	HIGH	High agreement, Medium evidence	66.1%
Navigational	Navigational obstacles	**HIGH**	**30.40**	HIGH	High agreement, Medium evidence	68.3%
Sea Ice	Sea ice melt	**HIGH**	**30.05**	HIGH	High agreement, Robust evidence	78.1%
Navigational	Operating in shallow waters	**HIGH**	**28.88**	VERY HIGH	High agreement, Robust evidence	81.0%
Environmental	Climate fluctuation	**HIGH**	**28.16**	HIGH	High agreement, Medium evidence	79.2%
Operational	Fire onboard	**HIGH**	**27.75**	HIGH	Medium agreement, Medium evidence	60.9%
Sea Ice	Sea ice concentration	**HIGH**	**27.26**	HIGH	High agreement, Robust evidence	69.6%
Environmental	Extreme winter conditions	**HIGH**	**26.83**	HIGH	High agreement, Medium evidence	63.7%
Environmental	Severe weather	**HIGH**	**26.58**	HIGH	High agreement, Medium evidence	67.6%
Environmental	Low air temperature	**HIGH**	**26.25**	HIGH	Medium agreement, Medium evidence	61.3%
Environmental	Remoteness	**HIGH**	**25.94**	HIGH	High agreement, Medium evidence	67.5%
Operational	Crew inexperience	MODERATE	**24.57**	HIGH	High agreement, Medium evidence	70.8%
Technological	Navigational aids failure or error	MODERATE	**23.59**	HIGH	High agreement, Medium evidence	65.7%
Navigational	Ship speeding	MODERATE	**22.86**	HIGH	High agreement, Medium evidence	78.2%
Environmental	Low visibility	MODERATE	**22.69**	HIGH	High agreement, Medium evidence	73.6%
Human	Human error	MODERATE	**22.40**	HIGH	High agreement, Medium evidence	66.7%
Environmental	Bioaccumulation - flora/fauna	MODERATE	**21.84**	HIGH	High agreement, Medium evidence	67.1%
Environmental	High wind speeds	MODERATE	**20.63**	HIGH	High agreement, Medium evidence	72.8%
Operational	Excessive ice accumulation on vessels	MODERATE	**19.76**	HIGH	High agreement, Medium evidence	70.2%
Operational	Mechanical failure	MODERATE	**19.60**	HIGH	High agreement, Medium evidence	73.9%
Environmental	Sea conditions	MODERATE	**19.00**	HIGH	High agreement, Medium evidence	68.0%

Priority hazards that are recommended for further investigation follow the thematic trend of emitting pollution to the environment and the reduction or change in sea ice extent. Transportation of dangerous goods (RR: 41.36) is seen as a high priority hazard and has been observed being correlated with risks such as HFO carriage and transport, operational discharges, and black carbon emissions (Comer et al., 2017; Vorkamp & Rigét, 2014). All these hazards are created and perpetuated due to increased vessel activity that is occurring within Arctic waters (Comer et al., 2017; Vorkamp & Rigét, 2014).

Risk variables were observed more frequently than hazards, 47 risk variables were classified as 'VERY HIGH' or 'HIGH' data quality scores (99 identified among all risks). Three risk variables (3% of all identified risks) were categorized with a 'VERY HIGH' RR score, though one variable had a 'MODERATE' DQ score ('Hydrocarbon release') while the other variables ('Community member displacement' and 'Socioeconomic impacts to indigenous peoples') were classified as 'LOW' data quality due to limited evidence and low agreement. 'Lack of Inuit agency (33.0)', 'Degradation of indigenous cultural and natural resources (32.8)', and 'Reduction in resources to locals (32.0)' were risk variables with the largest scores affiliated with community-based concerns. Data quality scores classified as 'VERY HIGH' (DQ score >80%) accounted for 1.1% of all risk variables (2.7% among selected risks as seen in Table 15). Table 15 depicts a comprehensive list of inventoried risk variables classified as a 'VERY HIGH' or 'HIGH' data quality, listed from greatest to least via RR score.

Table 15. Comprehensive list of all risks inventoried that are classified as 'VERY HIGH' and 'HIGH' data quality scores and organized via greatest to least using RR scores.

Thematic Group	Risk Name	RR Index	RR Score	DQ Index	DQ Description	DQ Score
Environmental	Operational discharges	**HIGH**	**33.40**	HIGH	High agreement, Medium evidence	76.0%
Community	Lack of Inuit agency	**HIGH**	**33.00**	HIGH	High agreement, Medium evidence	64.8%
Community	Degradation of indigenous cultural and natural resources	**HIGH**	**32.80**	HIGH	High agreement, Medium evidence	73.2%
Environmental	Underwater noise pollution	**HIGH**	**32.55**	HIGH	High agreement, Medium evidence	66.8%
Social	Reduction in resources to locals	**HIGH**	**32.00**	HIGH	Medium agreement, Medium evidence	60.1%
Community	Lack of support for indigenous communities	**HIGH**	**31.50**	HIGH	Medium agreement, Medium evidence	60.3%
Pollutants	Black carbon air emissions	**HIGH**	**31.23**	HIGH	High agreement, Medium evidence	73.8%
Environmental	Exploitation of natural reserves	**HIGH**	**30.56**	HIGH	High agreement, Medium evidence	75.8%
Economic	Oil spill clean-up costs	**HIGH**	**29.88**	HIGH	High agreement, Medium evidence	68.8%

Thematic Group	Risk Name	RR Index	RR Score	DQ Index	DQ Description	DQ Score
Environmental	Travelling through marine protected areas	**HIGH**	**29.06**	HIGH	High agreement, Medium evidence	64.8%
Operational	Reduced search and rescue capacity	**HIGH**	**29.01**	HIGH	High agreement, Medium evidence	72.9%
Social	Lacking shipping infrastructure and services	**HIGH**	**28.00**	HIGH	High agreement, Medium evidence	73.4%
Environmental	Reduced ecosystem recovery time	**HIGH**	**28.00**	HIGH	High agreement, Medium evidence	68.4%
Political	Sovereignty claims and disputes	**HIGH**	**27.08**	HIGH	High agreement, Medium evidence	74.7%
Sea Ice	Sea ice (generalized)	**HIGH**	**26.51**	HIGH	High agreement, Medium evidence	69.1%
Environmental	Animal disturbance	**HIGH**	**26.25**	HIGH	High agreement, Medium evidence	71.0%
Environmental	Remoteness	**HIGH**	**25.94**	HIGH	High agreement, Medium evidence	67.5%
Economic	Variable insurance costs	**HIGH**	**25.78**	HIGH	High agreement, Medium evidence	68.2%
Pollutants	BC Climate Forcing	**HIGH**	**25.60**	HIGH	High agreement, Medium evidence	68.2%
Political	Enforceability and accountability limitations regarding laws/regulations	**HIGH**	**25.33**	HIGH	High agreement, Medium evidence	73.4%
Environmental	Introduction of invasive species	**HIGH**	**25.33**	HIGH	High agreement, Medium evidence	75.4%
Pollutants	Oil spill (HFO)	MODERATE	24.92	HIGH	High agreement, Medium evidence	63.5%
Assessment	Lack of risk analysis	MODERATE	24.84	HIGH	High agreement, Medium evidence	75.0%
Navigational	Vessel traffic congestion	MODERATE	24.69	HIGH	High agreement, Medium evidence	63.9%
Navigational	Traffic intensification	MODERATE	24.36	HIGH	High agreement, Medium evidence	74.5%
Economic	Variable profit margins	MODERATE	24.00	HIGH	High agreement, Medium evidence	76.9%
Social	Increased tourism	MODERATE	24.00	HIGH	High agreement, Medium evidence	72.4%
Economic	Cargo volume intensification	MODERATE	24.00	HIGH	Medium agreement, Medium evidence	61.5%
Assessment	Lacking modelling	MODERATE	23.83	HIGH	High agreement, Medium evidence	73.9%
Navigational	Lacking navigation tools	MODERATE	23.63	HIGH	High agreement, Medium evidence	75.7%
Political	Lack of clear policy and/or regulations	MODERATE	23.08	HIGH	High agreement, Medium evidence	70.0%
Social	Rapid tourism growth	MODERATE	23.00	HIGH	High agreement, Medium evidence	76.1%
Assessment	Lack of data	MODERATE	22.50	HIGH	High agreement, Medium evidence	79.4%
Operational	Lack of emergency planning	MODERATE	21.22	HIGH	High agreement, Medium evidence	70.8%
Political	Competing global interests	MODERATE	21.14	HIGH	High agreement, Medium evidence	72.1%
Operational	Lack of monitoring capabilities	MODERATE	21.08	HIGH	High agreement, Medium evidence	72.5%
Technological	Lacking technological advances	MODERATE	20.80	HIGH	High agreement, Medium evidence	72.7%
Navigational	Vessel accident (generalized)	MODERATE	20.60	HIGH	High agreement, Medium evidence	73.0%
Economic	Fluctuation in shipping cost	MODERATE	19.63	HIGH	High agreement, Medium evidence	78.3%
Political	Complex regulations	MODERATE	19.57	VERY HIGH	High agreement, Medium evidence	81.4%
Navigational	Iceberg collision	MODERATE	19.39	HIGH	High agreement, Medium evidence	77.6%
Navigational	Sinking vessel	MODERATE	18.67	HIGH	High agreement, Medium evidence	63.5%
Navigational	Vessel grounding	MODERATE	18.20	HIGH	High agreement, Medium evidence	69.1%
Operational	Poor communication between vessels	MODERATE	17.84	HIGH	High agreement, Medium evidence	73.1%
Navigational	Vessel-vessel collision	MODERATE	17.33	HIGH	High agreement, Medium evidence	73.8%
Political	Insufficient Arctic shipping jurisdiction	MODERATE	17.33	HIGH	High agreement, Medium evidence	69.5%
Navigational	Ship stuck in ice	MODERATE	15.89	HIGH	High agreement, Medium evidence	77.0%
Political	Trading implications/competitions	MODERATE	15.00	HIGH	High agreement, Medium evidence	65.3%

Risks identified with the highest risk rating scores all pertain to indigenous and community-based concerns (lack of Inuit agency, degradation of indigenous cultural and natural resources, reductions in local resources, and lack of support for indigenous communities). These concerns can be further validated through sources such as Boylan (2021) and Bennett et al. (2020), highlighting the disadvantages northern communities face regarding implementing and advocating for stronger policies within Arctic environments. This causes indirect implications to local resource supply and infrastructure opportunities (Boylan, 2021). This study's findings also reiterate the importance for further investigation of the economic benefits to local communities stemming from the tourism industry (Olsen et al., 2019; Johnston et al., 2017). As tourism overcrowding and inappropriate tourism behaviour can also pose threats to indigenous communities' culture and resources, this needs to be further validated through additional studies (Johnston et al., 2017).

Initially, 10 categories were selected as thematic groups prior to the completion of the FMECA. Two additional categories (operational and sea ice) were created due to the significant discrepancies of issues within each thematic group, while also providing sufficient data quantities for each group. These additional groups were created to separate environmental and sea ice specific patterns as well as operational and navigational hazards and risks. The environmental thematic group was separated due to the surplus of sea ice-specific hazards and risks noted during the FMECA analysis, after further consideration, sea ice hazards and risks calculated a higher risk rating scores on average. It was also decided that operational and navigational hazards and risks were increasingly unique from each other and was apparent in the FMECA analysis. Operational variables primarily focused on the ship operations and problematic behaviours/event aboard whereas navigational variables solely focused on the variables that influenced ship travel. As a result of this reclassification of thematic groups, four groups were classified with 'HIGH' data quality scores (25%). One thematic group (8.3%)

accumulated a data quality score less than 50%, ‘Human’ (48.2%). Thematic groups with ‘HIGH’ RR scores account for 41.67% of all categories; where the ‘Community’ (32.06), ‘Pollutants’ (29.383), and ‘Sea Ice’ (29.376) groups were identified as the highest risks. Table 16 identifies all thematic groups listed from greatest risk rating score to least.

The sea ice category received the third highest risk rating score overall and had the highest data quality index score (64.9%). The study findings further validate previous research, which highlights the significant implications sea ice has on navigability, accessibility, and overall concern regarding Arctic shipping operations (Ho, 2010; Chircop, 2009; Jensen, 2008). A study by Pizzolato et al. (2016) and Howell et al. (2022) highlights how the decline in sea ice concentration is perpetuating and intensifying other listed hazards to occur. This creates conditions that increase navigability into the NWP, increasing shipping season length, and decreased, unpredictable challenges to mobility within northern communities. As stated within an article by Stewart et al. (2013) and Copland et al. (2021), sea ice is important for the mobility of northern communities to hunt species during colder months.

Table 16. List of all thematic groups that include RR scores, indices, and data quality values.

Thematic Group	RR Index	RR Score	DQ Index	DQ Description	DQ Score
Community	**HIGH**	**32.061**	MODERATE	Medium agreement, Medium evidence	50.1%
Pollutants	**HIGH**	**29.383**	MODERATE	Medium agreement, Medium evidence	57.0%
Sea Ice	**HIGH**	**29.376**	HIGH	High agreement, Medium evidence	64.9%
Environmental	**HIGH**	**26.374**	HIGH	High agreement, Medium evidence	60.7%
Social	**HIGH**	**26.116**	MODERATE	Medium agreement, Medium evidence	54.5%
Economic	MODERATE	24.623	MODERATE	High agreement, Medium evidence	60.0%
Operational	MODERATE	23.394	MODERATE	Medium agreement, Medium evidence	55.1%
Assessment	MODERATE	22.948	MODERATE	Medium agreement, Medium evidence	58.2%
Navigational	MODERATE	22.143	HIGH	High agreement, Medium evidence	60.4%
Human	MODERATE	21.755	MODERATE	Medium agreement, Medium evidence	48.2%
Political	MODERATE	21.379	HIGH	High agreement, Medium evidence	62.5%
Technological	MODERATE	21.233	MODERATE	Medium agreement, Medium evidence	56.8%

3.5 Conclusions

Maritime Ship operations within the Arctic are complex and intricate in nature. Numerous studies are required to determine the full extent of how hazards and risks influence each other. These assessments will allow for a thorough analysis of their associated consequences and level of frequency regarding both hazards and risks. A total of 94 data observations identified a total of 154 hazards and risks regarding maritime ship operations within the Arctic. From the 154 identified, 99 (64.3% of total) have been identified as risks, including 3 being identified as 'VERY HIGH' and 37 labelled as 'HIGH' risk ratings. Also, 55 (35.7% of total) were identified as hazards, including 2 were identified as 'VERY HIGH' and 24 labelled as 'HIGH' risk ratings. Data quality scores indicated that 46% is considered 'VERY HIGH' or 'HIGH' data quality status. Community (32.06), pollutant (29.38), and sea ice (29.37) thematic groups obtained the highest risk ratings within the analysis and are recommended for prioritization in future risk assessments. Though, a total of 5 out of 12 thematic groups were identified as high risk, two (environmental, sea ice) of which assumed 'HIGH' data quality scores respectively.

To understand hazards and risks in Arctic Canada, the following are areas of future focus that are recommended for further exploration: 1) completion of a spatial analysis to identify important nodes, vessel routes, and points of interest within Arctic Canada. This can be completed using Automatic Identification System (AIS) data via ArcGIS and a reliability-centred maintenance analysis to determine important nodes and routes through the Arctic, aiding the creation of Vessel Operational Spatial Tracts. The completion of an AIS-based spatial analysis using ArcGIS for Canadian migratory patterns of species at-risk that migrate through, breed, feed, and/or reside among the Arctic would be beneficial. The implementation of a comprehensive risk assessment and spatial analysis of present-day Arctic shipping-specific hazards and risks will allow researchers to visualize where risks are most prevalent in Arctic

Canada. Both recommended assessments will pose as an introduction in examining the relationships amongst hazards and risks more thoroughly. Determining where hazards and risks are situated spatially, in conjunction with their severity, may aid in the prioritization of funding for conservation, development, and enforcement in hopes of mitigating priority risks. This can also lead to the development of tools that can predict risk severity based on ecological and climate indicators that can be used in Polar regions for ship operations.

3.6 References cited in Chapter 3

Afenyo, M., Khan, F., Veitch, B., & Yang, M. (2017). Arctic shipping accident scenario analysis using Bayesian network approach. *Ocean Engineering, 133*, 224–230. https://doi.org/10.1016/j.oceaneng.2017.02.002

Akbayirli, K., & Tuna, O. (2022). How do practitioners view arctic shipping routes? A cognitive appraisal approach. *Transportation Research Part D: Transport and Environment, 110, 103432*. https://doi.org/10.1016/j.trd.2022.103432

Arctic Council. (2021). Expert Group on Black Carbon and Methane–3rd Summary of Progress and Recommendations. Arctic Council: Tromsø, Norway.

Bard, S. M. (1999). Global transport of anthropogenic contaminants and the consequences for the arctic marine ecosystem. *Marine Pollution Bulletin, 38(5*), 356–379. https://doi.org/10.1016/s0025-326x(99)00041-7

Baylis, P., Obradovich, N., Kryvasheyeu, Y., Chen, H., Coviello, L., Moro, E., Cebrian, M., & Fowler, J. H. (2018). Weather impacts expressed sentiment. PLOS ONE, 13(4). https://doi.org/10.1371/journal.pone.0195750

Bennett, N., Schuhbauer, A., Skerritt, D., & Ebrahim, N. (2021). Socio-Economic Monitoring and Evaluation in Fisheries. *Fisheries Research, 239*, 105934. https://doi.org/10.1016/j.fishres.2021.105934

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

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

Chen, J.-L., Kang, S.-C., Guo, J.-M., Xu, M., & Zhang, Z.-M. (2021). Variation of sea ice and perspectives of the Northwest Passage in the Arctic Ocean. *Advances in Climate Change Research, 12(4),* 447–455. https://doi.org/10.1016/j.accre.2021.02.002

Chircop, A. (2009). The growth of international shipping in the Arctic: Is a regulatory review timely? *The International Journal of Marine and Coastal Law, 24(2), 355–380*. https://doi.org/10.1163/157180809x421699

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017). Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025. Washington DC, *International Council on Clean Transportation*. DOI: http://dx.doi.org/10.25607/OBP-1733

Conachey, R., & Montgomery, R. (2005, October). Development of machinery survey requirements based on reliability-centered maintenance. In SNAME Maritime Convention. OnePetro.

Conrow, E. (2003). Effective risk management: Some keys to Success. American Institute of Aeronautics and Astronautics.

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

Ehlers, S., Kujala, P., Veitch, B., Khan, F., & Vanhatalo, J. (2014). Scenario based risk management for Arctic Shipping and Operations. *Polar and Arctic Science and Technology, 10*. https://doi.org/10.1115/omae2014-23112

Fu, S., Zhang, Y., Zhang, M., Han, B., & Wu, Z. (2023). An object-oriented Bayesian network model for the quantitative risk assessment of navigational accidents in ice-covered Arctic Waters. *Reliability Engineering & System Safety, 238,* 109459. https://doi.org/10.1016/j.ress.2023.109459

Fu, S., Yu, Y., Chen, J., Xi, Y., & Zhang, M. (2022). A framework for quantitative analysis of the causation of grounding accidents in Arctic shipping. *Reliability Engineering & System Safety, 226,* 108706. https://doi.org/10.1016/j.ress.2022.108706

Ghosh, S., and Rubly, C. (2015). The emergence of Arctic shipping: Issues, threats, costs, and risk-mitigating strategies of the Polar Code. A*ustralian Journal of Maritime & Ocean Affairs,* 7(3), 171–182. https://doi.org/10.1080/18366503.2015.1093695

Gross, M. (2018). Arctic shipping threatens wildlife. *Current Biology, 28(15)*. https://doi.org/10.1016/j.cub.2018.07.053

Halliday, W., & Dawson, J. (2021). Ship-Source Noise Modeling from 2015-2018 in the Kitikmeot Region and Lancaster Sound (Northwest Passage), Nunavut. http://hdl.handle.net/10393/41926

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

Ho, J. (2010). The implications of Arctic sea ice decline on shipping. *Marine Policy, 34(3), 713–715*. https://doi.org/10.1016/j.marpol.2009.10.009

International Maritime Organization (IMO). (2020). International Code for Ships Operating in Polar Waters (Polar Code). International Maritime Organization. Retrieved February 2023, from https://www.imo.org/en/OurWork/Safety/Pages/polar-code.aspx

International Maritime Organization (IMO). (2018, April 9). REVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA). International Maritime Organization (IMO). Retrieved February 2023, from https://www.imo.org/en/OurWork/Circulars/Pages/default.aspx

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. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562, doi:10.1017/9781009157940.008.

International Organization for Standardization (ISO). (2018). Risk Management - Guidelines (ISO 31010:2009). Retrieved from: https://shahrdevelopment.ir/wp-content/uploads/2020/03/ISO-31000.pdf

International Organization for Standardization (ISO). (2009a). Risk Management - Vocabulary (ISO Guide 73:2009). Retrieved from: https://www.iso.org/obp/ui/#iso:std:iso:guide:73:ed-1:v1:en:term

International Organization for Standardization (ISO). (2009b). Risk Management - Risk Assessment Techniques (IEC/FDIS 31010:2009). Retrieved from: https://bambangkesit.files.wordpress.com/2015/12/iso-31010_risk-management-risk-assessment-techniques.pdf

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

Jing, D., Dai, L., Hu, H., Ding, W., Wang, Y., & Zhou, X. (2021). CO2 emission projection for Arctic Shipping: A system dynamics approach. *Ocean & Coastal Management, 205*, 105531. https://doi.org/10.1016/j.ocecoaman.2021.105531

Johnston, M., Dawson, J., & Maher, P. (2017). Strategic development challenges in marine tourism in Nunavut. *Resources, 6(3),* 25. https://doi.org/10.3390/resources6030025

Lancaster, M. L., Winsor, P., & Dumbrille, A. (2021). Underwater noise from shipping: A special case for the Arctic. *Sustainability in the Maritime Domain*, 271–289. https://doi.org/10.1007/978-3-030-69325-1_14

Liang, Y., Yin, J., Pan, B., Chi, G., & Andris, C. (2020, June 7). Understanding Demographics and Experience of Tourists in Yellowstone National Park through Social Media. University of Massachusetts Amherst. Retrieved January 2022, from https://scholarworks.umass.edu/cgi/viewcontent.cgi?article=2559&context=ttra

Mastrandrea, M., Field, C., Stocker, T., Edenhofer, O., Ebi, K., Frame, D., Held, H., Kriegler, E., Mach, K., Matschoss, P., Plattner, G.-K., Yohe, G., & Zwiers, F. (2010). Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of

Uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at <http://www.ipcc.ch>.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M.M.C. , Ottersen, G., Pritchard, H., and Schuur, E. (2019). Polar Regions. *In: 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, pp. 203-320. https://doi.org/10.1017/9781009157964.005.

Messner, S. (2020). Future arctic shipping, black carbon emissions, and climate change. *Maritime Transport and Regional Sustainability, 195–208*. https://doi.org/10.1016/b978-0-12-819134-7.00012-5

Mousavi, M., Ghazi, I., and Omaraee, B. (2017). Risk assessment in the Maritime Industry. Engineering, Technology & Applied Science Research, 7(1), 1377–1381. https://doi.org/10.48084/etasr.836

Mullen, L., Benoit, K., Keyes, O., Selivanov, D., & Arnold, J. (2018). Fast, consistent tokenization of natural language text. Journal of Open Source Software, 3(23), 655. https://doi.org/10.21105/joss.00655

Mudryk, L., Dawson, J., Howell, S., Derksen, C., Zagon, T., & Brady, M. (2021). Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change, 11(8),* 673–679. https://doi.org/10.1038/s41558-021-01087-6

Olsen, J., Carter, N., & Dawson, J. (2019). Community perspectives on the environmental impacts of arctic shipping: Case studies from Russia, Norway, and Canada. *Cogent Social Sciences, 5(1*). https://doi.org/10.1080/23311886.2019.1609189

Peeters, W., & Peng, Z. (2015). An Approach Towards Global Standardization of the Risk Matrix. Journal of Space Safety Engineering, 2(1), 31–38. https://doi.org/10.1016/s2468-8967(16)30037-4

Pizzolato, L., Howell, S., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophysical Research Letters, 43(23)*. https://doi.org/10.1002/2016gl071489

Qian, H., Zhang, R., & Zhang, Y. (2020). Dynamic Risk Assessment of natural environment based on dynamic Bayesian network for key nodes of the Arctic Northwest Passage. *Ocean Engineering*, 203, 107205. https://doi.org/10.1016/j.oceaneng.2020.107205

Somanathan, S., Flynn, P., & Szymanski, J. (2009). The northwest passage: A simulation. *Transportation Research Part A: Policy and Practice, 43(2)*, 127–135. https://doi.org/10.1016/j.tra.2008.08.001

Somanathan, S., Flynn, P. C., and Szymanski, J. K. (2007). Feasibility of a sea route through the Canadian Arctic. *Maritime Economics & Logistics*, *9(4)*, 324–334. https://doi.org/10.1057/palgrave.mel.9100185

Suominen, M., & Kujala, P. (2014). Variation in short-term ice-induced load amplitudes on a ship's hull and related probability distributions. *Cold Regions Science and Technology, 106–107,* 131–140. https://doi.org/10.1016/j.coldregions.2014.07.001

Stevens, H. R., Graham, P. L., Beggs, P. J., & Hanigan, I. C. (2020). In cold weather we bark, but in hot weather we bite: Patterns in social media anger, aggressive behavior, and temperature. Environment and Behavior, 53(7), 787–805. https://doi.org/10.1177/0013916520937455

Stewart, E., Dawson, J., Howell, S., Johnston, M., Pearce, T., and 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. https://doi.org/10.1080/1088937x.2012.705352

Teoh, W., Khoo, M., Castagliola, P., Yeong, W., & Teh, S. (2017). Run-sum control charts for monitoring the coefficient of variation. *European Journal of Operational Research, 257(1),* 144–158. https://doi.org/10.1016/j.ejor.2016.08.067

Vorkamp, K., & Rigét, F. (2014). A review of new and current-use contaminants in the Arctic environment: Evidence of long-range transport and indications of bioaccumulation. *Chemosphere, 111*, 379–395. https://doi.org/10.1016/j.chemosphere.2014.04.019

Wang, J., Obradovich, N., & Zheng, S. (2020). A 43-million-person investigation into weather and expressed sentiment in a changing climate. One Earth, 2(6), 568–577. https://doi.org/10.1016/j.oneear.2020.05.016

Würsig, B., & Koski, W. (2021). Natural and potentially disturbed behavior of Bowhead Whales. *The Bowhead Whale, 339–363*. https://doi.org/10.1016/b978-0-12-818969-6.00023-6

Zhang, M., Zhang, D., Zhang, C., & Cao, W. (2020). Navigational risk factor analysis of Arctic shipping in ice-covered waters. *Maritime Transport and Regional Sustainability, 153–177*. https://doi.org/10.1016/b978-0-12-819134-7.00010-1

Zhou, X. (2022). A comprehensive framework for assessing navigation risk and deploying maritime emergency resources in the South China Sea. *Ocean Engineering, 248,* 110797. https://doi.org/10.1016/j.oceaneng.2022.110797

Chapter 4: Discussion and Conclusions

4.1 Discussion

4.1.1 Responding to Research Objectives

4.1.1.1 Comprehensive inventory of (a) hazards and (b) risks impacting Arctic shipping

Creating a comprehensive inventory of Arctic shipping hazards was facilitated using natural language processing in the FMECA analysis. *Chapter 2* highlights the methodology and how word frequency and word association analysis were used together to identify common trends among data sources and to validate them through associated words. Word frequency and association examination enabled us to depict micro-level conversations connecting previous research findings with highly used words and associated terms in the study. For example, ‘ice’ was the most frequently used word among all data sources. This term was correlated with terms such as 'sea,' 'melt,' 'multi-year,' and 'iceberg.' Understanding the general context of sea ice implications allowed us to identify hazards using literature depicted from the frequently used terminology. This created a preliminary list of hazards and risks used as keywords to identify peer-reviewed publications within *Chapter 3*, the comprehensive risk analysis.

Hazards were primarily identified within *Chapter 2*, and their corresponding information was validated and expanded upon within the FMECA analysis within *Chapter 3*. Among 94 peer-reviewed journal articles, a manual literature review identified 154 variables (55 hazards and 99 risks). During this step, information such as data quality, hazard and risk description, consequence, probability of occurrence, control mechanisms, and impacts were collected to understand the full extent of each hazard and risk identified. Hazards and risks that could be identified among numerous data sources were seen with a more holistic and fulsome analysis. In contrast, variables with limited data did not have complete controls, causes, and consequences. This is primarily due to the author's chosen scope of research, which limits the amount of information presented and extracted. Various authors articulated the most significant hazards and risks in-depth, often overlooking other hazards in the analysis. Some hazards and risks are not expanded upon and linked to others regarding control mechanisms and impacts. Most articles selected needed information for all metrics within the FMECA analysis and were left unanswered. However, most hazards and risks identified accumulate more than one observation, decreasing the odds of having incomplete data for an identified hazard or risk. To view a blank FMECA analysis worksheet, please see Appendix 6. To view a completed list of inventoried hazards (Appendix 8) and risks (Appendix 7), please refer to the Appendix.

A similar process for risk identification was followed to obtain a list of inventoried comprehensive risks among Arctic shipping processes. It was increasingly difficult to identify risks within the comprehensive content analysis rather than the formalized risk analysis. This is primarily because many identified risk variables required more information to confirm the variable was correct. As many factors influence the shape of a risk variable, this made it increasingly difficult to utilize word frequency and correlation analysis to pinpoint exact risks. Since hazards were easily identified in a simplistic sense, hazards required less explanation and could be easily identified via key words and phrases. This process resulted in more risks being identified during the FMECA analysis, where risks were explained more thoroughly. A total of 99 unique risks were identified in this research. The risks observing the highest risk rating scores were community-based (community member displacement, socioeconomic impacts on indigenous peoples, cultural and archaeological threats). The findings from Johnston et al. (2017) complement the completed risk analysis as they utilized northern community members' perspectives to illustrate the consequences, severity, and frequency of Arctic shipping operations at the community level.

4.1.1.2 Classification and synthesis of individual hazard and risk information into thematic groups

To effectively synthesize individual and thematic group hazards and risks, this was completed after all information from the FMECA analysis was completed. Hazards and risks were initially synthesized individually, comparing findings among data sources. Hazards and risks were separated into ten thematic groups, as outlined in *Chapter 2*. When completing this step, two conflicting factors existed within the navigational thematic group. As this bin was to be utilized for all navigational hazards and risks, it also became a host for all vessel-specific operational risks. As a result of this, the category was divided into two new categories: a category was created that focused on navigational hazards and risks, whereas the other new category focused on hazards and risks that occurred due to vessel operations. This clarification was also apparent in studies such as Fu et al. (2023) and Afenyo et al. (2017), highlighting the distinct differences between these types of hazards when completing each risk assessment. For instance, a navigational risk may include 'Deviation from the suggested route' whereas an operational risk may include a 'Hull failure.'

The study prioritized separating sea ice and other environmental hazards and risks. This decision was made because sea ice has been researched extensively, observing iceberg presence, sea ice melting patterns, spatial patterns, and distribution of multi-year and first-year sea ice. Studies such as Copland et al. (2021), Zhang et al. (2020), and Pizzolato et al. (2016) highlight the severity and significance sea ice presence has on navigation throughout Arctic Canada. As a result, other environmental hazards and risk factors were deemed appropriate for placing them into a separate category. Creating an environmental category encompassing all issues would have needed to be narrower and easier to understand the trends within the metadata during a risk assessment. Also, many articles identified the severity and historical risks of the presence of sea ice during shipping operations. Similar findings resulted from

Chapter 2 that are related to the study by Akbayirli and Tuna (2022), where they examined social media data (X and LinkedIn) to identify critical thematic groups among Arctic shipping hazards and risks. The findings from Akbayirli & Tuna are consistent with the word patterns seen within the content analysis, identifying themes such as the 'environment,' 'policy,' 'navigational,' and 'economic' that were of importance through the analysis (Akbayirli & Tuna, 2022).

These thematic groups were initially deemed sufficient until the FMECA analysis was underway, where it was realized many of the hazard and risk variables within the environmental and navigational thematic groups received conflicting scores. There was notable trend towards navigational hazards and risks appearing as an operational concern. Since these two distinct categories were creating varied results, navigational risks were separated into two categories, operational and navigation, to avoid misinterpretation and skewing of the data. A study by Fu et al. (2023) also indicates the discrete differences between navigational and operational risks. The research states that navigational risks are more closely and directly related to environmental hazards and risks, whereas operational risks are related to human behaviour and vessel practices. Similar studies such as Fu et al. (2023) and Zhou (2022) have effectively utilized binning recognized risks into categories to identify broader data trends among alike individual hazards. Since these studies typically identify hazards within one thematic group, these bins breakdown topics such as the environment into smaller categories (i.e. Environment – Topographic, Weather-based, and Anthropocentric) (Zhou, 2022).

Table 17. List of thematic group general information.

Thematic Group Name	***TOTAL***	**No. inventoried hazards**	**No. inventoried risks**
Assessment	***7***	0	7
Community	***10***	0	10
Economic	***9***	0	9
Environmental	***26***	18	8
Human	***6***	4	2
Navigational	***24***	12	12
Operational	***25***	10	15
Political	***11***	0	11
Pollutants	***13***	13	0
Sea Ice	***7***	6	1
Social	***11***	5	6
Technological	**5**	2	3

Table 17 illustrates the sum of hazards and risks identified as per their categorized thematic group. This table also indicates how many hazards and risks were affiliated with each thematic group while also providing the entire sum. Environmental (26), operational (25), and navigational (24) categories were seen being inventoried the most frequently. Environmental and climate-based variables were typically identified as hazards, as most variables were climate-focused and could possibly implicate other human-created processes or risks. Operational variables were typically observed because of human practices or processes occurring, therefore being identified as risks. Navigational variables were inventoried equally among hazards and risks. This is expected to be due to some perpetuated human processes, such as crew inexperience, being identified as a hazard due to the implications it may have on other human-induced processes or systems. For more information regarding thematic group risk rating scores, please see Appendix 9.

4.1.1.3 Establishing risk rating scores among inventoried hazards, risks, and groups

Risk rating scores were calculated once all FMECA analysis data regarding hazard and risk consequence and probability was collected. Specific text from each peer-reviewed journal article was directly quoted within each consequence and probability section. This was to ensure all scores had a specific reference to justify the chosen score. Once all individual consequences and probability scores was calculated, the product of each score was determined by multiplying the quantitative probability and consequence scores, which created the risk rating score for every individual hazard and risk. These scores were then averaged to create individual hazard and risk rating scores. Subsequently, the average individual hazard and risk rating scores were calculated to determine each thematic group's risk rating. The exact process was calculated for data quality scores at the individual and category levels.

Once risk rating and data quality scores were calculated, emerging trends were identified among more frequently used hazards and risks. Hazards and risks with higher data observations also typically had higher data quality scores for level of evidence. Although, the Level of Agreement scores did not necessarily correlate with the quantity of evidence observed. The increased data quantity created difficulties in reaching a unanimous consensus among hazard and risk observations, specifically when comparing studies that examined theoretical probability versus observational probabilities. This can be validated through numerous risk assessments by Fu et al. (2023), Afenyo et al. (2021), Peeters & Peng (2015) and highlighting the difficulty of finding a comprehensive consensus among numerous studies surrounding the economic viability of the Northwest Passage (NWP).

Not only does data observation impact data quality ratings, but it also indicates the discrepancies between theoretical and observational studies. Hazards and risks identified in a theoretical publication often observe probability and consequences scoring in the worst-case scenario. Theoretical studies typically evaluate probability based on the likelihood of occurrence in a spatial sense, identifying whether a hazard or risk is present throughout a trip. On the other hand, observational studies use real-time data observations to evaluate the probability of a hazard or risk occurring. For example, when calculating the vessel-vessel collisions through an observational study, the noted probability within a study by Fu et al. (2023) is considered 'rare', occurring less than 20% of the time. A theoretical study by Ho (2010) examines that the risk of vessel-vessel collision is present 100% of the voyage, therefore being classified as an 'Almost certain' probability. The discrepancies noted in the example above highlight the complexity of this issue and the struggle of assessing theoretical and operational studies together. The perspectives researchers use when identifying hazard and risk information can be influenced by the author's verbiage and can contradict one another, creating inconsistent data quality.

Figure 9 depicts a boxplot distribution of thematic groups' risk rating scores. Mean risk rating values per thematic group are highlighted using a black 'x' and compared using a trend line. A solid black line within each box represents the median value within each category, and the boxes represent the interquartile range. Figure 9 allows us to quickly understand the average estimated value amongst all groups of this analysis. According to the boxplot diagrams, categories such as community, environmental, pollutants, sea ice, and social represent thematic groups with the highest risk rating scores. Sea ice has the smallest boxplot, indicating that observations among these categories are similar and were classified with the highest quality (64.9%).

Figure 9. Boxplot distribution of thematic group risk rating scores.

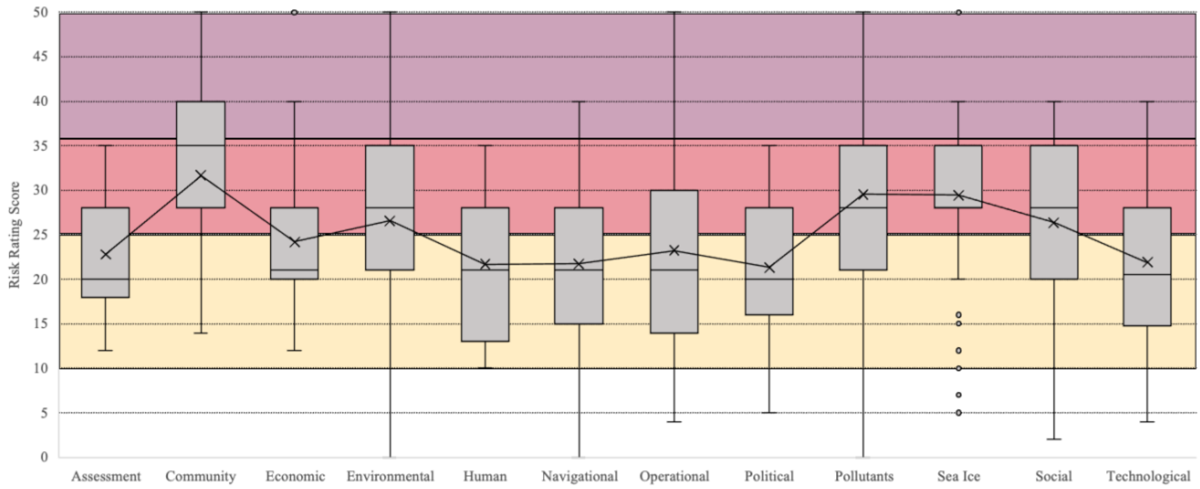


Table 18 compares the information collected among two 'VERY HIGH' risk rated variables, 'Community member displacement' and 'Multi-year sea ice,' to explore the dissimilarities between variables that were classified with differing data quality scores. Table 18 serves as a solid introduction to a discussion regarding the strengths and weaknesses of tangible and intangible variables.

Table 18. Comparison between variables that are of high and low data quality.

Variable	**Community member displacement**	**Multi-year sea ice**
Classification	Risk	Hazard
Category	Community	Sea Ice
Number of Observations	1	13
Risk Rating	VERY HIGH (50.00)	VERY HIGH (36.31)
Data Quality Score	LOW (35.8%)	VERY HIGH (80.5%)
Data Quality - Details	Medium agreement, limited evidence	High agreement, robust evidence
Average Consequence Score	Catastrophic (10)	High (8.5)

Variable	Community member displacement	Multi-year sea ice
Average Probability Score	Almost certain (5)	Likely (4.5)
Data availability	0%	77%
Causes	● Increases in vessel concentration (indirect), vessel traffic (indirect)	● Extreme cold temperatures (direct), regional cooling (direct), snow accumulation (indirect), and vessel presence (indirect).
Consequences	● **Community** - prolonged displacement, inability to gather resources, community mobility issues. ● **Social** – Lack of resources available, decreased community safety, deterioration of living conditions.	● **Environmental** – Increased sea ice movement, Sea ice melt, sea ice decline. ● **Navigational** – difficulties in navigational performance, increased accessibility for human activity (oil exploration and shipping), navigational route planning limitations. ● **Operational** - hull/rudder damage, vessel stuck in ice, vessel sinking, vessel-ice collision, increased vessel activity.
Controls	*Unknown*	● **Policy** – Regulations such as the Arctic Shipping Pollution Prevention Regulations (ASPPR) and Canadian Ice Classification (CAC). ● **Standards** - CAC Ice condition requirements regarding open water vessel navigation. ● **Technology** - Navigational aids and navigational planning resources.

4.1.2 Complex nature and nuanced process of Arctic shipping

4.1.2.1 Tangible hazards and risks

There have been numerous instances where tangible hazards and risks have been identified, specifically from the FMECA analysis. This is primarily a result of tangible hazards that have been specifically identified and targeted, as it is easier to measure and identify climate-related variables that directly influence Arctic shipping operations.

The presence of multi-year sea ice has been identified as a priority hazard (VERY HIGH, 36.31), recommended for further examination. As seen in Table 18, multi-year sea ice was observed numerous times as this hazard has a high probability of occurrence on a regular basis. As consequences range from environmental, navigational, and operational threats, the causes of this hazard were quite basic, being very closely linked to weather related concerns (average regional temperatures, previous conditions). Multi-year sea ice is an ideal tangible hazard as it is easily measured using satellite imagery on a regular basis. There are limited discrepancies among researchers regarding data collection methods and methods to assess sea ice's risk level on Arctic shipping operations. This can be further confirmed through various studies such as Copland et al. (2021) and Xu et al. (2021) that signify how multi-year sea ice limits navigability throughout the Northwest Passage while also providing protection to Arctic marine life.

The implications of Arctic shipping also create emerging sources of underwater noise pollution, harming marine wildlife. This hazard was assessed on numerous occasions, where vessels were able to track the quantity of noise pollutants being emitted, as well as other cascading impacts, such as ship speed, sea conditions, and sea ice coverage to understand acoustic propagation associated hazards and risks. Research supported by Halliday & Dawson (2021) and Halliday et al. (2017) identified how underwater noise pollution significantly alters marine life behaviour, such as breeding, feeding, and migration patterns of Arctic marine mammals. This caused indirect implications to local communities' access to resources and wildlife (Halliday et al., 2017; Johnston et al., 2017). Marine mammals and seabirds change habitat locations and thus, create a reduction in available resources for hunting (Halliday et al., 2017; Johnston et al., 2017).

4.1.2.2 Intangible hazards and risks

Determining quantitative risk scores for intangible hazards has been seen as a limiting factor to the analysis as many of the identified hazards and risks such as social (Boylan, 2021;

Bennett et al., 2020), cultural (Bennett et al., 2020), and community impacts (Bennett et al., 2020; Johnston et al., 2017) are considered intangible, increasing difficulties for data collection. Intangible impacts typically cannot be defined and measured through traditional field sampling – these hazards and risks are not considered to have a physical presence, though they can benefit, or harm the local community (Bennett et al., 2021; Bennett et al., 2020). Since intangible elements are not visible to the naked eye, this increases the difficulty in accurately collecting and assessing data regarding these risks and placing them into quantitative data bins for the risk analysis (Afenyo et al., 2017; Mousavi et al., 2017). Intangible hazards and risks are often identified through methods such as community interviews, resident surveys, and literature reviews of policies and procedures (Johnston et al., 2017). Many of these studies have varied methods of defining hazards and risks within these studied areas, and as a result, cause a minor deviation among all sources. This makes it difficult to assess all hazards and risks accurately and comprehensively.

From all inventoried hazards and risks, 28 were affiliated as intangible risks (3 hazards, 25 risks). Political (82%), Community (60%), and Human (50%) are all thematic groups that observed most inventoried hazards and risks that are considered intangible variables. A key commonality between the top three listed intangible variable categories is that they all pertain to indirect human involvement. Factors such as human behaviour, community well-being, and cultural significance all play a significant role when these intangible hazards and risks are identified (Bennett et al., 2021; Ehlers et al., 2014). Due to the complexity of identifying and quantifying these variables, many were identified throughout the risk analysis phase. The FMECA analysis obtained more thorough information associated with hazards and risks and their descriptions, impacts, controls, and data quality metrics. Findings throughout the FMECA analysis and from academia highlighted how humans' connections to the land can be difficult to calculate using quantitative terminology (Bennett et al., 2021). This has to do with a multiplicity of factors, such as different data collection and methodologies, unconscious and subconscious biases, lacking baseline information, and community members perceptions (Bennett et al., 2021). Intangible risks pose a significant impact to the cultural identity of people within a localized area, as their perceptions and relationship with a given risk or environment do not have a quantitative value associated with them. Nevertheless, this is not seen as less of a priority. The academic community must find a systematic solution in addressing this complex matter. As a result, increased complications arise in effectively quantifying intangible elements of selected hazards and risks. It is recommended that a standard process be put in place when determining quantitative values for intangible hazards and risks within the risk assessment process to ensure all variables are dealt with in a fair and just manner.

4.1.4 Future outlook of assessing risk in Arctic Canada

Throughout the risk identification analysis process, five critical sections have been identified as high risk that need to be further examined. A total of 71 hazards and risks require further examination in a future, more thorough risk assessment process. The findings from this study have determined that it is feasible to conduct a comprehensive risk analysis of complex and intricate problems like Arctic shipping. This will aid in the creation of a standardized template that will support researchers in developing a comprehensive risk assessment and identification framework. This research will inform others and aid in solving issues with similar sentiments regarding data availability, quality, and complexities when assessing and comparing relationships between hazards and risks.

The next step within the risk assessment process is to conduct a thorough risk assessment of all recommended hazards and risks associated with Arctic shipping that have adequately available and quality data. The IPCC's three-pronged approach, which assesses risks through exposure, vulnerability, and severity, is essential in fully understanding the extent of hazards and risks (IPCC, 2022). This approach will allows researchers to understand the relationships between hazards and risks and further understand whether cascading, compounding, or exponential implications influence variables. A future risk assessment will also begin the facilitation of spatially analyzing data, identifying where hazards and risks are most prominent along with the severity of these variables, and determine if they are correlated with present and future shipping routes. As this risk assessment process is not complete, this analysis leaves many risk-related questions left unanswered and open for further discussion, as listed below:

- How might researchers address the current knowledge gaps where low data quality is present, also considering the prioritization of monitoring prominent hazards and risks with more available evidence?
- Can spatial or temporal patterns influence the severity or frequency of individual hazards and risks? How will this be accounted for within the risk assessment process?
- How might researchers objectively identify how hazards and risks influence one another, identifying relationships between hazards and risks to thoroughly understand the complexities of Arctic shipping within Arctic Canada?

4.2 Contributions

4.2.1 Scientific Contributions

This scientific approach has begun the lengthy process of creating a standardized comprehensive risk assessment framework, specifically within the realm of risk identification and risk analysis. Present-day research will support further studies that thoroughly identify hazard and risk variables, comprehensively setting precedents for future risk assessments in polar environments. *Chapter 2* illustrates a novel approach to subject matter expert consultation, resulting in additional data sources to be utilized for gaining perspectives on more complex issues. This also allows researchers to understand complex problems from a top-down approach, examining broader research problems and trends such as hazard and risk identification using broader identification strategies.

Once hazards and risks had been holistically identified, Chapter 3 collected and analyzed more standardized hazard and risk information such as descriptions, consequences, impacts, data quality, and probability of occurrence. Once this was assessed, priority risks should be subject to further assessment within a formal risk assessment, where selected risks with sufficient data quality and priority will be examined using a granular approach to identify emerging trends, concepts, and relationships between other hazards and risks. This is the first comprehensive risk analysis that identifies hazards and risks regarding Arctic shipping practices in a holistic manner and begins to compare them to one another. Combining the findings from numerous disciplines has demonstrated how it is possible to facilitate an analysis that addresses a complex problem such as Arctic shipping. A total of 154 hazard and risk variables have been identified amongst 12 unique thematic groups. Variables that are considered a 'VERY HIGH' risk rating score account for 3.2% (2 hazards, 3 risks) of all variables observed. Hazards and risks with 'VERY HIGH' risk rating scores include the following: community member displacement, hydrocarbon release, transportation of dangerous goods, socio economic impacts to indigenous peoples, and multi-year sea ice. Secondary priority with variables indicating a 'HIGH' risk rating score account for 39.6% (24 hazards, 37 risks) of all variables observed.

4.2.2 Methodological Contributions

A comprehensive risk identification and risk analysis methodology has been created and utilized for the Canadian Arctic using previously completed academic publications (Chapter 3).

- **Comprehensive**: the methodological framework presented allows for hazards and risks to be comprehensively identified using a logical and rigorous process. The use of a FMECA collects all required information regarding the composition of each hazard and risk while the consequence-probability matrix uses the data to provide a risk rating score used as a means for assessing risk priority.
- **Replicable**: This methodological approach uses both risk identification and analysis in a matter that allows for ample replication where most data sources were obtained via open-source publications. This framework was comprehensive enough to include and be applicable to other sectors requiring risk management within the Arctic such as climate impacts, development within northern communities, and other processes that require risk identification and analysis.

4.2.3 Policy Contributions

Findings from this study can aid in the development of policies and regulations that direct and manage priority risks relating to maritime shipping operations within Arctic waters throughout Canada. *Chapter 2* completes the following objectives that can aid policy and decision making:

- **RO I: Create a comprehensive risk rating for all hazards and risks affecting maritime shipping operations within the Northwest Passage.** All comprehensive risks and hazards identified from this study will inform decision-makers, increasing their capacity to fully understand the extent and severity maritime shipping hazards and risks have on the Arctic natural and human environment. As the identified hazards and risks are produced with a risk rating, this enables decision- and policy-makers to have the option to amend and enact new laws and/or regulations that protect the Arctic using an evidence-based approach. Risk rating categories provide a hierarchy for priority status, increasing the readability for public audiences, which will further inform priorities regarding future research, development, and conservation efforts.

- **RO II: Classifying hazards and risks into thematic groups.** All thematic group risk rating categories provide a hierarchy for priority status as per their corresponding risk rating score. The creation of thematic groups enables governments to understand the complex processes associated with shipping in Arctic Canada. Enabling this process sparks a sense of agency at the local and regional level, where regions have control to prioritize and select individual hazards and risks. Choosing individual variables within a thematic group can effectively address community needs and localized problems while still contributing effectively to the overarching priority. Identifying each group's priority status will improve readability for public audiences, allowing clear recommendations when actioning priorities and investing in risk mitigation strategies. Actions may result in, but are not limited to, options such as future research funding, increased development in the region, and/or increased conservation presence.

4.3 Study Limitations

Limitations have been identified throughout the methods section within Chapter 2 regarding any data analysis. This section will summarize the key limitations throughout the research. For *Chapter 2*, the limitations are as follows:

- **Text sensitivity using natural language processing**
  - The use of synonyms and acronyms to describe maritime ship operations throughout all data observations were treated as separate observations. Without the grouping of alike terms, this created dispersed findings among terms that are used interchangeably with one another. For example, 'FY ice' and 'First-year ice' are interchangeably used to describe sea ice conditions and would be

separately grouped. This is also like words that are spelt using American or British English, or in rare instances, being misspelt.

- The process of 'stemming' data, that takes lengthy terms and reduces them to the base term (i.e., terms such as 'running', 'runs', 'run' would be condensed to 'run') can be used to streamline processes. Stemming data was considered, though was not used as it has a high possibility to cause confusion to bi-gram frequency charts. Stemming can also incorrectly condense terms into words that have divergent meanings, creating misleading results.

Limitations have been identified throughout the methods section within Chapter 3 were made that were specific in conducting any form of risk analysis or assessment. This section will summarize the key limitations throughout the research, expanding upon points directly or indirectly made in the previous chapter. For *Chapter 3*, the limitations are as follows:

- **Subjectivity of consequence and probability scores**
    - Individual subjectivity was used to complete consequence and probability scoring upon completion of the FMECA analysis. Individual subjectivity influenced the determination of each consequence and probability scores given to the identified hazards and risks. Table 7 was created to limit the amount of subjectivity regarding consequence ratings by incorporating a thematic group approach to quantifying and assessing the associated level of consequence for every hazard and risk observed. Probabilities were also subjectively identified based in Table 8, limiting subjectivity by providing the probability expressed in a percentage score as well as via a ship years metric. Ship years was previously used to quantify probability by Fu et al. (2023) to assess risks regarding shipping accidents in the Arctic.

- As mentioned within the IPCC guidance note regarding consistent treatment of uncertainties, assessing hazards and risks based on qualitative data can be difficult to represent the true probability and consequence of each hazard (IPCC, 2018). This specifically was seen again throughout the completion of the FMECA during Step 2, specifically within Theoretical studies. Defining the consequence and probability was difficult and varied among each data score based on the study scope, objectives, and pre-defined terms used. If terms were not specifically defined, this could perpetuate the possibility of biases being present within the reader, resulting in implications towards risk rating scoring.
- When analyzing qualitative data in the context of identifying quantitative information, issues arise regarding the limited quantitative evidence to support claims. As a result, risk rating scores can be heavily influenced by the author's tone, verbatim when conveying messages, and word choices that influences the scoring of the risk analysis.

- **Normalization of the consequence, probability, and risk ratings**
  - After the calculation of risk rating scores, the scores were averaged during the calculation. Since both consequence and probability score statistics for all hazards and risks identified were averaged initially, this increases the possibility of influencing outliers within the data. Due to the high variability of the data available, the median was not selected due to 60% of all hazards and risks identified have less than three data observations found. Since there was not an even distribution of data observations amongst all hazards and risks observed, it was deemed appropriate to use the mean when the risk scores were calculated.

  - Due to the average values being taken from both consequence and probability risk scores, this increased the likelihood of risk rating scores being normalized values. Having normalized risk rating scores for hazards and risks limits the overall quantity of polarized data, increasing the difficulty in determining the differentiation between priority and non-priority hazards and risks.

- **Language discrepancies among ‘hazard’ and ‘risk’**
  - It was established that each author defined consequences, hazards, risks, and probability using a different methodology, increasing the difficulty to interpret to a high degree of precision throughout the completion of the FMECA analysis. Incorporating the ‘thematic group-specific’ consequence ratings reduced the discrepancies among consequence scores to easily identify the level of confidence based on the different risk category. This was similarly applied to the probability scores with the uses of percentage of probability or the value noted in ship years.
  - For this study, all language use has been primarily adopted from and to be in alignment with IPCC writing standards. While other authors have adhered to different technical standards such as the ISO, this has possibly resulted in mislabelled and the creation of a grey area surrounding the differentiation between the terminology of hazards and risks.

- **Uncertainty of understudied and unknown risk variables**
  - Many studies did not discuss the possibilities of unaccounted for risks or hazards. Not being able to account for specific hazards and risks can influence the severity and frequency of the variables’ occurrences, as well as the ability to influence the behaviour and probability of other risks occurring in tandem. While some articles mention the presence of ‘pandemics’, ‘geomagnetic

storms', or 'outliers events', such as asteroid impacts and tsunamis, these are currently understudied and any definitive values or risk rating scores are unknown due to no data availability. Assessing unknown variables in a systematic way for future analysis should be implemented to ensure unknown variables are accounted for in the future.

4.4 Future Research

As this study is the first of many that comprehensively examines Arctic shipping hazards and risks, continuous work is still needed to address the knowledge gaps presented throughout this research. The next step in preparation of a thorough risk assessment is the collection of baseline data regarding Arctic shipping-related hazards and risks. Risk analyses can also be conducted on a periodic basis, where baseline data and recorded historical averages can be calculated to determine priority status.

It is possible to expand the research presented in *Chapter 2* via conducting a spatial analysis of all shipping routes and nodes throughout the NWP. This analysis would utilize ArcGIS for spatial analytics and the reliability-centred maintenance methodology. The combination of these methods would allow the research to determine important nodes and transit routes through the NWP and creating Vessel Operational Spatial Tracts (VOSTs). First, the reliability-centred maintenance method recognizes policies that require implementation to manage failures and efficiently and effectively maintain adequate comprehensive standards (ISO, 2009). This method will be modified to recognize vessel routes rather than policies to determine which present-day and future vessel routes are deemed the safest and of most interest (i.e. shortest route, most cost-effective route, etc.). Second, data sources with spatial locations noted will be inputted into ArcGIS and joined using the spatial join tool, merging all data together. This will allow for the comparison of densities regarding commonly studied areas, nodes of interest, and popular vessel routes using the spatial analyst Kernel Density (KDE) mapping tool in ArcGIS. The AIS dataset will calculate KDE for vessel transit polylines and individual point locations. The union overlay tool will spatially analyze the peer-reviewed sources to combine all study area polygons and create a map highlighting oversized versus understudied areas. The recommendations from the study will assist in creating vessel operational spatial tract (VOST) polygons to identify nodes/areas along different NWP routes. The VOSTs will be used to recommend the present and projected operational NWP routes while also recommending VOSTs polygons to collect and further analyze the risks of the recommended vessel routes. The spatial analysis will create an accessible format to identify widespread transit paths and areas of interest while considering seasonality, data strength, and vessel classification.

Another possibility of expanding upon the research presented in *Chapter 2* is to facilitate a comprehensive risk assessment of all identified Arctic shipping risks. The use of all the data collected regarding hazard, risk, and data quality information is recommended as baseline data for the analysis. The IPCC's three-pronged approach to assessing risks is an ideal assessment tool that thoroughly examines how individual risks cause a positive and/or negative impact on the environment (Lavell et al., 2012). This tool uses features such as hazard severity, vulnerability, and exposure to determine risk. Once this initial definition is calculated, this can aid in the identification of a sequence of heatmap and network graphs, examining the relationship between hazards and risks to determine cascading, indirect, and cumulative risks that occur throughout maritime ship operations that may not be identifiable on the surface. This will bridge the knowledge gap in creating a spatial risk assessment tool that provides accurate risk assessments of each significant location throughout the NWP. This tool will allow easy access for researchers, community members, decision-makers, and ship operators to customize, manipulate, and add additional data that has the possibility to provide real-time assessment to aid in creating a safer and healthier shipping environment in the Canadian Arctic.

To further understand risk assessments in the Arctic, the following list lays out preliminary ideas that can be used as general themes or topics for future research projects:

- Conduct policy analysis between state/provincial/territorial, national, and international legislation among all countries that are included within the Northwest Passage to determine specific laws, regulations, and sections that are of higher risk of non-compliance and lacking cohesiveness in protecting the Arctic;
- Complete a social impact assessment that compares each coastal community that is implicated by an increase in maritime shipping activity within the Northwest Passage;
- Map Canadian migratory patterns and populations of species at-risk that utilize or reside amongst the NWP; and
- Conduct a content analysis on previously studied adaptation methodologies, determining the feasibility and effectiveness of the approaches used and formulating recommendations on adaptation methods that provided the most benefits to communities.

4.5 References cited in Chapter 4

Afenyo, M., Khan, F., Veitch, B., & Yang, M. (2017). Arctic shipping accident scenario analysis using Bayesian network approach. *Ocean Engineering, 133*, 224–230. https://doi.org/10.1016/j.oceaneng.2017.02.002

Akbayirli, K., & Tuna, O. (2022). How do practitioners view arctic shipping routes? A cognitive appraisal approach. *Transportation Research Part D: Transport and Environment, 110, 103432*. https://doi.org/10.1016/j.trd.2022.103432

Bennett, N., Schuhbauer, A., Skerritt, D., & Ebrahim, N. (2021). Socio-Economic Monitoring and Evaluation in Fisheries. *Fisheries Research, 239*, 105934. https://doi.org/10.1016/j.fishres.2021.105934

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

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

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

Ehlers, S., Kujala, P., Veitch, B., Khan, F., & Vanhatalo, J. (2014). Scenario based risk management for Arctic Shipping and Operations. Polar and Arctic Science and Technology, 10. https://doi.org/10.1115/omae2014-23112

Fu, S., Zhang, Y., Zhang, M., Han, B., & Wu, Z. (2023). An object-oriented bayesian network model for the quantitative risk assessment of navigational accidents in ice-covered Arctic Waters. *Reliability Engineering & System Safety, 238*, 109459. https://doi.org/10.1016/j.ress.2023.109459

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

Ho, J. (2010). The implications of Arctic sea ice decline on shipping. *Marine Policy, 34(3), 713–715*. https://doi.org/10.1016/j.marpol.2009.10.009

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. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Johnston, M., Dawson, J., & Maher, P. (2017). Strategic development challenges in marine tourism in Nunavut. *Resources, 6(3)*, 25. https://doi.org/10.3390/resources6030025

Lavell, A., M. Oppenheimer, C. Diop, J. Hess, R. Lempert, J. Li, R. Muir-Wood, and S. Myeong, 2012: Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation[Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 25-64.

Mousavi, M., Ghazi, I., and Omaraee, B. (2017). Risk assessment in the Maritime Industry. Engineering, Technology & Applied Science Research, 7(1), 1377–1381. https://doi.org/10.48084/etasr.836

Peeters, W., & Peng, Z. (2015). An Approach Towards Global Standardization of the Risk Matrix. Journal of Space Safety Engineering, 2(1), 31–38. https://doi.org/10.1016/s2468-8967(16)30037-4

Pizzolato, L., Howell, S., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophysical Research Letters, 43(23)*. https://doi.org/10.1002/2016gl071489

Protection of the Arctic Marine Environment (PAME). (2009). Arctic Marine Shipping Assessment 2009 Report. Arctic Council, April 2009, second printing. Retrieved from: https://pame.is/images/03_Projects/AMSA/AMSA_2009_report/AMSA_2009_Report_2nd_print.pdf

Xu, S., Kim, E., & Haugen, S. (2021). Review and comparison of existing risk analysis models applied within shipping in ice-covered waters. *Safety Science, 141*, 105335. https://doi.org/10.1016/j.ssci.2021.105335

Zhang, M., Zhang, D., Zhang, C., & Cao, W. (2020). Navigational risk factor analysis of Arctic shipping in ice-covered waters. Maritime Transport and Regional Sustainability, 153–177. https://doi.org/10.1016/b978-0-12-819134-7.00010-1

Bibliography and Appendices

Bibliography

Afenyo, M., Khan, F., Veitch, B., & Yang, M. (2017). Arctic shipping accident scenario analysis using Bayesian network approach. Ocean Engineering, 133, 224–230. https://doi.org/10.1016/j.oceaneng.2017.02.002

Agard, J., and Schipper, E. (2018). Intergovernmental Panel on Climate Change (IPCC) AR5- Annex II - Glossary. IPCC Working Group II - AR5 Report. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf

Akbayirli, K., & Tuna, O. (2022). How do practitioners view arctic shipping routes? A cognitive appraisal approach. Transportation Research Part D: Transport and Environment, 110, 103432. https://doi.org/10.1016/j.trd.2022.103432

Arctic Council. (2020). Guideline for Arctic Marine Risk Assessment. Arctic Council. Retrieved January 2023, from https://eppr.dnvgl.com/

Arctic Council. (2021). Expert Group on Black Carbon and Methane–3rd Summary of Progress and Recommendations. Arctic Council: Tromsø, Norway.

Arctic Council. (n.d.). Addressing arctic pollution. Arctic Council. Retrieved April 2023, from https://arctic-council.org/explore/topics/pollutants/

Baksh, A.-A., Abbassi, R., Garaniya, V., & Khan, F. (2018). Marine Transportation Risk Assessment using bayesian network: Application to arctic waters. Ocean Engineering, 159, 422–436. https://doi.org/10.1016/j.oceaneng.2018.04.024

Baram-Tsabari, A., Wolfson, O., Yosef, R., Chapnik, N., Brill, A., & Segev, E. (2020). Jargon use in public understanding of science papers over three decades. Public Understanding of Science, 29(6), 644–654. https://doi.org/10.1177/0963662520940501

Barber, D. G., Asplin, M. G., Gratton, Y., Lukovich, J. V., Galley, R. J., Raddatz, R. L., & Leitch, D. (2010). The International Polar Year (IPY) Circumpolar Flaw lead (CFL) system study: Overview and the physical system. Atmosphere-Ocean, 48(4), 225–243. https://doi.org/10.3137/oc317.2010

Bard, S. M. (1999). Global transport of anthropogenic contaminants and the consequences for the arctic marine ecosystem. Marine Pollution Bulletin, 38(5), 356–379. https://doi.org/10.1016/s0025-326x(99)00041-7

Baylis, P., Obradovich, N., Kryvasheyeu, Y., Chen, H., Coviello, L., Moro, E., Cebrian, M., & Fowler, J. H. (2018). Weather impacts expressed sentiment. PLOS ONE, 13(4). https://doi.org/10.1371/journal.pone.0195750

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

Bennett, N., Schuhbauer, A., Skerritt, D., & Ebrahim, N. (2021). Socio-Economic Monitoring and Evaluation in Fisheries. Fisheries Research, 239, 105934. https://doi.org/10.1016/j.fishres.2021.105934

Benoit, K., Muhr, D., & Watanabe, K. (2021). stopwords: Multilingual Stopword Lists. R package version 2.2. https://CRAN.R-project.org/package=stopwords

Berge, J., Renaud, P. E., Darnis, G., Cottier, F., Last, K., Gabrielsen, T. M., Johnsen, G., Seuthe, L., Weslawski, J. M., Leu, E., Moline, M., Nahrgang, J., Søreide, J. E., Varpe, Ø., Lønne, O. J., Daase, M., & Falk-Petersen, S. (2015). In the dark: A review of ecosystem processes during the Arctic Polar Night. Progress in Oceanography, 139, 258–271. https://doi.org/10.1016/j.pocean.2015.08.005

Borch, O., Andreassen, N., Marchenko, N., Ingimundarson, V., Gunnarsdóttir, H., Iudin, I., Petrov, S., Jakobsen, U., & Dali, B. (2016, October 7). Maritime activity in the high north : Current and estimated level up to 2025 : MARPART Project Report 1. Nord Open Research Archive. https://nordopen.nord.no/nord-xmlui/handle/11250/2413456

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

Brzic, B., Boticki, I., & Bagic Babac, M. (2023). Detecting deception using natural language processing and machine learning in datasets on COVID-19 and climate change. Algorithms, 16(5), 221. https://doi.org/10.3390/a16050221

Chapman, E. (2022). Revocalising Human geography: Decolonial language geographies beyond the nation-state. Progress in Human Geography, 47(1), 24–42. https://doi.org/10.1177/03091325221131852

Chen, J., Kang, S., Guo, J., Xu, M., & Zhang, Z. (2021). Variation of sea ice and perspectives of the Northwest Passage in the Arctic Ocean. Advances in Climate Change Research, 12(4), 447–455. https://doi.org/10.1016/j.accre.2021.02.002

Chen, P., & Liu, T. (2022). Environmental and economic analysis on sailing from Taiwan through Arctic passages. Water, 14(13), 2099. https://doi.org/10.3390/w14132099

Chircop, A. (2009). The growth of international shipping in the Arctic: Is a regulatory review timely? The International Journal of Marine and Coastal Law, 24(2), 355–380. https://doi.org/10.1163/157180809x421699

Christensen, M., Georgati, M., & Arsanjani, J. J. (2019). A risk-based approach for determining the future potential of commercial shipping in the Arctic. Journal of Marine Engineering & Technology, 21(2), 82–99. https://doi.org/10.1080/20464177.2019.1672419

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017). Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025. Washington DC, International Council on Clean Transportation. DOI: http://dx.doi.org/10.25607/OBP-1733

Conachey, R., & Montgomery, R. (2005, October). Development of machinery survey requirements based on reliability-centered maintenance. In SNAME Maritime Convention. OnePetro.

Conrow, E. (2003). Effective risk management: Some keys to Success. American Institute of Aeronautics and Astronautics.

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

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

Corbett, J. J., Wang, H., & Winebrake, J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. Transportation Research Part D: Transport and Environment, 14(8), 593–598. https://doi.org/10.1016/j.trd.2009.08.005

Dawson, J., Holloway, J., Debortoli, N., & Gilmore, E. (2020). Treatment of international economic trade in Intergovernmental Panel on Climate Change (IPCC) reports. Current Climate Change Reports, 6(4), 155–165. https://doi.org/10.1007/s40641-020-00163-x

Dawson, J., Johnston, M., Stewart, E., Lemieux, C., Lemelin, R., Maher, P., & Grimwood, B. (2011). Ethical considerations of last chance tourism. Journal of Ecotourism, 10(3), 250–265. https://doi.org/10.1080/14724049.2011.617449

Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., and Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. ARCTIC, 71(1). https://doi.org/10.14430/arctic4698

Dawson, J., Pizzolato, L., Howell, S., Copland, L., & Johnston,M. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. Arctic, 71. 15-26. https://doi.org/10.14430/arctic4698

Dawson, J., Stewart, E. J., Johnston, M. E., and Lemieux, C. J. (2016). Identifying and evaluating adaptation strategies for Cruise Tourism in Arctic Canada. Journal of Sustainable Tourism, 24(10), 1425–1441. https://doi.org/10.1080/09669582.2015.1125358

Daya, A. A., & Lazakis, I. (2023). Developing an advanced reliability analysis framework for Marine Systems Operations and Maintenance. Ocean Engineering, 272, 113766. https://doi.org/10.1016/j.oceaneng.2023.113766

Dowle, M., & Srinivasan, A. (2021). data.table: Extension of `data.frame`. R package version 1.14.0. https://CRAN.R-project.org/package=data.table

Dyrcz, C. (2017). Safety of navigation in the Arctic. Scientific Journal of Polish Naval Academy, 211(4), 129–146. https://doi.org/10.5604/01.3001.0010.6742

Ebinger, C., & Zambetakis, E. (2009). The geopolitics of Arctic melt. International Affairs, 85(6), 1215–1232. https://doi.org/10.1111/j.1468-2346.2009.00858.x

Ehlers, S., Kujala, P., Veitch, B., Khan, F., & Vanhatalo, J. (2014). Scenario based risk management for Arctic Shipping and Operations. Polar and Arctic Science and Technology, 10. https://doi.org/10.1115/omae2014-23112

Feinerer, I., & Hornik, H. (2020). tm: Text Mining Package. R package version 0.7-8. https://CRAN.R-project.org/package=tm

Filipiak, D., Węcel, K., Stróżyna, M., Michalak, M., & Abramowicz, W. (2020). Extracting Maritime Traffic Networks from AIS data using evolutionary algorithm. Business and Information Systems Engineering, 62(5), 435–450. https://doi.org/10.1007/s12599-020-00661-0

Fu, S., Goerlandt, F., & Xi, Y. (2021). Arctic Shipping Risk Management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents. Safety Science, 139, 105254. https://doi.org/10.1016/j.ssci.2021.105254

Fu, S., Yu, Y., Chen, J., Xi, Y., & Zhang, M. (2022). A framework for quantitative analysis of the causation of grounding accidents in Arctic shipping. Reliability Engineering & System Safety, 226, 108706. https://doi.org/10.1016/j.ress.2022.108706

Fu, S., Zhang, D., Montewka, J., Zio, E., & Yan, X. (2018). A quantitative approach for risk assessment of a ship stuck in ice in Arctic Waters. Safety Science, 107, 145–154. https://doi.org/10.1016/j.ssci.2017.07.001

Fu, S., Zhang, Y., Zhang, M., Han, B., & Wu, Z. (2023). An object-oriented bayesian network model for the quantitative risk assessment of navigational accidents in ice-covered Arctic Waters. Reliability Engineering & System Safety, 238, 109459. https://doi.org/10.1016/j.ress.2023.109459

Ghosh, S., & Rubly, C. (2015). The emergence of Arctic shipping: Issues, threats, costs, and risk-mitigating strategies of the Polar Code. Australian Journal of Maritime & Ocean Affairs, 7(3), 171–182. https://doi.org/10.1080/18366503.2015.1093695

Goldsmit, J., McKindsey, C., Archambault, P., and Howland, K. L. (2019). Ecological risk assessment of predicted marine invasions in the Canadian Arctic. PLOS ONE, 14(2). https://doi.org/10.1371/journal.pone.0211815

Government of Canada. (2022, June 6). Shipping in the Arctic. Crown-Indigenous Relations and Northern Affairs Canada. Retrieved from https://www.rcaanc-cirnac.gc.ca/eng/1648145733596/1648145784817

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

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

Haas, C., and Howell, S. E. (2015). Ice thickness in the northwest passage. Geophysical Research Letters, 42(18), 7673–7680. https://doi.org/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. https://doi.org/10.1016/j.marpolbul.2017.09.027

Halliday, W. D., Le Baron, N., Citta, J. J., Dawson, J., Doniol-Valcroze, T., Ferguson, M., Ferguson, S. H., Fortune, S., Harwood, L. A., Heide-Jørgensen, M. P., Lea, E. V., Quakenbush, L., Young, B. G., Yurkowski, D., and Insley, S. J. (2022). Overlap between bowhead whales (balaena mysticetus) and vessel traffic in the North American arctic and implications for conservation and management. Biological Conservation, 276, 109820. https://doi.org/10.1016/j.biocon.2022.109820

Halliday, W., & Dawson, J. (2021). Ship-Source Noise Modeling from 2015-2018 in the Kitikmeot Region and Lancaster Sound (Northwest Passage), Nunavut. http://hdl.handle.net/10393/41926

Hauser, D., Laidre, K., & Stern, H. (2018). Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. Proceedings of the National Academy of Sciences, 115(29), 7617–7622. https://doi.org/10.1073/pnas.1803543115

Headland, R. (2022, December 8). Transits of the Northwest Passage to the End of 2022 Navigation Season. Polar Information Sheets. Retrieved March 2023, from https://www.spri.cam.ac.uk/resources/infosheets/northwestpassage.pdf

Heidari, N., Sebastian Feser, M., Scholten, N., Schwippert, K., & Sprenger, S. (2022). Language in primary and Secondary Geography Education: A systematic literature review of empirical geography education research. International Research in Geographical and Environmental Education, 32(3), 234–251. https://doi.org/10.1080/10382046.2022.2154964

Ho, J. (2010). The implications of Arctic sea ice decline on shipping. Marine Policy, 34(3), 713–715. https://doi.org/10.1016/j.marpol.2009.10.009

Hu, S., Fang, Q., Xia, H., and Xi, Y. (2007). Formal safety assessment based on relative risks model in ship navigation. Reliability Engineering and System Safety, 92(3), 369–377. https://doi.org/10.1016/j.ress.2006.04.011

Huang, L., Perry, P., Nielsen, F., Porter, M., & Boulton, R., (2021, May 2). corpus: Text Corpus Analysis. ‘Corpus’. R package version 0.10.2. https://CRAN.R-project.org/package=corpus

International Maritime Organization (IMO). (2018, April 9). REVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA). International Maritime Organization (IMO). Retrieved February 2023, from https://www.imo.org/en/OurWork/Circulars/Pages/default.aspx

International Maritime Organization (IMO). (2019). History of IMO. International Maritime Organization. Retrieved March 2023, from https://www.imo.org/en/About/HistoryOfIMO/Pages/Default.aspx

International Maritime Organization (IMO). (2020). International Code for Ships Operating in Polar Waters (Polar Code). International Maritime Organization. Retrieved February 2023, from https://www.imo.org/en/OurWork/Safety/Pages/polar-code.aspx

International Maritime Organization (IMO). (n.d.). Formal Safety Assessment (FSA). International Maritime Organization. Retrieved March 2023, from https://www.imo.org/en/OurWork/Safety/Pages/FormalSafetyAssessment.aspx

International Organization for Standardization (ISO). (2009a). Risk Management - Vocabulary (ISO Guide 73:2009). Retrieved from: https://www.iso.org/obp/ui/#iso:std:iso:guide:73:ed-1:v1:en:term

International Organization for Standardization (ISO). (2009b). Risk Management - Risk Assessment Techniques (IEC/FDIS 31010:2009). Retrieved from: https://bambangkesit.files.wordpress.com/2015/12/iso-31010_risk-management-risk-assessment-techniques.pdf

International Organization for Standardization (ISO). (2018). Risk Management - Guidelines (ISO 31010:2009). Retrieved from: https://shahrdevelopment.ir/wp-content/uploads/2020/03/ISO-31000.pdf

IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562, doi:10.1017/9781009157940.008.

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. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

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

Jing, D., Dai, L., Hu, H., Ding, W., Wang, Y., & Zhou, X. (2021). CO2 emission projection for Arctic Shipping: A system dynamics approach. Ocean & Coastal Management, 205, 105531. https://doi.org/10.1016/j.ocecoaman.2021.105531

Johnston, M., Dawson, J., & Maher, P. (2017). Strategic development challenges in marine tourism in Nunavut. Resources, 6(3), 25. https://doi.org/10.3390/resources6030025

Johnston, M., Dawson, J., De Souza, E., and Stewart, E. J. (2016). Management challenges for the fastest growing marine shipping sector in Arctic Canada: Pleasure crafts. Polar Record, 53(1), 67–78. https://doi.org/10.1017/s0032247416000565

Kamal, B., and Kutay, Ş. (2021). Assessment of causal mechanism of ship bunkering oil pollution. Ocean and Coastal Management, 215, 105939. https://doi.org/10.1016/j.ocecoaman.2021.105939

Khyani, D., & B S, S. (2021). An Interpretation of Lemmatization and Stemming in Natural Language Processing. Journal of University of Shanghai for Science and Technology, 22(12). https://doi.org/1007-6735

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

Lancaster, M. L., Winsor, P., and Dumbrille, A. (2021). Underwater noise from shipping: A special case for the Arctic. Sustainability in the Maritime Domain, 271–289. https://doi.org/10.1007/978-3-030-69325-1_14

Lasserre, F. (2014). Case studies of Shipping along Arctic routes. Analysis and profitability perspectives for the container sector. Transportation Research A 66, 144-161

Lavell, A., M. Oppenheimer, C. Diop, J. Hess, R. Lempert, J. Li, R. Muir-Wood, and S. Myeong, 2012: Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation[Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 25-64.

Lemieux, C.J., Thompson, J., Dawson, J., and Shuster, R. (2013). Natural resource manager perceptions of agency performance on climate change. Journal of Environmental Management 114: 178-189. DOI: 10.1016/j.jenvman.2012.09.014

Liang, Y., Yin, J., Pan, B., Chi, G., & Andris, C. (2020, June 7). Understanding Demographics and Experience of Tourists in Yellowstone National Park through Social Media. University of Massachusetts Amherst. Retrieved January 2022, from https://scholarworks.umass.edu/cgi/viewcontent.cgi?article=2559&context=ttra

Mastrandrea, M., Field, C., Stocker, T., Edenhofer, O., Ebi, K., Frame, D., Held, H., Kriegler, E., Mach, K., Matschoss, P., Plattner, G.-K., Yohe, G., & Zwiers, F. (2010). Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at <http://www.ipcc.ch>.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M.M.C. , Ottersen, G., Pritchard, H., and Schuur, E. (2019). Polar Regions. In: 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, pp. 203-320. https://doi.org/10.1017/9781009157964.005.

Messner, S. (2020). Future arctic shipping, black carbon emissions, and climate change. Maritime Transport and Regional Sustainability, 195–208. https://doi.org/10.1016/b978-0-12-819134-7.00012-5

Moore, S., Reeves, R., Southall, B., Ragen, T. J., Suydam, R., and Clark, C. (2012). A new framework for assessing the effects of anthropogenic sound on marine mammals in a rapidly changing Arctic. BioScience, 62(3), 289–295. https://doi.org/10.1525/bio.2012.62.3.10

Mousavi, M., Ghazi, I., and Omaraee, B. (2017). Risk assessment in the Maritime Industry. Engineering, Technology & Applied Science Research, 7(1), 1377–1381. https://doi.org/10.48084/etasr.836

Mudryk, L., Dawson, J., Howell, S., Derksen, C., Zagon, T., & Brady, M. (2021). Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. Nature Climate Change, 11(8), 673–679. https://doi.org/10.1038/s41558-021-01087-6

Mullen, L., Benoit, K., Keyes, O., Selivanov, D., & Arnold, J. (2018). Fast, consistent tokenization of natural language text. Journal of Open Source Software, 3(23), 655. https://doi.org/10.21105/joss.00655

Müller, K., & Wickham, H. (2021). tibble: Simple Data Frames. R package version 3.1.6 https://CRAN.R-project.org/package=tibble

Olsen, J., Carter, N., & Dawson, J. (2019). Community perspectives on the environmental impacts of arctic shipping: Case studies from Russia, Norway, and Canada. Cogent Social Sciences, 5(1). https://doi.org/10.1080/23311886.2019.1609189

Ooms, J. (2021). writexl: Export Data Frames to Excel 'xlsx' Format. R package version 1.4.0. https://CRAN.R-project.org/package=writex

Pashkevich, A., Dawson, J., and Stewart, E. J. (2015). Governance of expedition cruise ship tourism in the Arctic: A comparison of the Canadian and Russian Arctic. Tourism in Marine Environments, 10(3), 225–240. https://doi.org/10.3727/154427315x14181438892883

Peeters, W., & Peng, Z. (2015). An Approach Towards Global Standardization of the Risk Matrix. Journal of Space Safety Engineering, 2(1), 31–38. https://doi.org/10.1016/s2468-8967(16)30037-4

Pizzolato, L., Howell, S., Dawson, J., Laliberté, F., & Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophysical Research Letters, 43(23). https://doi.org/10.1002/2016gl071489

Protection of the Arctic Marine Environment (PAME). (2009). Arctic Marine Shipping Assessment 2009 Report. Arctic Council, April 2009, second printing. Retrieved from: https://pame.is/images/03_Projects/AMSA/AMSA_2009_report/AMSA_2009_Report_2nd_print.pdf

Qian, H., Zhang, R., & Zhang, Y. (2020). Dynamic Risk Assessment of natural environment based on dynamic Bayesian network for key nodes of the Arctic Northwest Passage. Ocean Engineering, 203, 107205. https://doi.org/10.1016/j.oceaneng.2020.107205

Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth and Environment, 3(1). https://doi.org/10.1038/s43247-022-00498-3

Robinson, D. (2020). widyr: Widen, Process, then Re-Tidy Data. R package version 0.1.3. https://CRAN.R-project.org/package=widyr

Sand, M., Berntsen, T. K., Seland, Ø., and Kristjánsson, J. E. (2013). Arctic surface temperature change to emissions of black carbon within Arctic or Midlatitudes. Journal of Geophysical Research: Atmospheres, 118(14), 7788–7798. https://doi.org/10.1002/jgrd.50613

Schoeman, R. P., Patterson-Abrolat, C., and Plön, S. (2020). A global review of vessel collisions with Marine Animals. Frontiers in Marine Science, 7. https://doi.org/10.3389/fmars.2020.00292

Serreze, M. C., and Stroeve, J. (2015). Arctic sea ice trends, variability and implications for seasonal ice forecasting. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 373(2045), 20140159. https://doi.org/10.1098/rsta.2014.0159

Sheehan, R., Dalaklis, D., Christodoulou, A., Drewniak, M., Raneri, P., & Dalaklis, A. (2021). The Northwest Passage in the Arctic: A brief assessment of the relevant Marine Transportation System and current availability of search and rescue services. Logistics, 5(2), 23. https://doi.org/10.3390/logistics5020023

Silge, J., & Robinson, D. (2016). Tidytext: Text mining and analysis using tidy data principles in R. The Journal of Open Source Software, 1(3), 37. https://doi.org/10.21105/joss.00037

Somanathan, S., Flynn, P. C., & Szymanski, J. K. (2007). Feasibility of a sea route through the Canadian Arctic. Maritime Economics & Logistics, 9(4), 324–334. https://doi.org/10.1057/palgrave.mel.9100185

Somanathan, S., Flynn, P., & Szymanski, J. (2009). The northwest passage: A simulation. Transportation Research Part A: Policy and Practice, 43(2), 127–135. https://doi.org/10.1016/j.tra.2008.08.001

Stephenson, S. R., & Smith, L. C. (2015). Influence of climate model variability on projected arctic shipping futures. Earth's Future, 3(11), 331–343. https://doi.org/10.1002/2015ef000317

Stevens, H. R., Graham, P. L., Beggs, P. J., & Hanigan, I. C. (2020). In cold weather we bark, but in hot weather we bite: Patterns in social media anger, aggressive behavior, and temperature. Environment and Behavior, 53(7), 787–805. https://doi.org/10.1177/0013916520937455

Stewart, E. J., Dawson, J., Howell, S. E. L., Johnston, M. E., 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. https://doi.org/10.1080/1088937x.2012.705352

Suominen, M., & Kujala, P. (2014). Variation in short-term ice-induced load amplitudes on a ship's hull and related probability distributions. Cold Regions Science and Technology, 106–107, 131–140. https://doi.org/10.1016/j.coldregions.2014.07.001

Teoh, W., Khoo, M., Castagliola, P., Yeong, W., & Teh, S. (2017). Run-sum control charts for monitoring the coefficient of variation. European Journal of Operational Research, 257(1), 144–158. https://doi.org/10.1016/j.ejor.2016.08.067

The Canadian Encyclopedia. (2006). Arctic Archipelago. Retrieved March 2023, from https://www.thecanadianencyclopedia.ca/en/article/arctic-archipelago

Transport Canada. (2022). National Framework for Assessing the Cumulative Effects of Marine Shipping. 72 p. https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf

United States Environmental Protection Agency (US-EPA). (2022, November 29). Exxon Valdez Spill Profile. United States Environmental Protection Agency (US-EPA). Retrieved from https://www.epa.gov/emergency-response/exxon-valdez-spill-profile

van Hoof, L., van den Burg, S. W. K., Banach, J. L., Röckmann, C., and Goossen, M. (2020). Can multi-use of the sea be safe? A framework for risk assessment of multi-use at sea. Ocean and Coastal Management, 184, 105030. https://doi.org/10.1016/j.ocecoaman.2019.105030

van Luijk N, Carter NA, Dawson J, Song G, Parker C, et al. (2021) At the front lines of increased shipping and climate change: Inuit perspectives on Canadian Arctic sovereignty and security. Arctic Yearbook 2021. https://arcticyearbook.com/images/yearbook/2021/Scholarly-Papers/6_AY2021_Luijk_Dawson.pdf

Vorkamp, K., & Rigét, F. (2014). A review of new and current-use contaminants in the Arctic environment: Evidence of long-range transport and indications of bioaccumulation. Chemosphere, 111, 379–395. https://doi.org/10.1016/j.chemosphere.2014.04.019

Wang, J., Obradovich, N., & Zheng, S. (2020). A 43-million-person investigation into weather and expressed sentiment in a changing climate. One Earth, 2(6), 568–577. https://doi.org/10.1016/j.oneear.2020.05.016

Wang, J., Zhou, Y., Zhang, S., Zhuang, L., Shi, L., Chen, J., and Hu, D. (2022). Societal Risk Acceptance Criteria of the global general cargo ships. Ocean Engineering, 261, 112162. https://doi.org/10.1016/j.oceaneng.2022.112162

Wickham, H. (2019). stringr: Simple, Consistent Wrappers for Common String Operations. R package version 1.4.0. https://CRAN.R-project.org/package=stringr

Wickham, H. (2021). dtplyr: Data Table Back-End for 'dplyr'. R package version 1.1.0. https://CRAN.R-project.org/package=dtplyr

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, LD., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, TL., Miller, E., Bache, SM., Müller, K., Ooms, J., Robinson, D., Seidel, DP., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., & Yutani, H. (2019). “Welcome to the tidyverse.” Journal of Open Source Software, 4(43), 1686. doi:10.21105/joss.01686.

Wickham, H., François, R., Henry, L., & Müller, K. (2022). dplyr: A Grammar of Data Manipulation. R package version 1.0.8. https://CRAN.R-project.org/package=dplyr

Wunderling, N., Willeit, M., Donges, J. F., and Winkelmann, R. (2020). Global warming due to loss of large ice masses and Arctic Summer Sea ice. Nature Communications, 11(1). https://doi.org/10.1038/s41467-020-18934-3

Würsig, B., & Koski, W. (2021). Natural and potentially disturbed behavior of Bowhead Whales. The Bowhead Whale, 339–363. https://doi.org/10.1016/b978-0-12-818969-6.00023-6

Xu, S., Kim, E., & Haugen, S. (2021). Review and comparison of existing risk analysis models applied within shipping in ice-covered waters. Safety Science, 141, 105335. https://doi.org/10.1016/j.ssci.2021.105335

Zhang, C., Zhang, D., Zhang, M., Lang, X., and Mao, W. (2020). An integrated risk assessment model for safe arctic navigation. Transportation Research Part A: Policy and Practice, 142, 101–114. https://doi.org/10.1016/j.tra.2020.10.017

Zhang, M., Zhang, D., Zhang, C., & Cao, W. (2020). Navigational risk factor analysis of Arctic shipping in ice-covered waters. Maritime Transport and Regional Sustainability, 153–177. https://doi.org/10.1016/b978-0-12-819134-7.00010-1

Zhang, Z. (2018). Text Mining for Social and Behavioral Research Using R: A Case Study on Teaching Evaluation. Retrievable from https://books.psychstat.org/textmining.

Zhou, X. (2022). A comprehensive framework for assessing navigation risk and deploying maritime emergency resources in the South China Sea. Ocean Engineering, 248, 110797. https://doi.org/10.1016/j.oceaneng.2022.110797

Zhu, S., Ng, A., Afenyo, M., Panahi, R., & Bell, M. (2023). Socio-economic impacts of shipping along the Northwest Passage: The cost to locals. Marine Policy, 153, 105647. https://doi.org/10.1016/j.marpol.2023.105647

Appendices

Appendix 1: List of Definitions

Table 19. List of terms adopted from IPCC Working Group II – AR6 (IPCC, 2022).

Term	Definition
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.
Impact	The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.
Risk	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.
Risk assessment	The qualitative and/or quantitative scientific estimation of *risks*. See also *Risk*, *Risk management* and *Risk perception*.
Risk management	Plans, actions, strategies or policies to reduce the *likelihood* and/or consequences of *risks* or to respond to consequences. See also *Risk*, *Risk assessment* and *Risk perception*.
Risk perception	The subjective judgment that people make about the characteristics and severity of a *risk*. See also *Risk*, *Risk assessment* and *Risk management*.
Sensitivity	The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Appendix 2: List of Structured Analytical Techniques Considered

Table 20. List of Structured Analytical Technique (SAT) considered that are adopted from Arctic Council, IMO, and ISO guidelines (Arctic Council, 2020; IMO, 2018; ISO, 2009).

SAT	SAT Description	RID	RAnys	RAsmt
Brainstorming	A means of collecting a broad set of ideas and evaluation, ranking them by a team. Brainstorming may be stimulated by prompts or by one-on-one and one-on-many interview techniques.	SA	NA	NA
Structured or Semi-structured interviews	A means of collecting a broad set of ideas and evaluation, ranking them by a team. Brainstorming may be stimulated by prompts or by one-on-one and one-on-many interview techniques.	SA	NA	NA
Delphi	A means of combining expert opinions that may support the source and influence identification, probability and consequence estimation and risk evaluation. It is a collaborative technique for building consensus among experts. Involving independent analysis and voting by experts.	SA	NA	NA
Check-lists	A simple form of risk identification. A technique which provides a listing of typical uncertainties which need to be considered. Users refer to a previously developed list, codes or standards.	SA	NA	NA
Preliminary hazard analysis	A simple inductive method of analysis whose objective is to identify the hazards and hazardous situations and events that can cause harm for a given activity, facility or system.	SA	NA	NA
Hazard and operatablilty study	A general process of risk identification to define possible deviations from the expected or intended performance. It uses a guideword based system.	SA	A	A
Hazard Analysis and Critical Control Points (HACCP)	A systematic, proactive, and preventive system for assuring product quality, reliability and safety of processes by measuring and monitoring specific characteristics which are required to be within defined limits.	SA	A	NA
Environmental risk assessment	Hazards are identified and analysed and possible pathways by which a specified target might be exposed to the hazard are identified. Information on the level of exposure and the nature of harm caused by a given level of exposure are combined to give a measure of the probability that the specified harm will occur.	SA	SA	SA
Structure "What if?"(SWIFT)	A system for prompting a team to identify risks. Normally used within a facilitated workshop. Normally linked to a risk analysis and evaluation technique.	SA	SA	SA
Scenario analysis	Possible future scenarios are identified through imagination or extrapolation from the present and different risks considered assuming each of these scenarios might occur. This can be done formally or informally qualitatively or quantitatively.	SA	A	A
Business impact analysis	Hazards are identified and analysed and possible pathways by which a specified target might be exposed to the hazard are identified. Information on the level of exposure and the nature of harm caused by a given level of exposure are combined to give a measure of the probability that the specified harm will occur.	SA	A	A
Root cause analysis	A single loss that has occurred is analysed in order to understand contributory causes and how the system or process can be improved to avoid such future losses. The analysis shall consider what controls were in place at the time the loss occurred and how controls might be improved.	NA	SA	SA
Failure mode, effect, and criticality analysis	Failure Mode and Effect Analysis may be followed by a criticality analysis which defines the significance of each failure mode, qualitatively, semi-qualitatively, or quantitatively (FMECA). The criticality analysis may be based on the probability that the failure mode will result in system failure, or the level of risk associated with the failure mode, or a risk priority number.	SA	SA	SA
Fault tree analysis	A technique which starts with the undesired event (top event) and determines all the	A	A	A

	ways in which it could occur. These are displayed graphically in a logical tree diagram. Once the fault tree has been developed, consideration should be given to ways of reducing or eliminating potential causes / sources.			
Event tree analysis	Using inductive reasoning to translate probabilities of different initiating events into possible outcomes.	A	A	NA
Cause and consequence analysis	A combination of fault and event tree analysis that allows inclusion of time delays. Both causes and consequences of an initiating event are considered.	A	SA	A
Cause-and-effect anlaysis	An effect can have a number of contributory factors which may be grouped into different categories. Contributory factors are identified often through brainstorming and displayed in a tree structure or fishbone diagram.	SA	A	NA
Layer protection analysis (LOPA)	(May also be called barrier analysis). It allows controls and their effectiveness to be evaluated.	A	A	NA
Decision tree	A risk index is a semi-quantitative measure of risk which is an estimate derived using a scoring approach using ordinal scales. Risk indices can be used to rate a series of risks using similar criteria so that they can be compared. Scores are applied to each component of risk, for example contaminant characteristics (sources), the range of possible exposure pathways and the impact on the receptors.	NA	SA	A
Human reliability analysis	Human reliability assessment (HRA) deals with the impact of humans on system performance and can be used to evaluate human error influences on the system.	SA	SA	A
Bow tie analysis	A simple diagrammatic way of describing and analyzing the pathways of a risk from hazards to outcomes and reviewing controls. It can be considered to be a combination of the logic of a fault tree analyzing the cause of an event (represented by the knot of a bow tie) and an event tree analyzing the consequences.	NA	SA	A
Reliability centered maintenance	A method to identify the policies that should be implemented to manage failures so as to efficiently and effectively achieve the required safety, availability and economy of operation for all types of equipment.	SA	SA	SA
Sneak circuit analysis	A methodology for identifying design errors. A sneak condition is a latent hardware, software, or integrated condition that may cause an unwanted event to occur or may inhibit a desired event and is not caused by component failure. These conditions are characterized by their random nature and ability to escape detection during the most rigorous of standardized system tests. Sneak conditions can cause improper operation, loss of system availability, program delays, or even death or injury to personnel.	A	NA	NA
Markov analysis	A simple diagrammatic way of describing and analysing the pathways of a risk from hazards to outcomes and reviewing controls. It can be considered to be a combination of the logic of a fault tree analysing the cause of an event (represented by the knot of a bow tie) and an event tree analysing the consequences.	A	NA	NA
Monte Carlo simulation	Monte Carlo simulation is used to establish the aggregate variation in a system resulting from variations in the system, for a number of inputs, where each input has a defined distribution and the inputs are related to the output via defined relationships. The analysis can be used for a specific model where the interactions of the various inputs can be mathematically defined. The inputs can be based upon a variety of distribution types according to the nature of the uncertainty they are intended to represent. For risk assessment, triangular distributions or beta distributions are commonly used.	NA	NA	SA
Bayesian statistics and bayes nets	A statistical procedure which utilizes prior distribution data to assess the probability of the result. Bayesian analysis depends upon the accuracy of the prior distribution to deduce an accurate result. Bayesian belief networks model cause-and-effect in a variety of domains by capturing probabilistic relationships of variable inputs to derive a result.	NA	A	SA
FN curves	A risk index is a semi-quantitative measure of risk which is an estimate derived using a scoring approach using ordinal scales. Risk indices can be used to rate a series of risks using similar criteria so that they can be compared. Scores are applied to each component of risk, for example contaminant characteristics (sources), the range of	A	SA	SA

	possible exposure pathways and the impact on the receptors.			
Risk indices	A risk index is a semi-quantitative measure of risk which is an estimate derived using a scoring approach using ordinal scales. Risk indices can be used to rate a series of risks using similar criteria so that they can be compared. Scores are applied to each component of risk, for example contaminant characteristics (sources), the range of possible exposure pathways and the impact on the receptors. A risk index is a semi-quantitative measure of risk which is an estimate derived using a scoring approach using ordinal scales. Risk indices can be used to rate a series of risks using similar criteria so that they can be compared. Scores are applied to each component of risk, for example contaminant characteristics (sources), the range of possible exposure pathways and the impact on the receptors.	A	SA	SA
Consequence / probability matrix	A consequence/probability matrix is used to rank risks, sources of risk or risk treatments on the basis of the level of risk. It is commonly used as a screening tool when many risks have been identified, for example to define which risks need further or more detailed analysis.	SA	SA	A
Cost/benefit analysis	Cost/benefit analysis can be used for risk evaluation where total expected costs are weighed against the total expected benefits in order to choose the best or most profitable option.	A	A	A
Multi-criteria decision analysis (MCDA)	MCDA can be used for comparing multiple options for a first pass analysis to determine preferred and potential options and inappropriate options.	A	SA	A

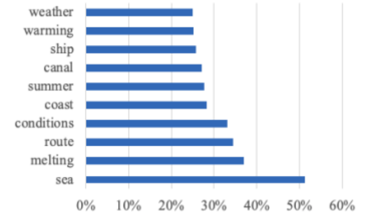
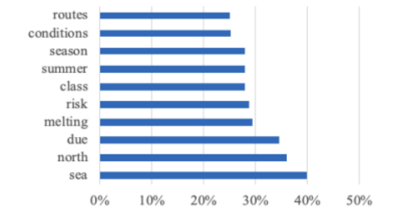
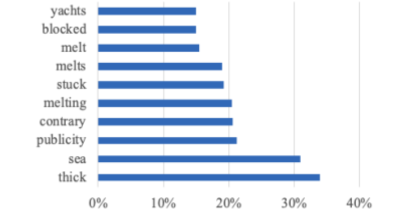
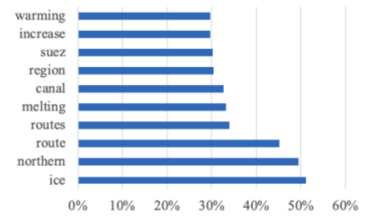
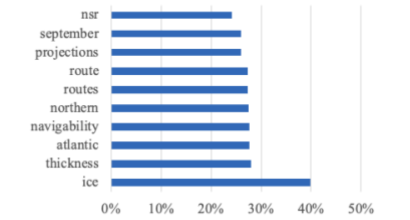
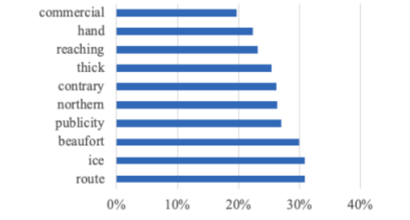
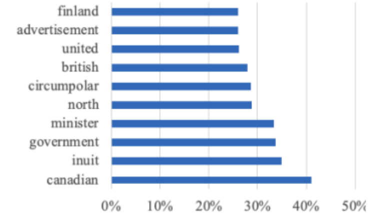
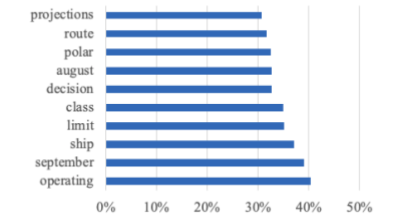
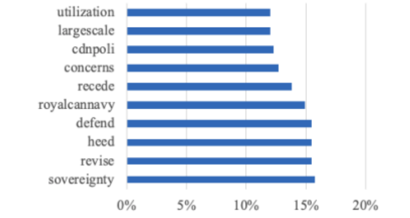
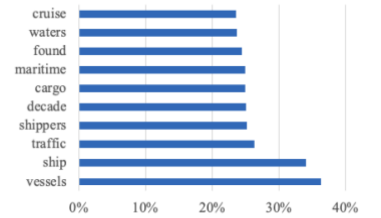
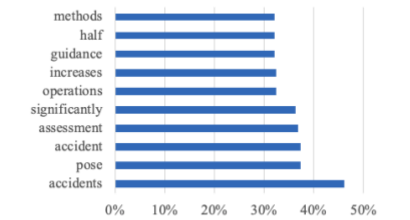
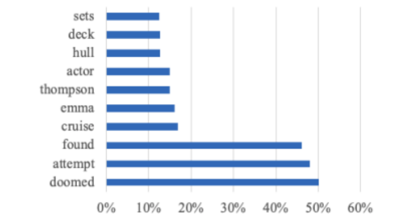
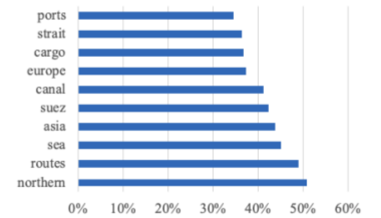
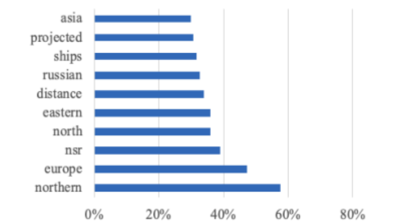
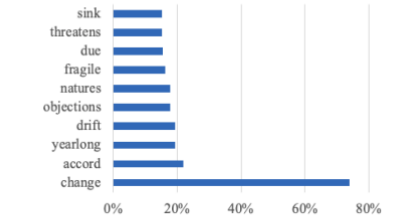
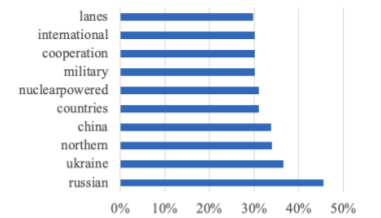
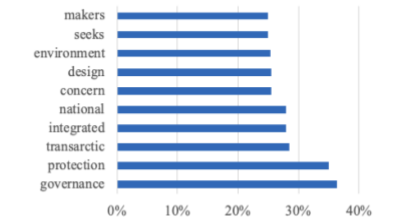
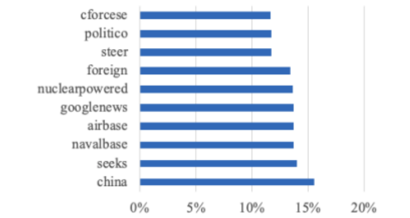
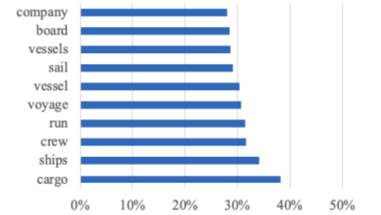
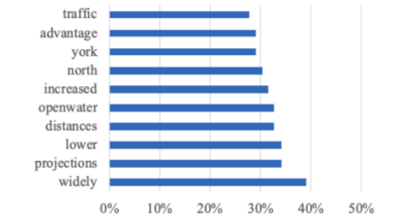
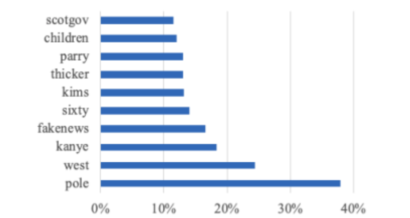
Note: RID - Risk Identification, RAnys - Risk Analysis, RAsmt - Risk Assessment, SA - Strongly Applicable, NA - Not Applicable, A - Applicable. Highlighted rows within the table above indicate the uses within the Methods section.

Appendix 3: List of Data Observations Collected by Year (Chronologically) via Data Source

Table 21. Breakdown of Yearly Data Observations Collected for Textual Analysis

News Articles		Publications		Social Media	
Year	*Value*	*Year*	*Value*	*Year*	*Value*
2006	1	2000	1	2010	17
2007	1	2003	1	2011	84
2009	1	2004	1	2012	157
2010	3	2005	1	2013	275
2011	7	2006	4	2014	338
2012	8	2007	3	2015	556
2013	20	2009	5	2016	647
2014	10	2010	4	2017	661
2015	7	2011	3	2018	535
2016	13	2012	2	2019	556
2017	14	2013	4	2020	215
2018	11	2014	7	2021	249
2019	22	2015	4	2022	212
2020	17	2016	3		
2021	21	2017	5		
2022	24	2018	5		
2023	20	2019	6		
		2020	9		
		2021	17		
		2022	13		
		2023	2		

Appendix 4: Word association distribution charts via top 15 most frequent n-gram terms

N-gram Rank	Data Source: *News Article*	Data Source: *Publication*	Data Source: *Social Media*
1			
2			
3			
4			
5			
6			
7			

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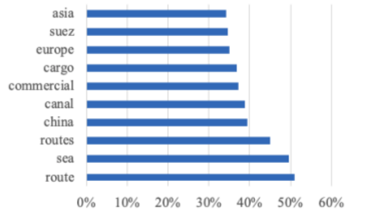
<td>
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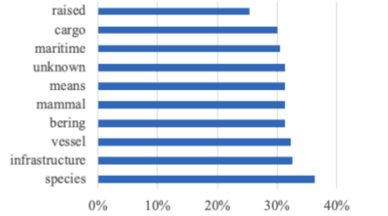
<td>
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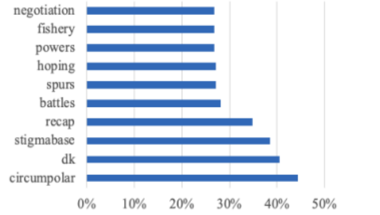
<td>
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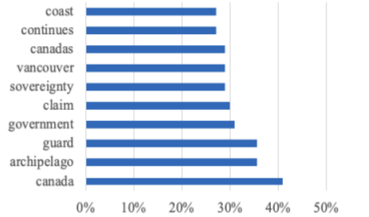
<td>
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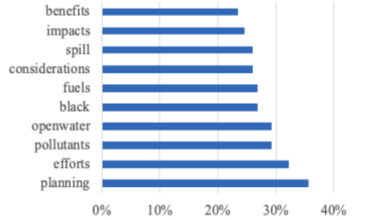
<td>
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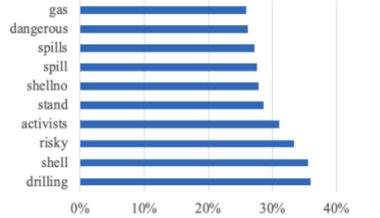
<td>
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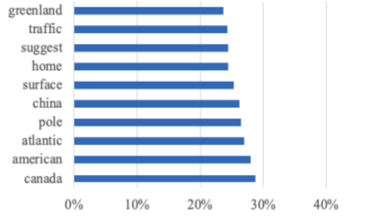
<td>
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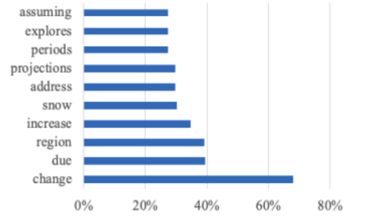
<td>
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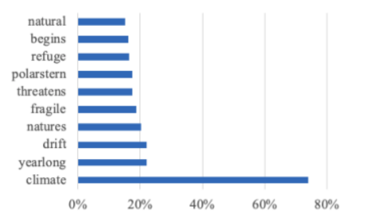
<td>
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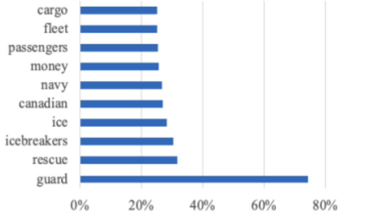
<td>
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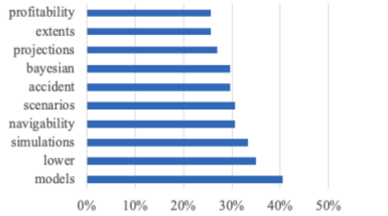
<td>
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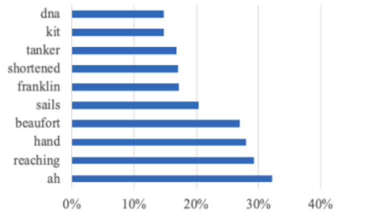
<td>
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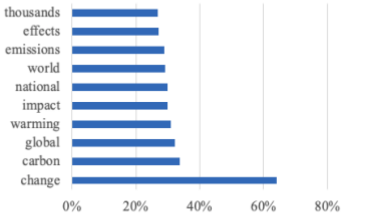
<td>
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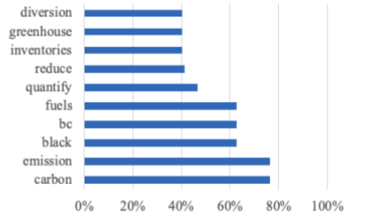
<td>
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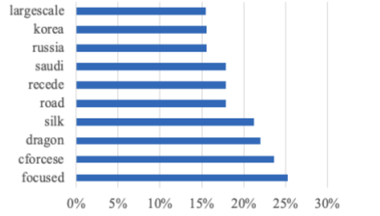
<td>
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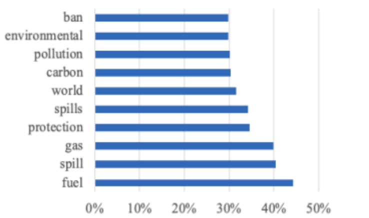
<td>
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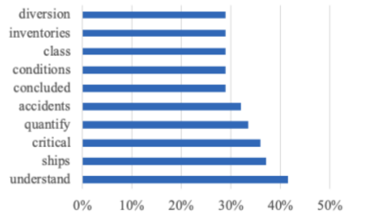
<td>
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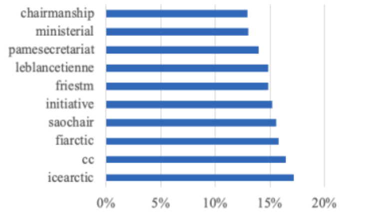
<td>
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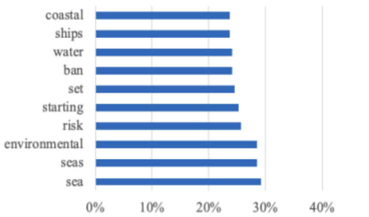
<td>
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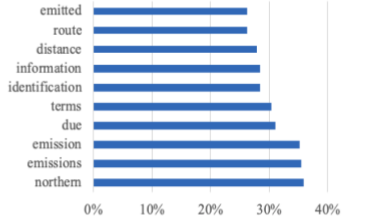
<td>
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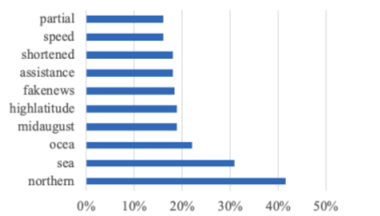
<td>
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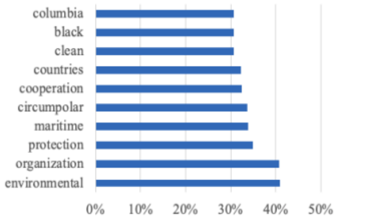
<td>
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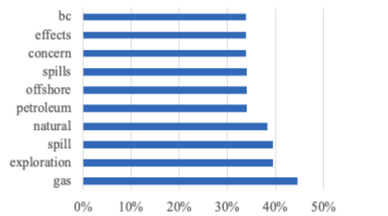
<td>
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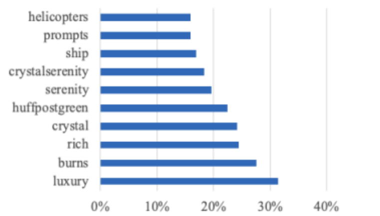
<td>
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Appendix 5: List of FMECA Analysis Articles Selected for Analysis

Table 22. Breakdown of Peer-reviewed Publications used for the FMECA Analysis.

Methodology Used	Lead Author	Article Title	DOI / Link
Content Analysis, FMECA Analysis	**A. Whitman Miller**	Arctic shipping and marine invaders	doi.org/10.1038/nclimate2244
Content Analysis, FMECA Analysis	**Aldo Chircop**	The Growth of International Shipping in the Arctic: Is a Regulatory Review Timely?	DOI: 10.1163/157180809X421699
Content Analysis, FMECA Analysis	**Ali Cheaitou**	Impact of CO2 emission taxation and fuel types on Arctic shipping attractiveness	doi.org/10.1016/j.trd.2022.103491
Content Analysis, FMECA Analysis	**Aurélie Sarrabezoles**	Arctic shipping insurance: towards a harmonisation of practices and costs?	doi:10.1017/S0032247414000552
Content Analysis, FMECA Analysis	**Bryan Comer**	Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025.	DOI: http://dx.doi.org/10.25607/OBP-1733
Content Analysis, FMECA Analysis	**Charles Ebinger**	The geopolitics of Arctic melt	doi.org/10.1111/j.1468-2346.2009.00858.x
Content Analysis, FMECA Analysis	**Christian Haas**	Ice thickness in the Northwest Passage	doi.org/10.1002/2015gl065704
Content Analysis, FMECA Analysis	**Chunjuan Wang**	Spatial match analysis of multiple factors in the geopolitical environment of the Arctic Passage.	doi.org/10.1371/journal.pone.0270262
Content Analysis, FMECA Analysis	**Chuya Wang**	Risk Assessment of Ship Navigation in the Northwest Passage: Historical and Projection	doi.org/10.3390/su14095591
Content Analysis, FMECA Analysis	**Danyue Jing**	CO2 emission projection for Arctic shipping: A system dynamics approach	doi.org/10.1016/j.ocecoaman.2021.105531
Content Analysis, FMECA Analysis	**Darko Špoljar**	Modelling GPS Positioning Performance in Northwest Passage during Extreme Space Weather Conditions	doi.org/10.12716/1001.15.01.16
Content Analysis, FMECA Analysis	**Diana Pietri**	The Arctic Shipping and Environmental Management Agreement: A Regime for Marine Pollution	doi.org/10.1080/08920750802398735
Content Analysis, FMECA Analysis	**Dongqin Lu**	An Economic Analysis of Container Shipping Through Canadian Northwest Passage	doi.org/10.1016/j.enavi.2014.12.001
Content Analysis, FMECA Analysis	**Donna Hausser**	Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route	https://doi-org.proxy.bib.uottawa.ca/10.1073/pnas.1803543115
Content Analysis, FMECA Analysis	**Erik J. Molenaar**	Status and Reform of International Arctic Shipping Law	doi.org/10.1007/978-3-642-38595-7_6
Content Analysis, FMECA Analysis	**Frédéric Lasserre**	Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector	doi.org/10.1016/j.tra.2014.05.005
Content Analysis,	**Frédéric Lasserre**	Simulations of shipping along Arctic routes: comparison,	doi.org/10.1017/S0032247413000958

FMECA Analysis		analysis and economic perspectives	
Content Analysis, FMECA Analysis	**G. P. Peters**	Future emissions from shipping and petroleum activities in the Arctic	doi:10.5194/acp-11-5305-2011
Content Analysis, FMECA Analysis	**Haakan Lindstad**	Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation	doi.org/10.1016/j.tranpol.2015.09.002
Content Analysis, FMECA Analysis	**Heng Qian**	Dynamic risk assessment of natural environment based on Dynamic Bayesian Network for key nodes of the arctic Northwest Passage	doi.org/10.1016/j.oceaneng.2020.107205
Content Analysis, FMECA Analysis	**Iu Guzov**	Factors of technological development of the Northern Sea Route	doi.org/10.1088/1755-1315/678/1/012021
Content Analysis, FMECA Analysis	**Ivana Kubat**	YEAR-ROUND SHIPPING IN THE CANADIAN ARCTIC: ICE CONDITIONS AND REGULATORY REQUIREMENTS	https://nrc-publications.canada.ca/eng/view/object/?id=e25a3403-c93b-4c34-bee5-0a63df709e52
Content Analysis, FMECA Analysis	**J. J. Corbett**	Arctic shipping emissions inventories and future scenarios	doi.org/10.5194/acp-10-9689-2010
Content Analysis, FMECA Analysis	**Jackie Dawson**	Analysis of Changing Levels of Ice Strengthening (Ice Class) among Vessels Operating in the Canadian Arctic over the Past 30 Years.	doi.org/10.14430/arctic75553
Content Analysis, FMECA Analysis	**Jackie Dawson**	Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015	doi.org/10.14430/arctic4698
Content Analysis, FMECA Analysis	**Jin-Lei Chen**	Variation of sea ice and perspectives of the Northwest Passage in the Arctic Ocean	doi.org/10.1016/j.accre.2021.02.002
Content Analysis, FMECA Analysis	**Jin-Lei Chen**	Projected changes in sea ice and the navigability of the Arctic Passages under global warming of 2 ℃ and 3 ℃	doi.org/10.1016/j.ancene.2022.100349
Content Analysis, FMECA Analysis	**Jo Browse**	Impact of future Arctic shipping on high-latitude black carbon deposition	doi:10.1002/grl.50876
Content Analysis, FMECA Analysis	**Joshua Ho**	The implications of Arctic sea ice decline on shipping	https://doi.org/10.1016/j.marpol.2009.10.009
Content Analysis, FMECA Analysis	**Julia Olsen**	Community perspectives on the environmental impacts of Arctic shipping: Case studies from Russia, Norway and Canada	doi.org/10.1080/23311886.2019.1609189
Content Analysis, FMECA Analysis	**Julian Roberts**	Proactive environmental planning for emerging shipping routes in Arctic waters	https://doi-org.proxy.bib.uottawa.ca/10.1007/BF03195115 https://doi-org.proxy.bib.uottawa.ca/10.1007/BF03195115 https://doi-org.proxy.bib.uottawa.ca/10.1007/BF03195115
Content Analysis, FMECA Analysis	**Karen E. Kelley**	Policies and practicalities of shipping in arctic waters: Inuit perspectives from Cape Dorset, Nunavut	https://doi.org/10.1080/1088937X.2012.666768
Content Analysis, FMECA Analysis	**Kristin Bartenstein**	Between the Polar Code and Article 234: The Balance in Canada's Arctic Shipping Safety and Pollution Prevention Regulations	doi.org/10.1080/00908320.2019.1617932
Content Analysis, FMECA Analysis	**Laurence Smith**	New Trans-Arctic shipping routes navigable by midcentury	doi.org/10.1073/pnas.121421211

Content Analysis, FMECA Analysis	**Longjiang Mu**	Arctic Ice Ocean Prediction System: evaluating sea-ice forecasts during Xuelong's first trans-Arctic Passage in summer 2017	doi.org/10.1017/jog.2019.55
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FMECA Analysis	Serdar Kum	A root cause analysis for Arctic Marine accidents from 1993 to 2011	doi.org/10.1016/j.ssci.2014.12.010
FMECA Analysis	Shanshan Fu	An object-oriented Bayesian network model for the quantitative risk assessment of navigational accidents in ice-covered Arctic waters	doi.org/10.1016/j.ress.2023.109459
FMECA Analysis	Shanshan Fu	Arctic shipping risk management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents	doi.org/10.1016/j.ssci.2021.105254
FMECA Analysis	Sue E. Moore	A New Framework for Assessing the Effects of Anthropogenic Sound on Marine Mammals in a Rapidly Changing Arctic	doi.org/10.1525/bio.2012.62.3.10
FMECA Analysis	William D. Halliday	Overlap between bowhead whales (Balaena mysticetus) and vessel traffic in the North American Arctic and implications for conservation and management	doi.org/10.1016/j.biocon.2022.109820
FMECA Analysis	William D. Halliday	Vessel risks to marine wildlife in the Tallurutiup Imanga National Marine Conservation Area and the eastern entrance to the Northwest Passage	doi.org/10.1016/j.envsci.2021.10.026
FMECA Analysis	Yulong Shan	Generation and Analysis of Gridded Visibility Data in the Arctic	doi.org/10.3390/atmos10060314

Appendix 6: Failure Modes, Effects and Criticality Analysis (FMECA) Worksheet

FMECA DATA OBSERVATION WORKSHEET

General Information:

Source:			
Type of study:	Theoretical / Observational / Hybrid		
Availability	Y/N/U	**Region:**	
SME opinion?	Y/N/U	**Sample size:**	
Data Deficient?	Y/N/U	**Data source:**	
Data source(s):			
Hazard/Risk:	Hazard / Risk		
Category:			
Name:			
Description:			
Consequence:		**explanation:**	
Probability:		**explanation:**	

Cause and Consequence Information:

Cause/Consequence	**Name of Cause/consequence**	**Direct/indirect**
cause		
consequence		

Controls Information:

Control category	**Name of control**	**Presently operational?**
		Yes / No / Unknown
		Yes / No / Unknown

Notes: Y- Yes, N - No, U - Unknown

Appendix 7: List of Arctic Shipping Risk Variables

Table 23. Comprehensive list of individual Arctic shipping risks related to maritime ship operations listed via risk rating score.

Thematic group	Risk Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
Community	Community member displacement	VERY HIGH	50.00	LOW	Medium agreement, Limited evidence	35.8%
Pollutants	Hydrocarbon release	VERY HIGH	45.00	MODERATE	Medium agreement, Medium evidence	47.0%
Social	Socioeconomic impacts on indigenous peoples	VERY HIGH	38.25	LOW	Low agreement, Medium evidence	37.9%
Community	Cultural and archaeological threat	HIGH	34.67	MODERATE	Medium agreement, Medium evidence	59.5%
Social	Lack of clean up infrastructure response	HIGH	34.00	MODERATE	Medium agreement, Medium evidence	57.9%
Community	Tourist overcrowding	HIGH	34.00	MODERATE	Low agreement, Medium evidence	41.2%
Environmental	Operational discharges	HIGH	33.40	HIGH	High agreement, Medium evidence	76.0%
Community	Lack of Inuit agency	HIGH	33.00	HIGH	High agreement, Medium evidence	64.8%
Pollutants	Black carbon land deposition	HIGH	32.94	MODERATE	Medium agreement, Medium evidence	59.9%
Community	Degradation of indigenous cultural and natural resources	HIGH	32.80	HIGH	High agreement, Medium evidence	73.2%
Environmental	Underwater noise pollution	HIGH	32.55	HIGH	High agreement, Medium evidence	66.8%
Social	Reduction in resources to locals	HIGH	32.00	HIGH	Medium agreement, Medium evidence	60.1%
Community	Lack of support for indigenous communities	HIGH	31.50	HIGH	Medium agreement, Medium evidence	60.3%
Pollutants	Black carbon air emissions	HIGH	31.23	HIGH	High agreement, Medium evidence	73.8%
Environmental	Exploitation of natural reserves	HIGH	30.56	HIGH	High agreement, Medium evidence	75.8%
Economic	Fluctuating fuel prices	HIGH	30.00	MODERATE	Medium agreement, Medium evidence	58.3%
Economic	Oil spill clean-up costs	HIGH	29.88	HIGH	High agreement, Medium evidence	68.8%
Navigational	Vessel ice classification	HIGH	29.17	MODERATE	Check Formula, Medium evidence	56.9%
Environmental	Travelling through marine protected areas	HIGH	29.06	HIGH	High agreement, Medium evidence	64.8%
Operational	Reduced search and rescue capacity	HIGH	29.01	HIGH	High agreement, Medium evidence	72.9%
Social	Lacking shipping infrastructure and services	HIGH	28.00	HIGH	High agreement, Medium evidence	73.4%
Environmental	Reduced ecosystem recovery time	HIGH	28.00	HIGH	High agreement, Medium evidence	68.4%
Community	Declining local air quality	HIGH	28.00	MODERATE	Medium agreement, Medium evidence	42.0%

Thematic group	Risk Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
Environmental	Vessel-Source Pollution in Sensitive Marine Regions	HIGH	28.00	MODERATE	Medium agreement, Medium evidence	42.0%
Environmental	Vulnerability of Arctic marine mammals	HIGH	28.00	MODERATE	Low agreement, Medium evidence	41.8%
Community	Declining physical health of community	HIGH	28.00	LOW	Low agreement, Medium evidence	37.8%
Political	Sovereignty claims and disputes	HIGH	27.08	HIGH	High agreement, Medium evidence	74.7%
Operational	Insufficient training and/or expertise	HIGH	26.56	MODERATE	Medium agreement, Medium evidence	56.6%
Sea Ice	Sea ice (generalized)	HIGH	26.51	HIGH	High agreement, Medium evidence	69.1%
Environmental	Animal disturbance	HIGH	26.25	HIGH	High agreement, Medium evidence	71.0%
Social	Accessibility to local communities	HIGH	26.25	LOW	Low agreement, Medium evidence	34.1%
Economic	Variable insurance costs	HIGH	25.78	HIGH	High agreement, Medium evidence	68.2%
Pollutants	BC Climate Forcing	HIGH	25.60	HIGH	High agreement, Medium evidence	68.2%
Human	Decision failure	HIGH	25.50	LOW	Low agreement, Medium evidence	39.9%
Human	Operator miscommunication	HIGH	25.50	LOW	Low agreement, Medium evidence	39.9%
Pollutants	Oil spills on ice	HIGH	25.50	LOW	Low agreement, Medium evidence	36.7%
Political	Enforceability and accountability limitations regarding laws/regulations	HIGH	25.33	HIGH	High agreement, Medium evidence	73.4%
Environmental	Introduction of invasive species	HIGH	25.33	HIGH	High agreement, Medium evidence	75.4%
Navigational	Vessel-animal collision	HIGH	25.19	MODERATE	Medium agreement, Medium evidence	56.0%
Navigational	Absence of layover sites	HIGH	25.00	MODERATE	Medium agreement, Medium evidence	56.1%
Pollutants	Oil spill (HFO)	MODERATE	24.92	HIGH	High agreement, Medium evidence	63.5%
Assessment	Lack of risk analysis	MODERATE	24.84	HIGH	High agreement, Medium evidence	75.0%
Assessment	Field-model descrepencies	MODERATE	24.75	MODERATE	Low agreement, Medium evidence	44.5%
Assessment	Dependance on climate modelling	MODERATE	24.75	MODERATE	Low agreement, Medium evidence	41.4%
Political	Geo-cultural differences	MODERATE	24.75	MODERATE	Low agreement, Medium evidence	41.4%
Operational	Vessel equipment and safety	MODERATE	24.75	LOW	Low agreement, Medium evidence	33.9%
Navigational	Vessel traffic congestion	MODERATE	24.69	HIGH	High agreement, Medium evidence	63.9%
Navigational	Traffic intensification	MODERATE	24.36	HIGH	High agreement, Medium evidence	74.5%
Economic	Variable profit margins	MODERATE	24.00	HIGH	High agreement, Medium evidence	76.9%

Thematic group	Risk Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
Social	Tourism	MODERATE	24.00	HIGH	High agreement, Medium evidence	72.4%
Economic	Cargo volume intensification	MODERATE	24.00	HIGH	Medium agreement, Medium evidence	61.5%
Assessment	Lacking modelling	MODERATE	23.83	HIGH	High agreement, Medium evidence	73.9%
Navigational	Lacking navigation tools	MODERATE	23.63	HIGH	High agreement, Medium evidence	75.7%
Operational	Fuel consumption	MODERATE	23.11	MODERATE	Medium agreement, Medium evidence	51.4%
Political	Lack of clear policy and/or regulations	MODERATE	23.08	HIGH	High agreement, Medium evidence	70.0%
Social	Rapid tourism growth	MODERATE	23.00	HIGH	High agreement, Medium evidence	76.1%
Assessment	Lack of data	MODERATE	22.50	HIGH	High agreement, Medium evidence	79.4%
Navigational	Accessibility to NWP	MODERATE	22.00	LOW	Low agreement, Medium evidence	38.4%
Community	Community resident safety	MODERATE	21.25	LOW	Low agreement, Medium evidence	38.7%
Operational	Insufficient tug assistance	MODERATE	21.25	LOW	Low agreement, Medium evidence	36.5%
Operational	Lack of emergency planning	MODERATE	21.22	HIGH	High agreement, Medium evidence	70.8%
Political	Competing global interests	MODERATE	21.14	HIGH	High agreement, Medium evidence	72.1%
Operational	Lack of monitoring capabilities	MODERATE	21.08	HIGH	High agreement, Medium evidence	72.5%
Technological	Limited Application of BC Abatement Technologies	MODERATE	21.00	MODERATE	Medium agreement, Medium evidence	45.1%
Technological	Lacking technological advances	MODERATE	20.80	HIGH	High agreement, Medium evidence	72.7%
Navigational	Vessel accident (generalized)	MODERATE	20.60	HIGH	High agreement, Medium evidence	73.0%
Political	Ununified technical standards	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	51.8%
Economic	Financial burden to small-scale operators/communities	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	49.8%
Community	Lost sense of wildness, isolation, and exclusiveness	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	48.3%
Environmental	National heritage degration	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	48.3%
Political	Geo-military factors	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	45.6%
Navigational	Vessel capsizing	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	45.3%
Assessment	Inadequate tools for socioeconomic impact assessment	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	45.1%
Political	Legal dispute over northwest passage status	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	42.0%
Economic	No toll requirements	MODERATE	20.00	LOW	Medium agreement, Limited evidence	35.8%

Thematic group	Risk Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
Economic	Fluctuation in shipping cost	MODERATE	19.63	HIGH	High agreement, Medium evidence	78.3%
Political	Complex regulations	MODERATE	19.57	VERY HIGH	High agreement, Medium evidence	81.4%
Navigational	Iceberg collision	MODERATE	19.39	HIGH	High agreement, Medium evidence	77.6%
Economic	Lack of insurance information disclosure	MODERATE	19.25	MODERATE	Medium agreement, Medium evidence	42.1%
Environmental	Species population migration/change	MODERATE	18.75	MODERATE	Medium agreement, Medium evidence	43.4%
Navigational	Sinking vessel	MODERATE	18.67	HIGH	High agreement, Medium evidence	63.5%
Operational	Lack of operator situational awareness	MODERATE	18.67	MODERATE	Medium agreement, Medium evidence	52.7%
Navigational	Vessel grounding	MODERATE	18.20	HIGH	High agreement, Medium evidence	69.1%
Operational	Load capacity	MODERATE	18.00	MODERATE	Medium agreement, Medium evidence	45.4%
Operational	Poor communication between vessels	MODERATE	17.84	HIGH	High agreement, Medium evidence	73.1%
Navigational	Improper route selection	MODERATE	17.44	MODERATE	Medium agreement, Medium evidence	57.0%
Navigational	Vessel-vessel collision	MODERATE	17.33	HIGH	High agreement, Medium evidence	73.8%
Political	Insufficient Arctic shipping jurisdiction	MODERATE	17.33	HIGH	High agreement, Medium evidence	69.5%
Navigational	Ship stuck in ice	MODERATE	15.89	HIGH	High agreement, Medium evidence	77.0%
Political	Trading implications/competitions	MODERATE	15.00	HIGH	High agreement, Medium evidence	65.3%
Technological	Technical errors due to Geomagnetic storms	MODERATE	14.00	MODERATE	Medium agreement, Medium evidence	48.3%
Operational	Vessel alarm and sensor malfunction	MODERATE	13.33	MODERATE	Medium agreement, Medium evidence	46.2%
Navigational	Unfamiliar route planning	MODERATE	12.00	MODERATE	Medium agreement, Medium evidence	57.8%
Assessment	Frequent calibration of model parameters	MODERATE	12.00	MODERATE	Medium agreement, Medium evidence	48.3%
Operational	Inadequate bunkering planning	MODERATE	12.00	MODERATE	Medium agreement, Medium evidence	45.1%
Navigational	Deviation from suggested route	MODERATE	10.50	LOW	Low agreement, Medium evidence	39.1%
Operational	Hull failure	MODERATE	10.00	MODERATE	Medium agreement, Medium evidence	45.1%
Operational	Improper bunker line-up	UNDETECTABLE	8.00	MODERATE	Medium agreement, Medium evidence	45.1%
Operational	Vessel-barge bunkering communication	UNDETECTABLE	8.00	MODERATE	Medium agreement, Medium evidence	45.1%

Appendix 8: List of Arctic Shipping Hazard Variables

Table 24. Comprehensive list of individual Arctic shipping hazards related to maritime ship operations listed via risk rating score.

ID	Thematic group	Hazard Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
H063	Operational	Transportation of dangerous goods	**VERY HIGH**	**41.36**	HIGH	High agreement, Medium evidence	72.5%
H043	Sea Ice	Multi-year sea ice	**VERY HIGH**	**36.31**	VERY HIGH	High agreement, Robust evidence	80.5%
H004	Pollutants	Air emissions (generalized)	**HIGH**	**35.54**	VERY HIGH	High agreement, Medium evidence	80.1%
H026	Pollutants	HFO carriage and transport	**HIGH**	**35.00**	HIGH	High agreement, Medium evidence	66.1%
H001	Pollutants	Above-water noise pollution	**HIGH**	**35.00**	MODERATE	Medium agreement, Medium evidence	46.8%
H033	Sea Ice	Iceberg presence	**HIGH**	**33.00**	MODERATE	Medium agreement, Medium evidence	52.4%
H037	Operational	Lack of icebreaking capability	**HIGH**	**31.00**	MODERATE	Medium agreement, Medium evidence	59.8%
H045	Navigational	Navigational obstacles	**HIGH**	**30.40**	HIGH	High agreement, Medium evidence	68.3%
H056	Sea Ice	Sea ice melt	**HIGH**	**30.05**	HIGH	High agreement, Robust evidence	78.1%
H042	Pollutants	Methane emissions	**HIGH**	**30.00**	MODERATE	Medium agreement, Medium evidence	51.3%
H007	Environmental	Animal mortality	**HIGH**	**30.00**	MODERATE	Medium agreement, Medium evidence	46.8%
H050	Environmental	Pollutant harms to marine life	**HIGH**	**29.75**	MODERATE	Medium agreement, Medium evidence	55.4%
H048	Navigational	Operating in shallow waters	**HIGH**	**28.88**	VERY HIGH	High agreement, Robust evidence	81.0%
H016	Environmental	Climate fluctuation	**HIGH**	**28.16**	HIGH	High agreement, Medium evidence	79.2%
H031	Sea Ice	Ice thickness	**HIGH**	**28.00**	MODERATE	Medium agreement, Medium evidence	47.0%
H066	Operational	Unsafe re-fuelling operations	**HIGH**	**28.00**	MODERATE	Medium agreement, Medium evidence	42.0%
H024	Operational	Fire onboard	**HIGH**	**27.75**	HIGH	Medium agreement, Medium evidence	60.9%
H055	Sea Ice	Sea ice concentration	**HIGH**	**27.26**	HIGH	High agreement, Robust evidence	69.6%
H005	Environmental	Animal displacement	**HIGH**	**27.00**	MODERATE	Medium agreement, Medium evidence	50.3%
H023	Environmental	Extreme winter conditions	**HIGH**	**26.83**	HIGH	High agreement, Medium evidence	63.7%
H057	Environmental	Severe weather	**HIGH**	**26.58**	HIGH	High agreement, Medium evidence	67.6%
H025	Sea Ice	First-year sea ice	**HIGH**	**26.56**	MODERATE	Medium agreement, Medium evidence	57.2%
H038	Environmental	Low air temperature	**HIGH**	**26.25**	HIGH	Medium agreement, Medium evidence	61.3%
R061	Environmental	Remoteness	**HIGH**	**25.94**	HIGH	High agreement, Medium evidence	67.5%

ID	Thematic group	Hazard Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
H017	Environmental	Climate impacts	**HIGH**	**25.67**	MODERATE	Medium agreement, Medium evidence	52.1%
H052	Environmental	Physical disturbance to wildlife	**HIGH**	**25.50**	LOW	Low agreement, Medium evidence	38.1%
H019	Operational	Crew inexperience	MODERATE	24.57	HIGH	High agreement, Medium evidence	70.8%
H044	Technological	Navigational aids failure or error	MODERATE	23.59	HIGH	High agreement, Medium evidence	65.7%
H058	Navigational	Ship speeding	MODERATE	22.86	HIGH	High agreement, Medium evidence	78.2%
H039	Environmental	Low visibility	MODERATE	22.69	HIGH	High agreement, Medium evidence	73.6%
H028	Human	Human error	MODERATE	22.40	HIGH	High agreement, Medium evidence	66.7%
H036	Social	Inappropriate tourist behaviour	MODERATE	22.00	MODERATE	Low agreement, Medium evidence	43.1%
H009	Environmental	Bioaccumulation - flora/fauna	MODERATE	21.84	HIGH	High agreement, Medium evidence	67.1%
H010	Social	Bioaccumulation - human	MODERATE	21.38	MODERATE	Medium agreement, Medium evidence	51.5%
H015	Pollutants	Chemical pollution due to spills	MODERATE	21.33	MODERATE	Medium agreement, Medium evidence	56.8%
H035	Human	Inadequate vessel maintenance	MODERATE	21.00	MODERATE	Medium agreement, Medium evidence	45.1%
H027	Environmental	High wind speeds	MODERATE	20.63	HIGH	High agreement, Medium evidence	72.8%
H003	Pollutants	Acoustic propagation effects	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	48.9%
H002	Pollutants	Accidental discharge of a substance	MODERATE	20.00	MODERATE	Medium agreement, Medium evidence	42.0%
H021	Operational	Excessive ice accumulation on vessels	MODERATE	19.76	HIGH	High agreement, Medium evidence	70.2%
H041	Operational	Mechanical failure	MODERATE	19.60	HIGH	High agreement, Medium evidence	73.9%
H054	Environmental	Sea conditions	MODERATE	19.00	HIGH	High agreement, Medium evidence	68.0%
H029	Human	Human negligence	MODERATE	18.67	MODERATE	Medium agreement, Medium evidence	52.7%
H065	Navigational	Unmaintained safety distance	MODERATE	17.50	MODERATE	Medium agreement, Medium evidence	43.1%
H067	Navigational	Vessel manoeuvre failure	MODERATE	17.00	MODERATE	Medium agreement, Medium evidence	41.2%
H020	Technological	Engine failure	MODERATE	15.63	MODERATE	Medium agreement, Medium evidence	52.1%
H040	Environmental	Marine mammal displacement due to noise	MODERATE	15.00	MODERATE	Medium agreement, Medium evidence	42.0%
H034	Navigational	Impact from other vessels	MODERATE	15.00	LOW	Low agreement, Medium evidence	34.8%
H053	Navigational	Reduced vessel ice strengthening	MODERATE	14.00	MODERATE	Medium agreement, Medium evidence	48.3%
H018	Human	Crew fatigue	MODERATE	14.00	MODERATE	Medium agreement, Medium evidence	45.1%
H061	Operational	Steering gear failure	MODERATE	10.00	MODERATE	Medium agreement, Medium evidence	45.1%

ID	Thematic group	Hazard Name	RR Index	RR Score	DQ Index	Data Quality - Description	DQ Score
H051	Social	Piracy	UNDETECTABLE	8.00	MODERATE	Medium agreement, Medium evidence	45.1%
H013	Operational	Bunker connection hose damaged/ruptured	UNDETECTABLE	4.00	MODERATE	Medium agreement, Medium evidence	45.1%
H014	Operational	Bunkering operations	UNDETECTABLE	4.00	MODERATE	Medium agreement, Medium evidence	45.1%
H070	Social	Violence or violent acts	UNDETECTABLE	2.00	MODERATE	Medium agreement, Medium evidence	48.3%

Appendix 9: List of Thematic group Arctic Shipping Risk Variables

Table 25. Comprehensive list of thematic groups regarding Arctic shipping risks related to maritime ship operations listed via risk rating score.

Acronym	Risk Category	Risk Rating	Risk Score	Data Quality Index	Data Quality Score	Data Quality - Description
COM	Community	HIGH	32.061	MODERATE	50%	Medium agreement, Medium evidence
POL	Pollutants	HIGH	29.383	MODERATE	57%	Medium agreement, Medium evidence
SEA	Sea Ice	HIGH	29.376	HIGH	65%	High agreement, Medium evidence
ENV	Environmental	HIGH	26.374	HIGH	61%	High agreement, Medium evidence
SOC	Social	HIGH	26.116	MODERATE	55%	Medium agreement, Medium evidence
ECN	Economic	MODERATE	24.623	MODERATE	60%	High agreement, Medium evidence
OPS	Operational	MODERATE	23.394	MODERATE	55%	Medium agreement, Medium evidence
ASM	Assessment	MODERATE	22.948	MODERATE	58%	Medium agreement, Medium evidence
NAV	Navigational	MODERATE	22.143	HIGH	60%	High agreement, Medium evidence
HMN	Human	MODERATE	21.755	MODERATE	48%	Medium agreement, Medium evidence
PLT	Political	MODERATE	21.379	HIGH	62%	High agreement, Medium evidence
TEC	Technological	MODERATE	21.233	MODERATE	57%	Medium agreement, Medium evidence