A CASE STUDY FOR ANALYZING FUTURE SCENARIOS OF UNDERWATER NOISE GENERATED BY SHIPPING TRAFFIC IN THE CANADIAN ARCTIC

by

Ana Laura Carvalho Bianco

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Abstract

The decrease of sea ice in the Canadian Arctic got the attention of the shipping community as this fact, associated with economic and social factors such as growing community re-supply needs and adventure tourism, are resulting in a considerable increase of shipping traffic levels and thus underwater radiated noise. Low frequency noise generated by propellers and ship machinery overlaps with sound frequencies used by mammals to communicate, reproduce and navigate, posing risks to the marine fauna.

Therefore, this study proposes a process to estimate the sound level generated by three kinds of vessels (cruise, cargo and tanker ships) in the regions of Lancaster Sound and Baffin Bay, including estimating future ship traffic volumes in 2040. The resulting sound field would depend on ship traffic levels, vessel sizes, changes to ship design which may affect generated noise, operating parameters (particularly vessel speed), and water conditions which can affect sound propagation. This study considers all of these factors.

Vessel traffic throughout the Canadian Arctic has tripled over the past 20 years and is not expected to decline. Through historical data analysis, derived from five years of ship traffic data, regression analysis was used to examine the relationship that the population and gross domestic product of the territory of Nunavut have with the shipping traffic levels and expert opinion was used to estimate most likely values of the noise generated by future fleets. Received Level (RL) and Sound Exposure Levels (SEL) were calculated through Monte-Carlo simulation and results were produced as a probabilistic distribution function (PDF) to understand the potential cumulative shipping noise that adjacent whales may be exposed to.

The results of this study showed higher sound levels expected for the areas, reaching levels that could result in temporary hearing loss, according to thresholds set out by the National Oceanic and Atmospheric Administration. The results also indicate which of the multiple factors considered would have the greatest effect in changing overall noise levels in the future. Modelling the escalation of underwater noise can help for risk mitigation planning and the advancement of spatial and vessel management tools for more sustainable shipping in the Canadian Arctic.

Keywords: Future shipping traffic, Underwater radiated noise, Canadian Arctic, forecasting, sound exposure level, impacts, Monte Carlo

List of Abbreviations and Symbols Used

ACIA Arctic Climate Impact Assessment

ACCOBAMS The Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area

AIRSS Arctic Ice Regime Shipping System

AIS Automatic Information System

AMAP Arctic Monitoring and Assessment Programme

AMSA Arctic Marine Shipping Assessment

CAC Canadian Arctic Class

CFD Computational fluid dynamics

CIS Cavitation inception speed

COSEWIC Committee on the Status of Endangered Wildlife in Canada

CSMAs Culturally Significant Marine Areas

CSV Comma-separated values

dB decibels

DFO Department of Fisheries and Oceans Canada

DOSITS Discovery of Sound in the Sea

DRDC Defence Research and Development Canada

EBSAs Ecologically and Biologically Significant Areas

ECHO Enhancing Cetacean Habitat and Observation

GHG Greenhouse Gas

HELCOM Helsinki Commission

Hz Hertz

IMO International Maritime Organization

IPCC Intergovernmental Panel on Climate Change

IRGC International Risk Governance Council

MEOPAR Marine Environmental Observation Prediction and Response

MMSI Maritime Mobile Service Identity

MTPY Metric Tons Per Year

NIRB Nunavut Impact Review Board

NMCA National Marine Conservation Areas

NMTC The Northern Marine Transportation Corridors

NOAA National Oceanic and Atmospheric Administration (United States)

NORDREG Northern Canada Vessel Traffic Services Zone Regulations

NSIDC National Snow and Ice Data Center

NSR Northern Sea Route

NWP Northwest Passage

PAME Protected Areas Management Effectiveness
PDF Probability Distribution Function
PTS Permanent threshold shift
RL Received Level
SEL Sound Exposure Level
SL Sound Level
SSP Sound Speed Profile
STL Sound Transmission Loss
TC Transport Canada
TdB Time dependent intensity level
TL Transmission Loss
TPK Turns per knot
TTS Temporary threshold shift
UN United Nations
URN Underwater Radiated Noise
WWF World Wildlife Fund
c Wave Speed (m/s)
f Frequency (Hz)
l Vessel length (ft)
l_0 Vessel reference length consisting of a baseline spectrum of an “average ship” (300ft)
L_{S_f} Source level (dB)
RL Received Level (dB)
SEL Sound Exposure Level
SL Source Level (dB)
T Wave period (page 13)
TL Transmission Loss (dB)
V Vessel Speed (knots)
V_c Reference speed for the ship class (table 3.1)
λ Wavelength (m)

Glossary

- **Ambient sound**: Natural background noises that are often generated through large ocean processes such as waves, wind, sediment movements, and rain (Broudic, Haywood, Masters, & Thomas, 2013).
- **Amplitude**: The maximum value of change in acoustic pressure. Often measured as the height of a wave at a given period of time, and is often called the peak pressure (Bradley and Stern, 2008).
- **Broadband**: A reference to a sound signal that involves acoustic energy across a wide range of frequencies (Knowlton, 2020).
- **Cavitation**: The rapid formation and collapse of bubbles in the water column. Typically produced by the rotation of a ships propeller, which rapidly creates small bubbles as it rotates, which then collapse and make noise (Roth, Schmidt, Hildebrand, & Wiggins, 2013).
- **Decidecade bands**: A logarithmic unit of frequency ratio acoustical data analysis that use base 10 frequency bands (Ainslie et al., 2021).
- **Temporary Threshold Shift**: The hearing sensitivities of a receiver (animal or human) are temporarily reduced due to a loud event (i.e. cavitation, air gun explosions, horn blasts, etc.; Gervaise, Simard, Roy, Kinda, and Ménard, 2012).
- **Permanent Threshold Shift**: injurious exposures can produce threshold sensitivity losses containing both temporary and permanent components, in which the majority of the temporary threshold shift resolves but a measurable permanent threshold shift has evolved (Ryan et al., 2020).
- **Received Level**: The resulting energy of a sound signal detected at a specific point and object. In ideal ocean environments, the sound intensity detected by a receiver would be weaker due to geometric spreading (Bradley et al. 2008).
- **Source Level**: the amount of sound radiated by a sound source. It is defined as the intensity of the radiated sound at a distance of 1 meter from the source, where intensity is the amount of sound power transmitted through a unit area in a specified direction (Knowlton, 2020).
- **Transmission Loss**: a measurement of the reduction in sound level of a sound source as it passes through an acoustic barrier. It is the number of decibels that are stopped by the acoustical barrier and is measured at different frequencies (Bradley et al. Stern, 2008).

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1 Introduction

Rising concentrations of greenhouse gases in the atmosphere have been widely spread throughout the scientific news since the decades of 1970 and 1980. As a result of human activities such as burning fossil fuels and the conversion of land for forestry and agriculture, the increase of greenhouse gas (GHG) concentration produces a global warming effect (Government of Canada, 2018). Consequently, effects that were once predicted by scientists are now occurring: sea ice loss, sea level rise and intense heat waves (AMAP, 2017).

With the cryosphere being the physical structure of the Arctic, it becomes increasingly clear that it is being altered by a warm and more variable environment. Global climate simulations indicate a continuing sea ice retreat and a possible ice-free ocean eventually for short periods of summer. Both alternative sea routes from the North Atlantic to Asia, the Northwest Passage in the north of Canada and the Northern Sea Route in the north of Russia, as shown in Figure 1.1, should be ice-free from three to six months of the year by the end of the twenty-first century (Khon, 2009).

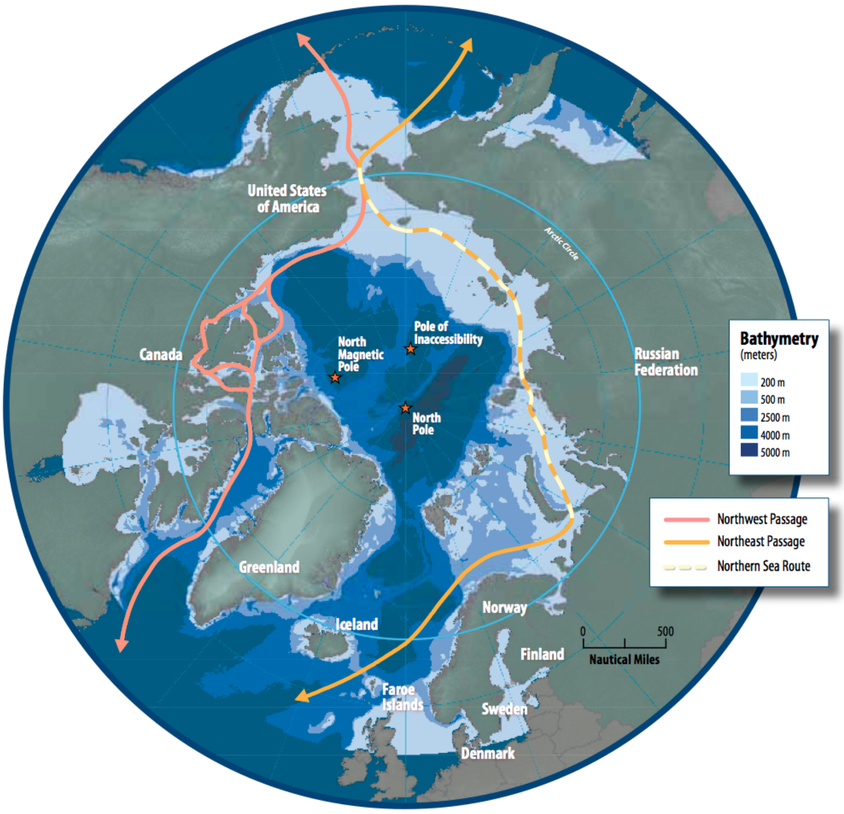

Figure 1.1: Arctic Shipping Routes. Source: AMSA (2009)

Among all the consequences, climate change has brought opportunities and better accessibility for ships to go up north, as sea ice is one of the main factors that make the Arctic a unique and challenging environment to be explored. Therefore, ice extent is an important and decisive factor for the economic viability of the region, for both shipping routes and resource exploration (Ryan et al., 2020).

According to the Trade and Development Report from 2017 (UNCTAD, 2022), the number of commercial ships increased 2.7 times between 1980 and 2017 in terms of weight-carrying capacity. The 2020 PAME report shows the increase in maritime activity (number of vessels and nautical miles traveled) between 2013 and 2019 (PAME, 2020), as shown in Figure 1.2. The Northwest Passage has experienced the greatest increase in vessel traffic ever over the past decade (Dawson et al., 2014). The growth trends vary across fishing vessels, bulk carriers, and cargo ships, as well as destinational versus intra-regional traffic (Roth et al., 2013; PAME, 2020).

As marine traffic increases, associated impacts to the ecosystem are also expected: ship-related underwater noise, oil spills caused by vessel-related accidents, ships striking marine mammals, vessel emissions, the introduction of invasive species through ballast water and hull fouling, and discharges of sewage and gray water (Bobbe, 2018).

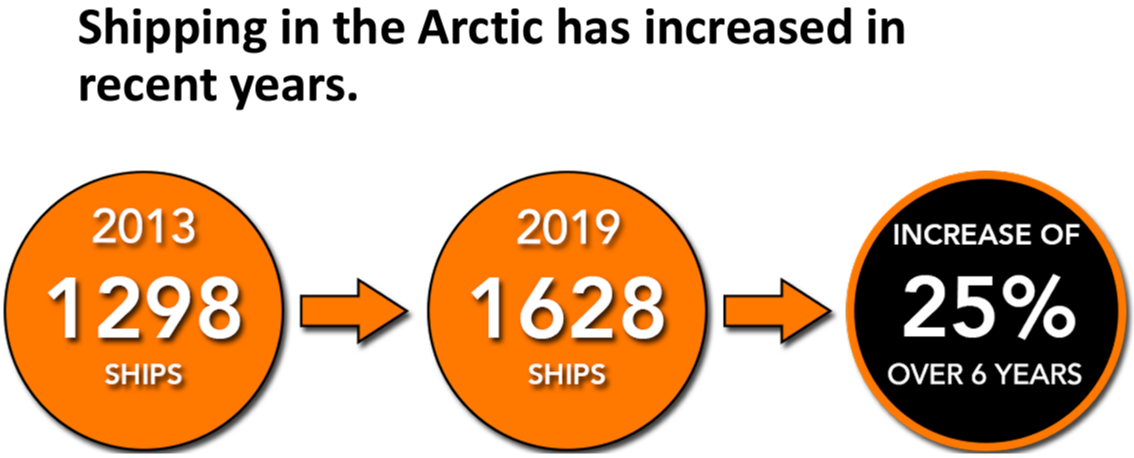

Figure 1.2: Unique ships entering the Polar Code area 2013 and 2019. Source: adapted from PAME (2020)

Amongst all of the consequences, underwater noise generated by shipping activities is highlighted in this project. Ship noises are broadband and cover an extensive frequency range, with a predominance at lower frequencies (which experiences relatively little attenuation and thus, results in long-range propagation) (PAME, 2020). Underwater ambient noise due to commercial shipping is set to continue to rise in the coming years, particularly in and around shipping lanes and in the Northern hemisphere (Hatch et al., 2008). It has become a major concern for the well-being of marine mammals and fish, as it falls within the audible frequency range used by these species to communicate, reproduce, navigate and detect prey and predators.

Underwater noise is strongly dependent on the type of vessel. Noise from large commercial ships of over 100 m in length is concentrated in low-frequency ranges between 5 and 500 Hz (Gulf of the Farallones & Cordell Bank National Marine Sanctuaries Advisory Councils, 2012). Medium-size ships' noise, such as modern freighters or fast ferries, mostly results in higher frequencies, of up to about 600 Hz to 2 kHz (Evans, 2003)

The main noise radiating from ships comes from the propeller. Analysis of the propulsion system showed that cavitation on propeller blades is a significant noise mechanism. Additionally, the ship machinery also contributes to the low-frequency band noise generated.

On average, it was found that noise levels are higher from larger vessels and during increased speed activity (Hildebrand, 2009). This fact aligns with the history of commercial ships, which not only has seen steady increases in the fleet size but also in ship size and propulsion system power (McKenna et al., 2012). The gross tonnage[1] of ships basically quadrupled between 1965 and 2003, which is highly correlated with the increasing level of underwater noise (Ross & Kuperman, 1989).

Therefore, there is a great concern on how human maritime activities may affect the concept of conservation and sustainability for different ecosystems. Besides the environmental factor, the social and cultural factors of different communities spread out over the Canadian Arctic are also required to adapt to all of the changes due to anthropogenic actions (Dawson et al., 2020). With shipping traffic being the most important source of the increase in underwater noise, as well as other adverse impacts such as the introduction of non-indigenous species, understanding the global shipping network and how it may develop over the coming decades allows for better preparation of mitigation plans, marine policy, emergency response plans, as well as efficient utilization of resources and marine areas while achieving social and environmentally sustainable objectives (Edwards & Evans, 2017).

Forecasting methods are widely used analysis tools for determining the direction of future trends in essentially every social, economic and environmental sector (Hyndman & Athanasopoulos, 2021). The methods explored in this project for the analysis of shipping traffic and underwater noise levels use a qualitative approach for scenario development and a quantitative one for statistical regression analysis.

Due to the complexity arising from various factors and drivers in the Arctic, this methodology provides a mechanism for examining possible futures from a wide perspective, resulting in a large range of outcomes (Hodgson et al., 2013). Also called judgmental forecast, this method uses a systematic approach based on experts' opinions and experience (Hyndman & Athanasopoulos, 2021).

An important aspect to consider is the time horizon for the projection. Long-range forecasts were shown to be the most appropriate for this project, as it allows time for implementing strategic decisions as noted throughout the thesis, such as examining continual and cumulative effects of shipping over the decades (Pelot, 2021). The time range chosen for this project goes up to 2040, an interval appropriate for planning, decisions consideration, analysis and project insights and techniques. Employing forecasting in risk management and decision planning processes can potentially reduce complexity, uncertainties, simplify scientific products, and increase transparency (Stelzenmüller et al., 2018).

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[1] the total volume of a vessel, in units of 100 cubic feet (gross ton). Open structures are exempted

1.1 Research questions and scope of study

The need for more comprehensive measurements and research on the anthropogenic activities that generate high levels of underwater noise that can cause injuries or modification in marine mammals' behavior is the main inspiration for this project. The outcomes from the forecasting analysis, both qualitative and quantitative, could support further research on the benefit of marine mammals and fish, as well as providing governments and other entities a more comprehensive knowledge of shipping traffic effects and assist with the decision process about new technologies to be developed, sustainable economic models to be created and, most important, life to be preserved. A better understanding of the shipping trends in the Arctic could also be useful in planning the use of marine protected areas and developing low-impact corridors, as cited by Pizzolato 2018. Additionally, recent studies have shown technical, as well as operational, mitigation measures that affect the sound generated by ships (Prins et al., 2016; Lee et al., 2015). So, given this context, this thesis aims at answering the following research questions: How will important key drivers influence shipping traffic in the future? Does an increase in shipping traffic to the Arctic also imply an increase in underwater noise levels? What will the underwater sound levels in the Canadian Arctic be in 20 years? How are technology improvements and environmental restrictions affecting underwater noise levels in the Arctic?

This thesis is divided into several chapters and sub-sections. Chapter 2 presents the literature review regarding topics such as climate change impacts on northern shipping, marine shipping activity in the Arctic, and underwater noise science. Chapter 3 presents the methodology used to analyze future scenarios for ship activities in the Canadian Arctic with the results delivered in chapter 4. Discussion and conclusions can be found in chapters 5 and 6, respectively. Additionally, the appendix section includes the questions used during interviews with subject matter experts.

2 Literature Review

2.1 Climate change and its effects on the Arctic ecosystem

The Arctic Ecosystem is of great interest to biologists and scientists all over the world: aside from being perceived as a harsh environment, it is one of the most unusual regions on the planet, it has a unique nature, and it is home for the most iconic endemic marine species (The Northern Forum, 2017). This important biodiversity also includes interactions between humans and the environment, which provides a social and cultural identity to the region.

According to NSIDC (National Snow and Ice Data Center), over the past 30 years, the Arctic has warmed twice or even almost three times the global average (NSIDC, 2022).

Studies show that human activities, especially the burning of fossil fuels (natural gas, coal, for example) have increased the concentration of greenhouse gases (carbon dioxide, methane, nitrous oxide, and industrial gases like hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride and nitrogen trifluoride) in the atmosphere (ACIA, 2004). The continuous emission of these gases is expected to lead to significant changes in the earth's climate, including a very important consequence of the increase of the average global temperature of 1.4 to 5.8 °C (Shukla et al., 2019).

The Arctic environment is also known for its vulnerability and high sensitivity to climate change. The primary reason for this feature is a chain of events known as Albedo Feedback: a positive feedback climate process where changes in the ice extent may alter the surface temperature of the planet as less sunlight is reflected (NOAA - National Oceanic and Atmospheric Administration & U.S. Department of Commerce, 2018).

Not only on the environmental aspect but Arctic communities, especially indigenous communities, are very vulnerable to climate-related risks. Climate change effects have both direct and indirect impacts on the health of the population, especially when it comes to small communities. Among them, we can cite risks to subsistence activities, exposure to pollutants, and changes in the availability of food, for example (Ford & Smit, 2004).

As a place of extreme temperatures and very limited accessibility, significant anthropogenic impacts on the environment were largely avoided, allowing nature life to stay undisturbed, until recent times (Intergovernmental Panel on Climate Change (IPCC), 2021).

The effects of the climate change process are broad and extensive. Consequently, sea ice cover in the Arctic is decreasing and more open water occurs in many months of the year, especially in the summer (see Figure 2.1) (PAME 2020; AMAP, 2017). Consequently, there is a higher exposure of the seawater to sunlight, causing significant changes to the properties of the water column and affecting sound propagation through changes in the roughness of the underside of the ice (Hines et al., 2020). Included in these properties, we can cite the water-column acidification. With the increase of CO2 in the atmosphere, its concentration also increases in the oceans' waters, reducing the ocean's pH. Consequently, the underwater acoustic is also affected: low-frequency sound absorption decreases with lower pH, allowing noise to propagate further distances (Hines et al., 2020).

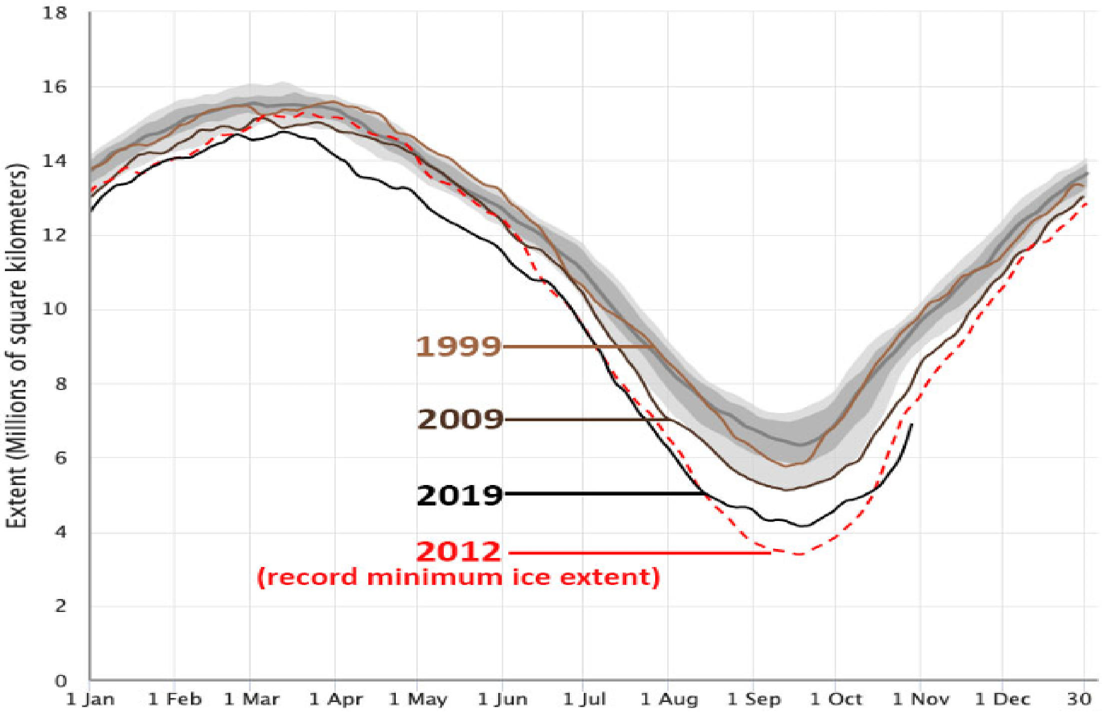


Figure 2.1: Sea Ice Extent. Source: adapted from (NSIDC, 2022)

Sea ice has also become thinner in recent decades, showing a reduction of 10 to 15%. An additional decrease of 10-50% in annual average sea ice is expected by the end of 2100. By mid-century, it is expected that most of the Arctic will be accessible to icebreakers (AMAP, 2017), and significant areas will be accessible to non-icebreaking vessels. This process of ice melting allows greater levels of maritime traffic and expansion of anthropogenic activities, as it implies improved ship accessibility to resources and new routes throughout the Arctic Ocean (AMAP, 2017).

It is essential to establish effective and proactive climate change adaptation initiatives in the Canadian Arctic, aiming not only at limiting the direct biophysical impacts of climate change (i.e., sea ice reduction), but that also target the indirect socioeconomic risks resulting from observed biophysical change (e.g. increase in shipping opportunities and disturbance of local communities' lives). Although shipping can enhance communities' well-being by bringing supplies, it can also pose dangers and threats to their way of living, as shipping can bring invasive species, disturb migration routes for Arctic animals and Inuit communities that rely directly on sea ice and access to marine animals (Dawson et al., 2020).

Although most scientists and researchers speculate about a rapid increase in Arctic shipping activity related to climate warming by the end of the twenty-first century, Dawson et al. 2016 shows that the relationship between ice and ships is very complicated and goes beyond a simple linear relation. Less ice could mean more opportunities, but it could also mean higher risks because of the high mechanical strength associated with multiyear sea ice, as its layers are now melting and moving, and choking up fundamental shipping routes, particularly in the Northwest Passage (Dawson et al., 2016).

Even though the connection between sea ice extension and shipping activities is still limited, Pizzolato et al. 2016 concluded that the climate change process is only one of a variety of factors influencing maritime traffic up north. According to Brigham, the changes in the sea ice cover are only a small part of the northern shipping process that is, in fact, driven by geopolitics and economics (Brigham, 2011).

The different drivers of change in the North are often interrelated and interlinked (AMAP, 2017). Among the factors, we find Arctic state cooperation, oil prices, changes in global trade, climate change variability, new resource discoveries, marine insurance industry roles, multiple use conflicts and Arctic marine technologies (Dawson et al., 2018). The changes in the Arctic have the potential to reshape not only the global economy but also the global power status quo and alliances between nations. According to the ACIA report (ACIA, 2004), another outcome of this increased access to the Arctic waterways will be growing conflicts among users (nations) of the Arctic routes.

Even though some attempts have already been made to understand the overall trend in shipping traffic (Dawson, 2019; Lasserre, 2018; Guy & Lasserre, 2016), still not much is known about patterns and long-term forecasting, as this scenario and situation involve various complex factors such as proximity to communities, seasonal variations, development of new shipping technologies, the types of vessels, and so forth (Dawson et al. 2018). Infrastructure is still a very important factor in the shipping context, thus an immediate or even future shift toward using Arctic routes more over existing southern routes, where infrastructure is well-established, is not simply expected just because of a more accessible or viable passage. Less ice could mean more opportunities for the economy of the region, but it could also mean increased risk (Dawson, 2019).

2.2 Marine Shipping in the Arctic

The Arctic Ocean has been used by mariners since ancient times. Given this very harsh environment to be explored, improvements in the Arctic shipping activity came with advances in ship design, construction and operations, better infrastructure throughout time, and specialized crew training (AMSA, 2009). The main types of shipping and vessel transits in the Arctic consist of arctic community re-supply, bulk transport of ore, oil and gas, tourism vessels, fishing vessels, ice-breakers, and research vessels (Hannah et al., 2020; AMSA, 2009).

Communities in the Arctic with no land transportation infrastructure, and who may be ice-locked for much of the year, rely upon re-supply vessels for dry foods, fuel, building materials and other products (Dawson et al., 2020).

Regarding marine tourism in the Canadian Arctic, its traffic level has more than doubled since 1990 and the average annual distance traveled has increased by nearly 4000%. This fact is significantly important as tourist vessels like to travel through government and community-identified areas of significance, such as Ecologically and Biologically Significant Areas (EBSAs) and Culturally Significant Marine Areas (CSMAs) (Dawson et al., 2021).

The shipping traffic can also be subdivided depending on the traffic routes: transit versus destinational traffic. The former refers to ships that navigate the waters of the Arctic only to link southern markets with one another (i.e., whereby the Arctic only offers a short-cut) while the latter refers to ships that are bound to the Arctic to load or unload cargo in the region, and in this situation there is obviously no alternative routing (Guy & Lasserre, 2016).

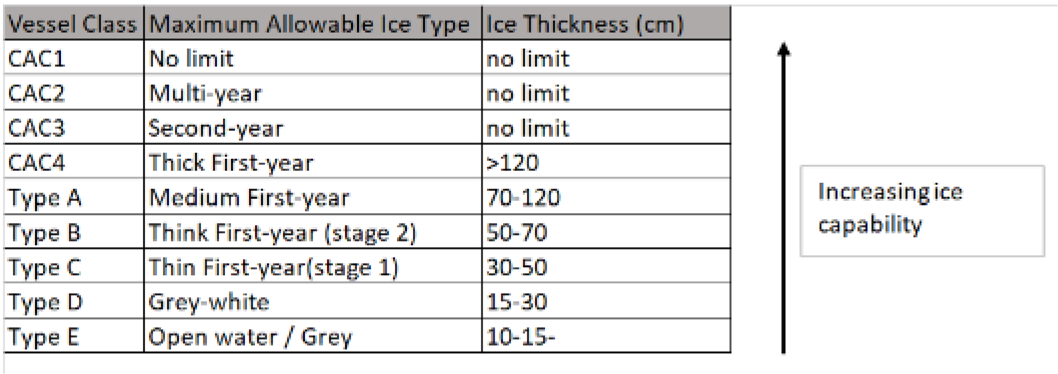
There are currently two major shipping routes through the Arctic Ocean as shown in Figure 1.1, the Northwest passage (NWP), which connects the Atlantic and Pacific Oceans through the Canadian Arctic Archipelago, and the Northern Sea Route (NSR), which runs along the Russian Arctic coast from the Kara Sea, along Siberia, to the Bering Strait (National Oceans Economics Program, 2017).

This research project analyses and takes into consideration tankers, cargo and cruise vessels, given their higher traffic levels observed in AIS data (Automatic Identification System for tracking ship movements), and the significant underwater noise generated by these vessel types in low-frequency bands. Fishing vessel operations constitute a significant portion of all vessel activity in the Arctic, however their activity was not considered herein, as small vessels usually generate sound in higher-frequency bands than those examined in this study. Furthermore, these vessels are not well tracked as AIS transceivers are not required for them. Research and government vessels were excluded from the study as well.

2.2.1 Arctic Ice Regime Shipping System (AIRSS) Zones

Because different vessels have different capabilities in ice-covered waters, each vessel is assessed and assigned to a vessel ice class. The class of the vessel reflects its structural strength and power for navigating in ice. The vessel class is determined by Transport Canada's regulation based on the vessel's characteristics (Transport Canada, 2010). Therefore, the class of the ship dictates where in the Arctic Ocean it can operate and through which kind of ice (seasonal or multiyear). The Canadian Arctic Class (CAC) follows the parameters shown in Figure 2.2.

The Arctic Ice Regime Shipping System (AIRSS), as shown in Figure 2.3 is a regulatory standard intended to minimize the risk of pollution in Canadian Arctic waters arising from potential damage to vessels by ice, emphasizing the responsibility of the shipowner for safety (Transport Canada, 2010). It is used to determine the operational risk based on a ship's ice class and the prevailing ice conditions observed from the ship's bridge. Regulated by the Canada Shipping Act and incorporated into the International Code for Ships Operating in Polar Waters (Polar Code), its regulations include requirements for



Vessel Class	Maximum Allowable Ice Type	Ice Thickness (cm)
CAC1	No limit	no limit
CAC2	Multi-year	no limit
CAC3	Second-year	no limit
CAC4	Thick First-year	>120
Type A	Medium First-year	70-120
Type B	Think First-year (stage 2)	50-70
Type C	Thin First-year(stage 1)	30-50
Type D	Grey-white	15-30
Type E	Open water / Grey	10-15-

Figure 2.2: Canadian Arctic Classes and Ice type related to each of them. Source: (Transport Canada, 2017)

a vessel's construction, ballast water management, pollution control, arrangements for emergency response, and crew qualifications (Transport Canada, 2017).

Nevertheless, in 2021, the WWF's (World Wildlife Fund) Arctic Programme conducted a review to identify gaps and challenges in implementing the Polar Code: the code does not address some of the environmental risks posed by ships such as grey water discharge from sinks and showers, air pollution nor underwater noise. In fact, there are no restrictions on the underwater noise produced by ships' propellers and onboard machinery (WWF Arctic, 2022).

2.2.2 Ship-building technology for Arctic Waters

With a warmer climate leading, consequently, to longer melting and ice-free periods, the movement of ice blocks through waters can become more frequent.

Thus, increasing access in the Arctic Ocean will require ships transiting the region to be built to higher construction standards compared with ships operating in open ocean. Ice conditions require the proper selection of hull materials. The two primary groups of steel used in ship construction are normal strength and high strength steels (referring to their minimum yield strength) (ACIA, 2004).

Regarding propellers, stainless steel and nickel-aluminum bronze are commonly used materials for the propeller blades of ice-class ships. Fixed-pitch propellers are used on most ice-breaking ships (Government of Canada, Canadian Coast Guard, 2022). Propeller nozzles offer increased propulsion thrust and protection and may reduce the strength requirements for propeller blades. However, shallow draft ships which operate in the Beaufort Sea have experienced clogging of the nozzles when in thick ice or in deformed ice conditions (such as rafted or ridged ice) (Fisheries and Oceans Canada & Canadian Coast Guard, 2022).

2.2.3 Commercial Shipping

Commercial vessel traffic in Canadian marine waters is diverse and includes container ships, general cargo, government vessels, icebreakers, oil and gas service and supply

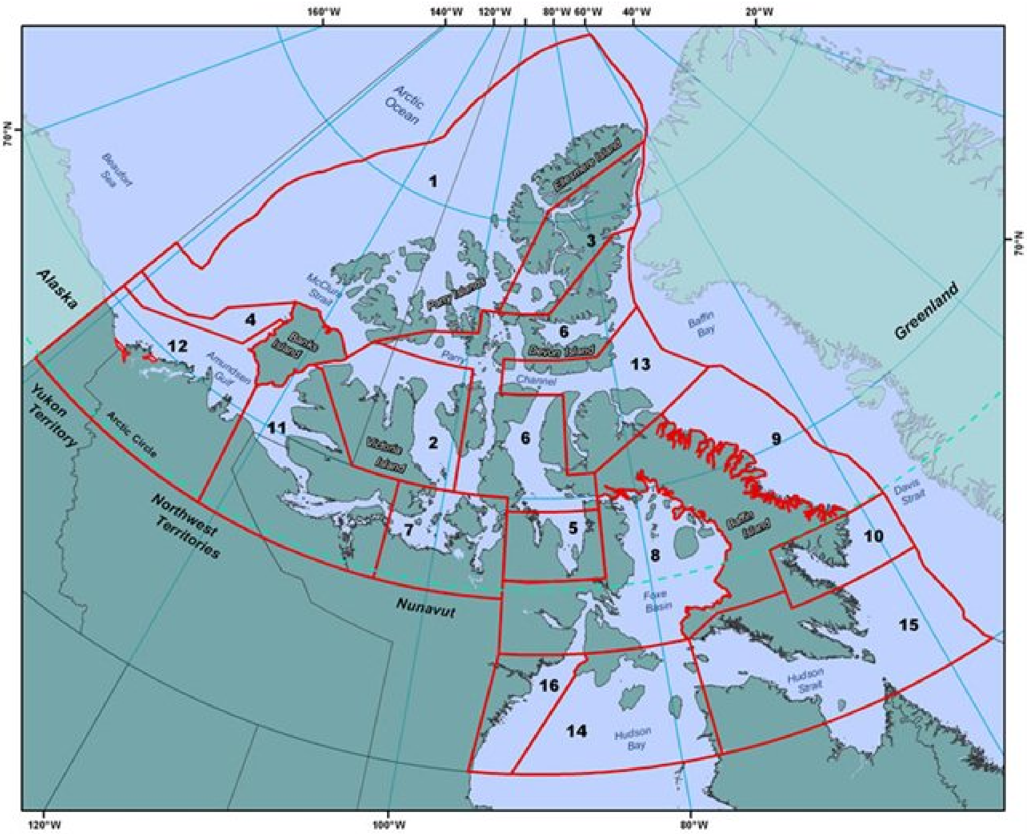


Figure 2.3: Shipping Safety Control Zones. Source: adapted from Government of Canada, Fisheries and Oceans Canada, 2023

vessels, passenger ships (including cruise ships and ferries), tankers, and tugs/barges (Brigham, 2010).

General Cargo

These are ships designed to transport various types and forms of cargo and the combined carriages of general cargo and passengers with 12 or less fare-paying passengers. (Hannah et al., 2020). They can carry a variety of commodities in different forms such as boxed, palletized, refrigerated, and with the possibility to accommodate bulk materials such as grain (Karanassos, 2016).

Tankers

Tankers are vessels that have specially designed containers to transport liquid cargo like petroleum products. Major types of tank ship include the oil tanker, the chemical tanker, and gas carriers. Tankers also carry commodities such as vegetable oils, molasses and wine.

2.2.4 Cruise Shipping

Arctic cruise shipping is an emerging tourism sector. Characterized by expedition cruise ships, this traffic is more fluid and flexible and rarely carries over 250 people, allowing them to traverse narrow channels and small, shallow bays in the north. Shore landings on an expedition cruise are very responsive to the environment depending on where wildlife is spotted and what the weather conditions are like (Mudd, 2022).

Tourism ships, which include passenger vessels and pleasure craft (yachts), is the class of vessel that shows the most significant relationship with the changing of the Arctic conditions. The numbers have increased by 75 and 400 percent respectively in Arctic Canada since 2005 (Dawson, 2019). The unique and remote landscapes attract a growing number of tourists interested in wildlife, adventure, and Arctic culture (Ghosh and Ruby, 2015).

The reduction of the ice coverage of the region has been one of the most influential factors leading to increased cruise ship numbers throughout the Arctic. According to Dawson et al. 2015, ice reduction acts more as an enabler than as a main factor driving the growth in this activity. Another enabler is the availability of stronger ice-strengthened vessels and the flexibility of cruise ships to take different routes (Dawson et al., 2014).

Even though Canada has a great area of the Arctic in its territory, the main cruise tourism markets are Greenland and Svalbard, as seen in Figure 2.4 (Lasserre, 2018).

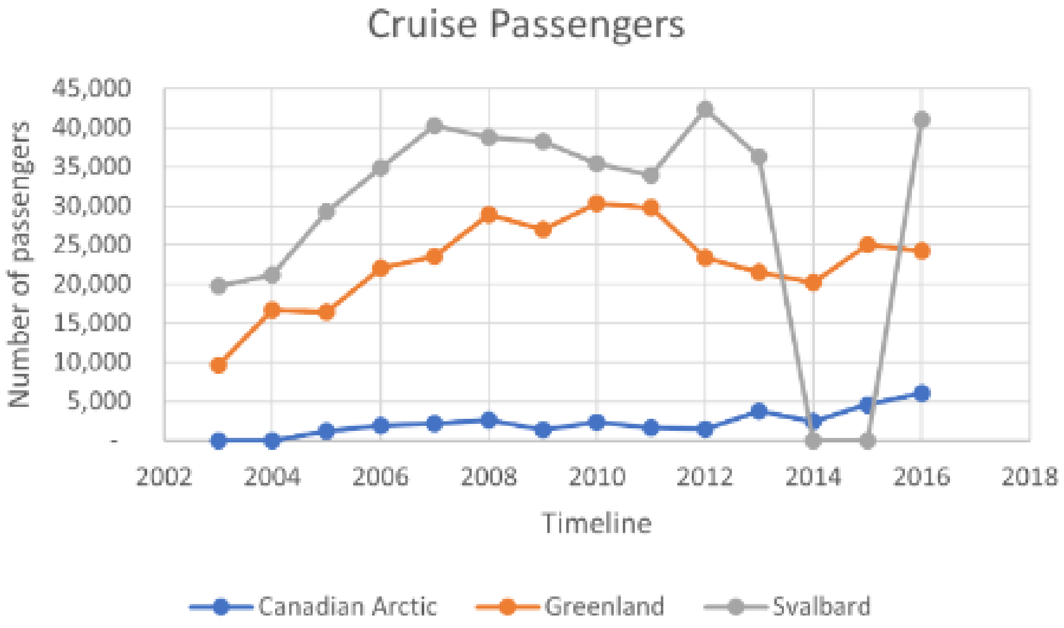


Figure 2.4: Number of cruise passengers, Canadian Arctic, Greenland and Svalbard, 2003– 2016. Source: adapted from (Lasserre & Têtu 2015)

2.2.5 The Northwest Passage (NWP)

Being the most direct shipping route between the Atlantic and Pacific Oceans as shown in Figure 1.1, decreasing the distance up to 9000 km compared with the traditional routes via the Panama Canal, the Suez Canal, and the Horn of Africa, the NWP produces notable economic benefits (Chen et al., 2021; Borgerson, 2008).

Destinational traffic, i.e., ships going to the Canadian Arctic to load, unload, or perform an economic activity there, is experiencing significant growth, primarily in fishing, but also cargo shipping. This expansion of destinational traffic is partly sustained by the expansion of community re-supply as well as by the construction of infrastructure and the development of natural resources exploitation (Lasserre, 2018).

2.2.6 The Northern Sea Route (NSR)

Running along the Russian Arctic coast from Murmansk on the Barents Sea (Figure 1.1), along Siberia, to the Bering Strait and Far East, the northern sea route is free of ice for only two months per year and connects the Pacific and Atlantic Ocean (National Oceans Economics Program, 2017). The NSR is an important element of Russia's Arctic strategy, which now incorporates active development of the hydrocarbon resources, development of Arctic ports and other infrastructure. Traffic along the route today is modest: total Arctic shipping last year in 2020 was equivalent to a day or two of traffic through the Suez Canal, although it is 30% to 40% shorter than the Suez one, saving fuel and reducing its associated environmental impact (Yanes, 2021).

However, it is expensive. The route comes with additional costs, like contracting the services of Russian icebreakers and building ships with special specifications (Dinneen, 2022).

2.3 Underwater noise science

2.3.1 The science of sound

According to Bradley et al. 2008, sound is a mechanical disturbance that moves through a material. It is also described as a wave created by vibrating objects that is propagated through a medium, which can be air, water or solid, as the seafloor. A wave transports energy from one location to another caused by a rapid change in pressure over time. The pressure changes result in the sound disturbance moving as a longitudinal or compressional wave, resulting in the transfer of energy in a uniform direction (Nolet, 2016). However, the particles of the medium do not travel with the wave but vibrate back and forth on a spot called the 'equilibrium position'. In the presence of a source of sound, the wave makes the particles contract in areas of high pressure and expand in low-pressure areas, as shown in Figure 2.5.

As a repeating pattern, one repetition of this pattern is called a cycle, and the time to complete it is the period T. The wavelength λ is the distance traveled by the wave in a single period, and therefore, related to the speed c it travels ($\lambda = c/f$ and $f = 1/T$) (where f is the wave frequency)(Nolet, 2016). The wavelength can be measured from one peak to another, which is the maximum change in acoustic pressure called amplitude, one crest to another or two troughs (Figure 2.6). The energy in a sound wave is referred as the acoustic intensity and is a measure of energy per second over a unit area, or $Watts/m^2$.

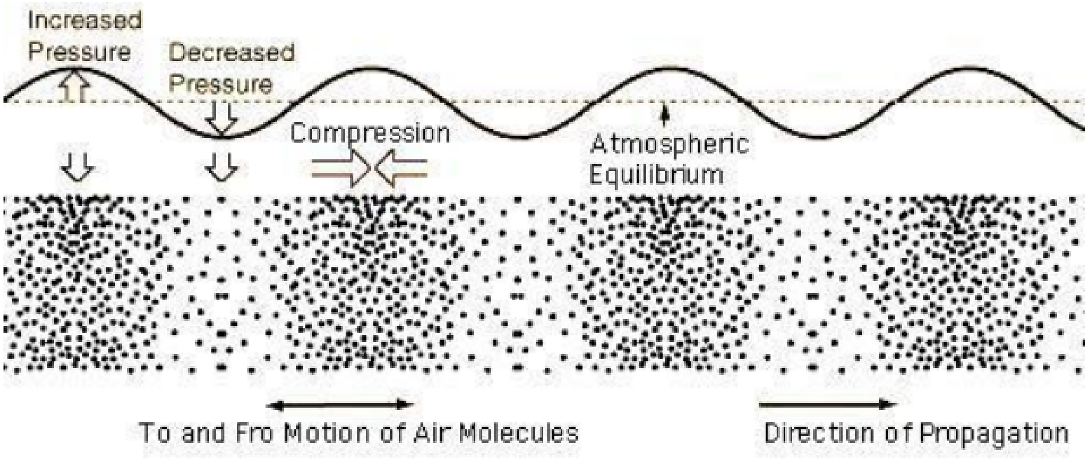


Figure 2.5: Sound waves. Source: adapted from (Explore Sound, 2020)

The frequency f of a wavelength is described as the number of wave cycles per second and is measured in Hertz (Hz).

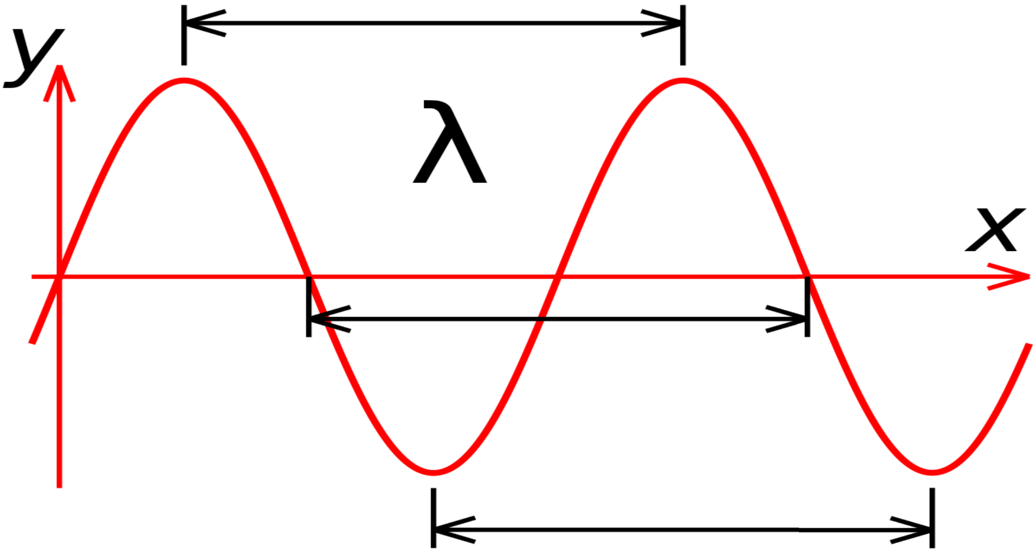


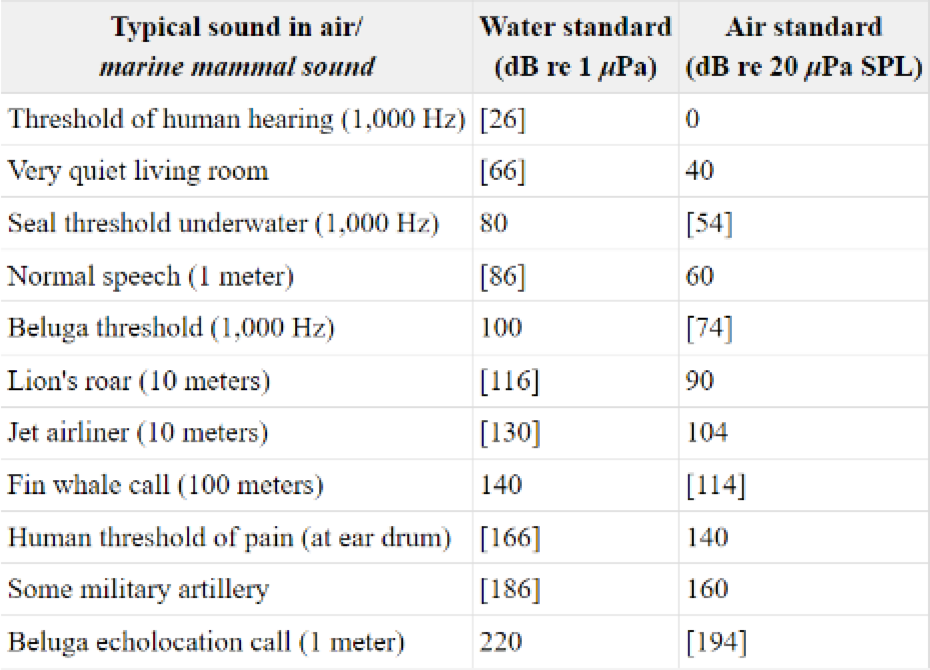
Figure 2.6: Wave Properties. Source: adapted from (Serway & Jewett, 2012)

Low frequencies mean that the wavelength is larger and, thus, fewer cycles in a period of time. On the other hand, high frequencies mean more cycles in a period of time, as the wavelength is short.

Due to the high degree of fluctuations in acoustic intensity, a logarithmic scale is used to create reference values: the decibel (dB) measures the sound level or the loudness of a sound relative to some reference (in air, the common reference is 20 µPa, because that is near the absolute lower audible threshold for a normal human listener for a sound frequency of 1,000 Hz) (Australian Learning and Teaching Council, 2014). It is employed to describe a ratio, which can be of power, sound pressure or intensity.

However, in water, a different reference is used: 1 µPa. As such, dB levels are always reported as “dB re 1 µPa” for a sound in water or “dB re 20 µPa” for a sound in the air, meaning that the volume in dB of a sound transmitted through the air cannot be directly compared with its volume in water (Stafford, 2021).

Figure 2.7 gives levels for some airborne sounds, and also shows the levels of some marine mammal sounds underwater.



Typical sound in air/ *marine mammal sound*	**Water standard (dB re 1 μPa)**	**Air standard (dB re 20 μPa SPL)**
Threshold of human hearing (1,000 Hz)	[26]	0
Very quiet living room	[66]	40
Seal threshold underwater (1,000 Hz)	80	[54]
Normal speech (1 meter)	[86]	60
Beluga threshold (1,000 Hz)	100	[74]
Lion's roar (10 meters)	[116]	90
Jet airliner (10 meters)	[130]	104
Fin whale call (100 meters)	140	[114]
Human threshold of pain (at ear drum)	[166]	140
Some military artillery	[186]	160
Beluga echolocation call (1 meter)	220	[194]

Figure 2.7: Typical Airborne Sounds and some sound levels of marine mammals. Source: adapted from (National Research Council et al., 1994)

2.3.2 Sound in water

Air has a density of about 1.2 g /liter, while water has a density of about 1 kg /liter. In this case, air is therefore about 830 times less dense than water. Thus, as neighboring particles will more easily bump into each other, the sound will travel faster in water than in air (DOSITS, 2018).

To characterize the potential effects of sound on marine animals, regulators use sound pressure levels (SPLs) and sound exposure levels (SELs) (DOSITS, 2018).

When sound travels through a medium, it becomes less loud as you get farther away from the source, losing its energy along the way, also known as Sound Transmission Loss (STL). Sound Transmission Loss (STL) represents the amount of sound, in decibels (dB), that is absorbed by a material or partition, in a particular frequency band. Through water, sound keeps its energy longer, as the density of the particles allows them to carry the sound waves better and much further than in air (DOSITS, 2018).

However, spreading loss occurs because the total amount of energy in a wave remains the same as it spreads out from a source, as the energy per unit length of the wave must get smaller. Waves that spread their energy out in all directions, as a sound source in the middle of the ocean, get smaller faster than waves at the water’s surface (the power is radiated equally in all directions from the sound source) (Kirsten, 2022). This is called spherical spreading and differs from cylindrical spreading when we assume that the sound is distributed uniformly over the surface of a cylinder having a radius equal to the range r and a height H equal to the depth of the ocean (Knowlton, 2020).

Another related acoustic phenomenon is scattering. It is explained as the reflection of a wave from small segments of a rough surface, diffracting in many directions. The light or sound is forced to deviate from its constant trajectory because of non-uniformities (particles such as salt, debris, air bubbles, micro-bubbles, droplets, and density fluctuations in fluids) in the medium through which they pass (Maurer, 1998). On a smooth water surface, water forms an almost perfect reflector of sound; when the surface is rough, the surface acts as a scatterer, “sending incoherent energy in all directions" (Urick, 1983).

For the purpose of this project and in order to understand the potential impacts shipping noise could have on cetaceans, a simplified sonar equation was utilized to calculate the received level: $RL = SL - TL$ (where SL is the source level in dB and TL is the transmission loss in dB) and then the sound exposure level can be calculated, which takes into consideration the exposure time to the underwater noise. This equation is further explained in the methodology section.

Underwater sound in the Arctic Ocean environment

Sound propagation in polar ocean environments is much different than in temperate ones. In mid-latitude oceans, temperature and salinity play larger roles in determining the refraction of sound waves than in Polar Regions (Giesbrecht, 2018).

The Arctic Ocean can have a wide range of soundscapes and ambient noises, depending on the season. Ice cover in Arctic regions has a profound effect on sound propagation (Cook et al., 2020). Under an ice-covered ocean with calm wind conditions, the ambient noise can be very low. Propagating sound energy will be attenuated due to scattering from the rough interface underneath the ice. When sea ice deforms or fractures due to wind, waves, or currents, it can produce loud sounds resulting in high ambient noise conditions (Cook et al., 2020).

Underwater noise is different in the Arctic in various ways: (i) due to the low ambient sound levels and greater distances traveled by some signals (low-frequency signals are absorbed less rapidly in the ocean than high-frequency signals, thus they can therefore travel longer distances and still be detected), noisy activities can be heard from great distances; (ii) the signal-to-noise ratio is greater in the Arctic as a consequence of low ambient sound levels; and (iii) marine animals may have a lower threshold when reacting to noise (as the different reference pressure in water lowers the hearing threshold for the same sound intensity). These are some of the reasons that the Arctic needs special attention in regulations, impact assessments, and policies related to shipping (Halliday et al., 2020; DOSITS, 2020).

With regard to studies in the field of sound, its transmission speed is one of the most important physical properties used to characterize its behavior. As noted earlier, with a higher-density medium, sound in water is allowed to travel faster than in the air.

However, a very complex sound speed profile exists as it varies with different factors such as depth, salinity, temperature and water and ice properties (Bradley et al., 2008).

Three physical parameters are the most important to the variation of sound speed: temperature, salinity and depth. When acoustic waves traveling through the water column encounter changes in the sound speed they are refracted, bending either towards the surface or towards the seabed in the case of vertical variation (Farcas et al., 2016).

Physical oceanographic properties are not isolated from each other, but they influence the sound speed profile (SSP) to varying degrees. The variation of the sound velocity plays a major role in predicting the path that sound takes as it travels through the ocean (Bradley et al., 2008). Figure 2.8 shows a typical sound speed profile in the blue water ocean.

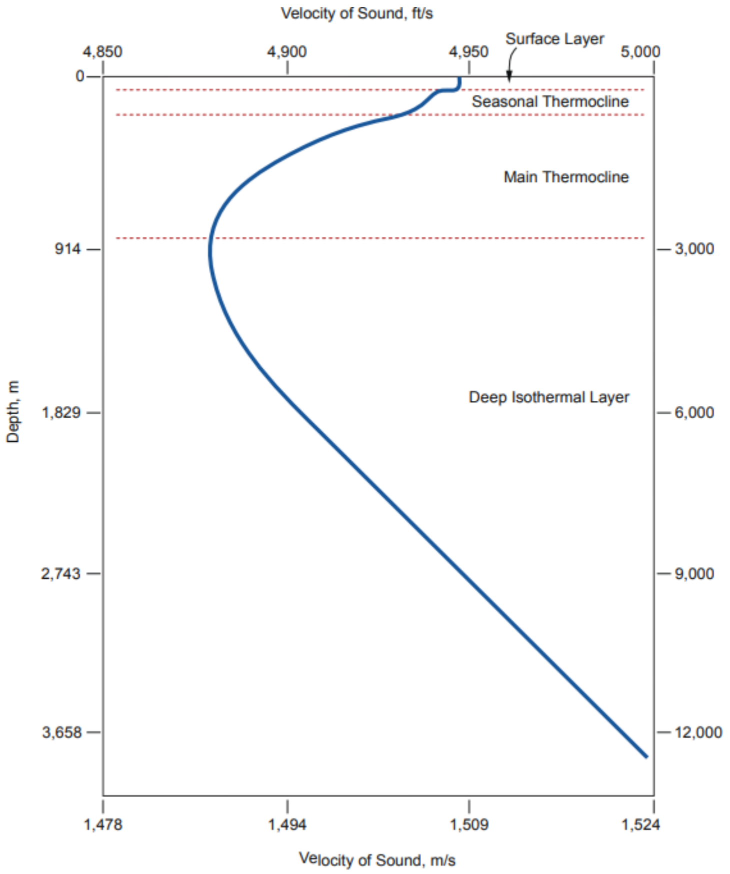


Figure 2.8: Typical sound velocity profile for the deep ocean. Source: adapted from (Urick 1983; Bradley & Stern, 2008b)

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The decrease in sound speed immediately below the surface is due to decreasing temperature. The sound speed at the surface is fast because the temperature is high from the sun warming the upper layers of the ocean. As the depth increases, the temperature gets colder and colder until it reaches a nearly constant value. At a certain point, however, the effect of depth, i.e., pressure, begins to dominate, and the sound speed increases to the ocean floor (Knowlton, 2020; Talley et al., 2011).

In the Arctic Ocean, the presence of sea ice is a unique feature that affects both underwater acoustics and ambient noise. These unique profiles keep cool freshwater at the surface and, together, generate a unique SSP which has a positive gradient with increasing depth causing horizontally propagating sound waves to be refracted toward the surface (Cook et al., 2020).

Under the ice, energy loss from spreading is increased dramatically when the sound path includes water-ice reflections, and the loss rapidly increases with higher frequencies and ice thicknesses (Roth et al., 2013). Therefore, sound is constrained to the first 250m of the water column (Giesbrecht, 2018).

Furthermore, the changing composition of Arctic ice cover affects sound propagation. The newer, thinner ice that is gradually replacing the thicker and older multi-year ice, is becoming more prominent and it does not muffle noise as effectively as the thicker, older ice does. As a result, larger areas can be flooded with noise.

2.4 Anthropogenic underwater noise sources

Underwater sounds are generated by various natural sources, such as the wind, underwater earthquakes, waves and marine animals, making up the so-called underwater 'soundscape' (Stafford, 2021). Besides the natural sources, it is also generated by anthropogenic activities such as shipping traffic, military sonar, pile driving, dredging and underwater drilling. Large and powerful watercraft such as ferries, container ships, and icebreakers have source levels of 200 dB re 1 Pa at 1m and more (Erbe & Farmer, 2000; Simard et al., 2016; Gassmann et al., 2017). Source levels may vary by 20–40 dB within a ship class due to variability in design, maintenance, and operational parameters such as speed.

With the increase in the world's marine traffic, ship noise is rising concomitantly, being the low-frequency band dominated by commercial shipping traffic (Halliday et al., 2020). An Arctic Council Report from 2021 found that the amount of underwater noise in the Arctic Ocean doubled in just six years because of shipping traffic. These activities are contributing to ambient noise across ocean basins, as low-frequency sounds experience little attenuation, propagating in further ranges.

The noise field generated by ships depends on the environment in which the vessel travels, and it changes with vessel speed, load, size, and other factors (MacGillivray & De Jong, 2021). The ship's propulsion system (mostly diesel engines and propellers) is the main and most important source of underwater noise, the propellers being the center of attention. Small ships usually equipped with high-speed engines produce high-frequency noises (Brooker & Humphrey, 2016). High frequency noises from small boats are modulated by engine tones (each pulse of air pressure during each piston's cycle makes a tone, which combined with the other pulses forms a harmonic series). This engine tone-modulated noise is a major difference between the acoustic emissions of large and small vessels. High-frequency noise modulated by engine tones is likely the product of the large volumes of exhaust gasses pumped underwater by popular small boat engines (Pollara et al., 2017).

Cavitation that occurs at the propeller blade tips is a particularly significant source of noise (Figure 2.9). Cavitation takes place when the rotating blades cause the local pressure in water to drop below a critical value and bubbles to form (Science Tutorial: Sound Pressure Levels and Sound Exposure Levels, 2018). The low-pressure zone is localized around the propeller, so when the bubbles leave that area, they return to the normal pressure for whatever depth they are. This causes them to revert from gas bubbles to liquid, and because the gas takes up more space than the liquid, the bubbles implode, which creates a great deal of noise (Brüel & Kjær, 2017). It can significantly reduce a ship's propelling efficiency while at the same time leading to rapid degradation of the propeller (Vard Marine Inc. et al., 2019).

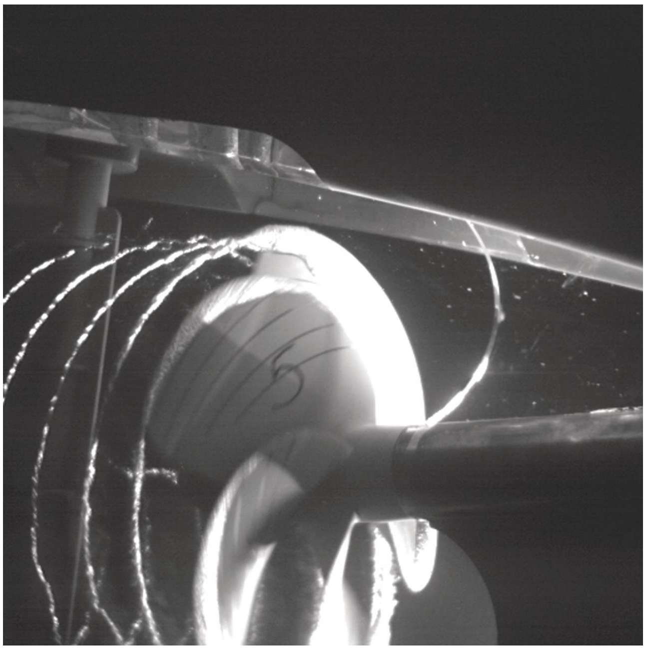


Figure 2.9: Cavitation pattern on the propeller. Source: adapted from (Marine Link, 2016)

Ships' machinery also generates a great amount of noise energy and it can be coupled to pipes, ducts, or shafts spreading structure-borne or fluid-borne noise over large areas. The vibration transmission occurs through the hull, which is partially submerged, and also depends on the dynamics of the structure as a whole, as well as the materials used for mitigating mechanical vibrations problems, like rubber and polyurethane, which can absorb the system's excess energy (Abrahamsen, 2012). This transmission process has a significant impact on the noise.

Note that when we refer to ship noise, we are specifically referring to propeller cavitation, engine noise, and other incidental noises from ship operations, but not to noise from air guns, sonar, or other noises not associated with normal shipping traffic.

Still, the noise field generated by a vessel changes as it navigates through different environments, from coastal to offshore waters. For example, in shallow waters, the propagating wave interacts with the surface of the water and the sea floor in a more continuous way, "going through" processes of reflection, scattering and absorption (Cucinelli, 2020).

In 2019, VARD Marine Company released a report presenting the results of a review of means of mitigating and predicting the underwater radiated noise (URN) from ships. The main outcome of the work undertaken is a matrix of URN mitigation measures, which are categorized in four main areas, covering: propeller noise reduction; machinery noise reduction; flow noise reduction. Each measure is described, and then defined in a standardized approach that aims to define the advantages and benefits to the ship's design and operations; disadvantages and challenges; technology readiness; cost impacts for implementation and operation; applicability to different ship types; and effectiveness; in terms of frequency ranges and reduction in sound levels (Vard Marine Inc. et al., 2019).

2.4.1 Implications of Underwater Noise from Shipping for Arctic Marine Mammals

The resistance and adaptability of marine mammals are being sorely tested with shipping routes being increasingly used by merchant shipping as the Arctic Ocean becomes ice-free for longer periods of the year. Besides the noise pollution caused by seismic explorations and commercial shipping, ship strikes, and increased light can be problematic for whales and seals (University of Washington, 2018).

Sound carries especially well underwater, animals rely on it for everything from finding their way around and feeding, to communicating and protecting themselves (Cummings & Holliday, 1987). The acoustic bandwidths used by marine mammals overlap with anthropogenic sound sources (Figure 2.10), for example in the critical range from 0 Hz to 200 kHz, raising concerns about potential effects on cetaceans from increasing ocean noise levels, such as behavioral disturbance, hearing damage, becoming a chronic stressor for individuals, and even resulting in permanent injury or death (Cranford & Krysl, 2015).

According to Halliday et al. 2020, since the Arctic had lower levels of anthropogenic activities than non-Arctic areas, the animals have had much lower exposure to anthropogenic noise, and may, therefore, be more sensitive to this kind of disturbance, so any increases in anthropogenic noise may have disproportionate implications for Arctic animals.

When discussing the effects of noise it is important to be aware of the distinction between the acute sound pressure level (expressed as dB re. 1 µPa) and the accumulated acoustic energy (SEL, expressed as dB re. $1Pa^2s$). Sound exposure is defined as the time integral, over the duration of the exposure, of the instantaneous sound pressure-squared. It refers to the sound exposure expressed in decibels, referenced to 1 $\mu 1Pa^2s$ in water or 20 $\mu 1Pa^2s$ in the air (ANSI, 1994). It allows sound exposures of different duration to be related to one another in terms of total acoustic energy.

In acoustics, there are impacts, most notably hearing threshold shifts that are better predicted by the accumulated (time-integrated) acoustic energy (Southall et al., 2021): Temporary Threshold Shift (TTS) which is a temporary hearing loss and Permanent Threshold Shift (PTS) being a loss that does not recover to pre-exposure levels. For the analysis of the impact of underwater noise on marine mammals, a precautionary thresh-

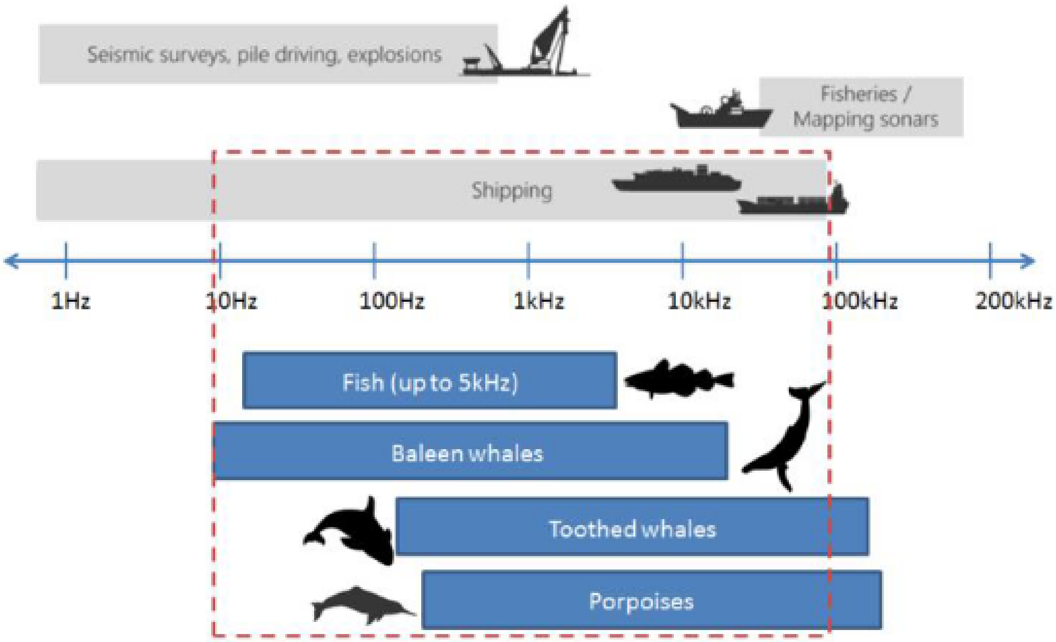


Figure 2.10: Overlap of Selected Emission and Hearing Frequencies - Source: adapted from (Vard Marine Inc. et al., 2019)

old for injury was needed (NOAA - National Oceanic and Atmospheric Administration & U.S. Department of Commerce, 2018). Temporary threshold shift, also referred to as "auditory fatigue" is the commonly observed reduction in hearing sensitivity following exposure to loud sound. According to Tougaard et al. (2015) and Finneran (2015), TTS correlates better with the acoustic energy than with the peak pressure, and the acoustic energy is more often expressed as the sound exposure level (SEL).

SELs can also be computed for multiple pulses or signals to generate a value equivalent to a single exposure for the cumulative sound energy (SEL_{cum}). If the individual pulses or signals are approximately the same, then the SEL_{cum} can be estimated as $SEL + 10log10(N)$, where N is the number of pulses (Science Tutorial: Sound Pressure Levels and Sound Exposure Levels, 2018).

Excess noise is defined by PAME (2019) as the sound energy level above 68 dB/Pa^2 at 63Hz and is considered the amount of noise above the expected background level on a moderately quiet day in the Arctic.

How the noise levels specifically affect the marine fauna is still not very well understood among the scientific community (Bradley & Stern, 2008). Determining the responses of marine mammals to watercraft noise has numerous challenges, including constraints in experimental design; variability in species-, population-, and individual-specific characteristics and responses. Also, for several species, there is little known about the location of biologically important habitats (breeding, calving and fishing grounds). What is known so far is that noise can alter animal behavior, like changes in swim direction and speed, dive duration, surfacing duration and interval, and, of course, their auditory system, which can result in a loss of hearing sensitivity (Erbe & Farmer, 2000).

Nonetheless, a few specific criteria should be considered to assess the potential risk to various marine mammal species, for instance: vulnerability of the species, seasonal variability in the potential risk due to migratory timing of occupancy, consideration of potential cumulative effects of an additional introduction of sound into the environment (Hawkins et al., 2017). Bryant et al. 1984 also documented habitat impacts in a few cases that observed the abandonment of habitat from Mysticete whales in areas during periods of intense noise (Bryant et al., 1984).

Another challenge related to understanding the impacts on mammals is that many studies suffer bias from the observer presence, as most of them are vessel-based. This introduces a potential source of bias from the presence of the research vessel, as well as the noise it creates (MacGillivray & De Jong, 2021).

Finally, the study of vessel effects on marine animals is an interdisciplinary field: sound generation, propagation, measurement, and modeling are physics problems, yet monitoring animals, determining impacts and understanding biological significance are biological problems. Table 2.1 summarizes the key impacts that ship noise can have on whales.

Potential effects	**Comments**	**Reference**
Behavioral changes	Changes in diving, resting, orientation and vocalization patterns	Gervaise et al., 2012
Masking	Interference on an animal's ability to perceive a sound	Halliday et al., 2018
Hearing Loss	Temporary and permanent hearing loss	McWhinnie et al., 2018
Strandings	Animal observed in an inappropriate location	Piantadosi & Thalmann, 2004

Table 2.1: Potential effects of sound on whales.

2.5 Underwater noise mitigation means

Even though underwater noise from shipping remains largely unregulated, an increasing number of international institutions acknowledge the impacts and relevance of the problem, such as the Arctic Council, HELCOM (Helsinki Commission), ACCOBAMS (The Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area) and the UN (PAME, 2020). According to the Department of Fisheries and Oceans' (DFO) perspective, mitigating the impacts of human activities on Canada's oceans is vital to protecting our marine species and their habitats (Virto et al., 2022).

The Marine Strategy Framework Directive, from the EU Coastal and Marine Policy (Marine Strategy Framework Directive, 2022), developed measures aimed at maintaining noise at levels that do not cause harm to marine ecosystems including defining specific areas for both impulsive and continuous noise, developing eco-friendly ships, raising awareness, carrying out research and developing guidelines for noise assessments.

A new draft of the action plan to mitigate man-made underwater noise was presented in 2019 from HELCOM (Helsinki Commission) together with guidelines for monitoring ambient noise (PRESSURE, 2019). Moreover, the International Whaling Commission (IWC) has worked together with governments and industries to develop guidelines for mitigation and monitoring when conducting seismic surveys and recommends an approach to identify the noisiest ships and assign a priority to replacing or modifying those ships (International Whaling Commission, 2022).

The Canadian Government launched a discussion document in mid-October 2020, providing an opportunity for provinces and territories, Indigenous peoples, industry stakeholders, coastal communities, and the public to influence the direction of the strategy and the Government's efforts to enhance coordination and management of underwater noise in Canada's oceans (Government of Northwest Territories, 2020).

Awareness of underwater noise from ships and its impacts on marine fauna has led to considerations in different mitigation measures to understand what kinds of technology, maintenance processes and design options exist to make ships quieter (Vard Marine Inc. et al., 2019). However, understanding how to reduce underwater noise requires a deeper knowledge of a vessel design and its features. Both the technical and cost-effectiveness of the measures considered will be strongly dependent on the design, operational parameters, and mandatory requirements for a particular ship. Costs for such measures also need to be pondered, since it might be a great obstacle when implementing them at the shipbuilding stage (Vard Marine Inc. et al., 2019).

Assigning limits to underwater noise is very difficult, as well as understanding how it affects marine mammals and to what extent it can adversely change their behavior. The international community recognizes that underwater-radiated noise from commercial ships may have both short and long-term negative consequences on marine life, especially marine mammals (IMO, 2014). Despite these obstacles, progress has been made and articles have been published presenting studies on animals' behavior when in the presence of anthropogenic sounds.

The IMO (International Maritime Organization) launched a voluntary guideline for the reduction of underwater noise from commercial shipping in 2014, intended to provide general advice about the reduction of underwater noise to designers, shipbuilders and ship operators, considering common technologies and measures as well as focusing on primary sources of underwater noise: propellers, hull form, onboard machinery, and operational aspects (IMO, 2014).

Virto et al. 2022 addresses an interesting topic when it comes to the role of the ports when acting to reduce underwater noises. Although some measures depend on the port's characteristics and local fauna, ports could act on design and operational measures while ships wait in their area. As an example, propeller and hull maintenance solutions (propeller repair or maintenance, hull cleaning) can be implemented during docking periods and result in modest reductions in noise emissions, with costs depending on the size of the propeller and hull. A series of ports are engaging in actions on air-borne noise from shipping, as it is a local concern that impacts the population living near ports. Local speed restrictions can also limit ship-generated noise (Virto et al. 2022).

Ship noise abatement measures can be separated into different categories, which will be thoroughly explained in the following sections.

2.5.1 Technological and Design factors

On the technological side, the focus is the performance of the propeller, especially when related to the phenomenon of cavitation, which is accompanied by an increase in hull vibrations, a reduction in propulsion performance, and an increase in noise (Jeong et al., 2021). Above the cavitation inception speed (CIS), i.e., the highest speed at which the ship can be operated without any cavitation on the propeller(s), or any appendix or rudder(s) for that matter, the propellers generate a water pressure high enough to cause bubbles of water vapor, releasing a broadband noise when they collapse (Farcas et al., 2016).

The pressure generated by the rotation can be controlled by changing the shape of the blade, attaching great importance to the design stage of the propeller (Lee et al., 2015). The designer's job would be to optimize the shape of the blade and angle of attack to provide the required thrust while minimizing cavitation. The use of computational fluid dynamics (CFD) tools to optimize propeller performance is increasing, and such efforts are most economical when performed at the design stage (Sodja et al., 2012).

The shape of the hull and the resulting wake distribution into the propeller are important factors in propeller performance, both with respect to thrust and cavitation noise (Vard Marine Inc., 2019).

In 2019, Strathclyde University and Oscar Propulsion, a UK-based innovation and technology transfer company, developed a revolutionary new technology capable of substantially reducing the underwater radiated noise (URN) generated by ships' propeller cavitation. The system reduces propeller tip vortex cavitation by applying a small number of strategically bored holes in the propeller blades (Strathclyde University & Oscar Propulsion, 2019). CFD modeling and a cavitation tunnel were used for the technology's development and tests (Sodja et al., 2012). The outcome showed that Pressure Pores technology substantially reduced tip vortex cavitation and URN. Further ship design noise mitigation measures will be presented in Section 4.3.1.

2.5.2 Operational Factors

Ship speed restrictions is also an important factor for emitting less noise, as there is a direct relationship between vessel speed and the amount of cavitation that is created, and the aspect of the cavitation inception speed, as stated. An exception for this are ships with controllable pitch propellers, whereby there may be no reduction in noise with reduced speed (IMO, 2014).

However, slower ships take longer to transit, leading to a trade-off between the duration and the intensity of noise exposure (McKenna et al., 2012). McKenna et al. showed that the optimal trade-off between noise intensity and trip duration would be achieved at around 8 knots.

Virto et al. 2022 shows that ports can also support the reduction in underwater noise through operational measures associated with reduced speed, change of route and traveling in convoys. Grouping the ships into convoys dramatically changes the temporal distribution of ship noise over the day and night. Ports could propose actions such as discounted port fees to induce desired temporal vessel movements and reduced ship waiting times at ports, both affecting underwater noise performance (Virto et al., 2022).

Another very important operational measure comes along with proper maintenance of the vessel as a whole. In many cases, they can be quieted significantly by undergoing routine maintenance (Renilson, 2012). Marine fouling on the propeller can increase cavitation, nicks on the propeller can cause loud tones, and surface roughness on the hull increases drag, heightening load on the propeller which can also increase noise (IMO, 2014). Poor vessel maintenance is the source of noise on 10% of merchant ships. Maintenance options for noise reduction include propeller and generator repair, and retrofitting generator baffles or noise-reducing mounts (WWF & Vancouver Aquarium, 2013).

When it comes to activity reduction measures, we cite that the use of fewer, larger vessels for shipping could lead to cumulative noise reductions (McKenna 2012), which leads to a trade-off that may not be well appreciated by shipping companies. Larger vessels offer greater capacity and cost reduction when compared to substituting it with smaller ones (Merchant, 2019).

2.6 Forecasting and prediction analysis

Forecasting refers to the practice of predicting what will happen in the future by taking into consideration events in the past (historical data) and present (Schmidt, 2023). Forecasting is required in many situations: deciding whether to build another power generation plant in the next five years requires forecasts of future demand; scheduling staff in a call centre next week requires forecasts of call volumes; stocking an inventory requires forecasts of stock requirements (Hyndman & Athanasopoulos, 2021). It is generally considered as a good practice for indicating the degree of uncertainty attached to forecasts.

Depending on the period to be forecasted, we can find three different categories:

- Short-term forecasts: are needed for the scheduling of personnel, production and transportation.
- Medium-term forecasts: are needed to determine future resource requirements, in order to purchase raw materials, hire personnel, or buy machinery and equipment.
- Long-term forecasts: are used in strategic planning. Such decisions must take account of market opportunities, environmental factors and internal resources (Hyndman & Athanasopoulos, 2021)

The appropriate forecast analysis depends on the available data. If no data are available, or if they are irrelevant, qualitative forecasting methods must be used, in which experts' opinion and knowledge is taken into consideration. On the other hand, quantitative forecasting is used when numerical information about the past is available and when it is reasonable to assume that some aspects of past patterns will continue into the future (Hyndman & Athanasopoulos, 2021). These two methods are better explained in the section 2.6.1 and 2.6.2.

2.6.1 Quantitative methods

Quantitative forecasting is a data-based process used to understand business and process performance, to forecast stock prices, weather, business planning, and resource allocation, for example, and predict future behaviors based on historical data and patterns. It is an objective method based on statistics, mathematics and predictive algorithms to project future situations, usually used for relatively short-term predictions (Hyndman & Athanasopoulos, 2021).

An example that is widely used, and commonly applied for analyzing sales, is the time-series method. This method involves an analysis of past data, to gain an understanding of a phenomenon and to be able to determine underlying aspects, trends and patterns. Forecasting has historically been a key area of academic research in many topics, including climate modeling and biological sciences (Lim & Zohren, 2020; Mudelsee, 2019).

Statistical data-driven techniques provide useful insights when integrating with global climate models projections (based on global patterns in the ocean and atmosphere, and records of the types of weather that occurred under similar patterns in the past) (NOAA - National Oceanic and Atmospheric Administration, 2020). This approach has been utilized to provide probabilistic projections (Rasmussen et al., 2020), and to provide computational efficiency for regional climate modeling (Duchêne et al., 2020). For example, a statistical forecasting model— the auto regressive integrated moving average (ARIMA) model — was used in Lai and Dzombak (2020) to obtain city-specific near-term forecasts of temperature and precipitation based on long-term historical city-level observations (Lai & Anastas, 2020).

A time series is usually modeled through a stochastic process $Y(t)$, i.e. a sequence of random variables. In a forecasting setting, we find ourselves at time t and we are interested in estimating Y(t+h), using only information available at time t (Burba, 2021).

Time series data tend to exhibit patterns such as trends (when there is a long-term increase or decrease in the data), seasonal fluctuations (when a time series is affected by seasonal factors such as the time of the year or the day of the week), cycles (when the data exhibit rises and falls but not at a fixed frequency), and occasional shifts in levels (Hyndman & Athanasopoulos, 2021). The analysis of such type of data is employed to extrapolate the dynamic pattern in the data for forecasting future observations (Lai & Anastas, 2020).

Figure 2.11 shows exactly these patterns: the top-left graphic shows strong seasonality within each year and also a cyclic behavior in a period of 6 to 10 years. The top-right shows a downward trend, while the bottom left shows an increasing trend. The last one (bottom-right) has no trend, seasonality or cyclic behavior, but exhibits significant random fluctuations.

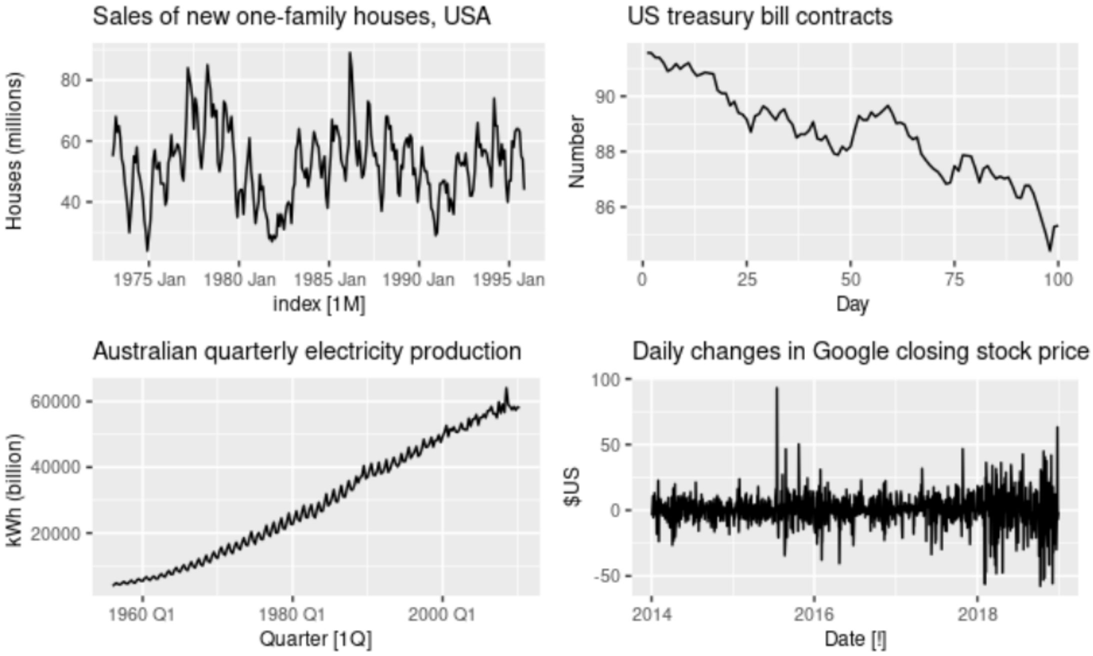


Figure 2.11: Data patterns on time series. Source: adapted from (Hyndman & Athanasopoulos, 2021)

2.6.2 Qualitative methods

Qualitative forecasting techniques are based on human judgment. It revolves around the knowledge of customer journey, market research, experts' opinion, or senior industry leaders' experience in the field (Pangea Tech, 2022). Forecasting with the use of judgments is a common practice between experts and it's often used when there is a complete lack of historical data, or when a new product is being launched, or when a new competitor enters the market, or during completely new and unique market conditions (Hyndman & Athanasopoulos, 2021).

Three primary approaches can be cited:

1. Delphi Method: involves a repeated cycle of questionnaires presented to a panel of selected experts in a field;
2. Market Survey: popular in the business area, this method forecasts future demand through consumer surveys and questionnaires.
3. Experts' opinion: a technique that brings internal experts of an organization together for an open discussion and consensus on products and services (Hyndman & Athanasopoulos, 2021)

A different approach to judgmental forecasting is scenario-based forecasting. This procedure generates forecasts based on plausible scenarios, and each of them has the same probability of occurrence. The scenarios consider all possible drivers and factors (along with their interactions between them) that may affect the future. It also allows a wide range of possible forecasts to be generated and some extremes to be identified.

With scenario forecasting, decision makers often participate in the generation of scenarios (Hyndman & Athanasopoulos, 2021).

Arctic Future Scenarios

Creating scenarios are aimed at displaying a range of possible futures for a specific situation, which provides a point of departure for leadership discussions and decision-making processes (Belostotskaya et al., 2021). A recent Arctic Climate Change update from 2021 made by the Arctic Council shows that the latest climate models continue to project that the Arctic will warm (3.3–10°C above the 1985–2014 average) rapidly over the course of this century. Its models also project an ice-free Arctic summer occurring before 2050 (Figure 2.12) (AMAP, 2021).

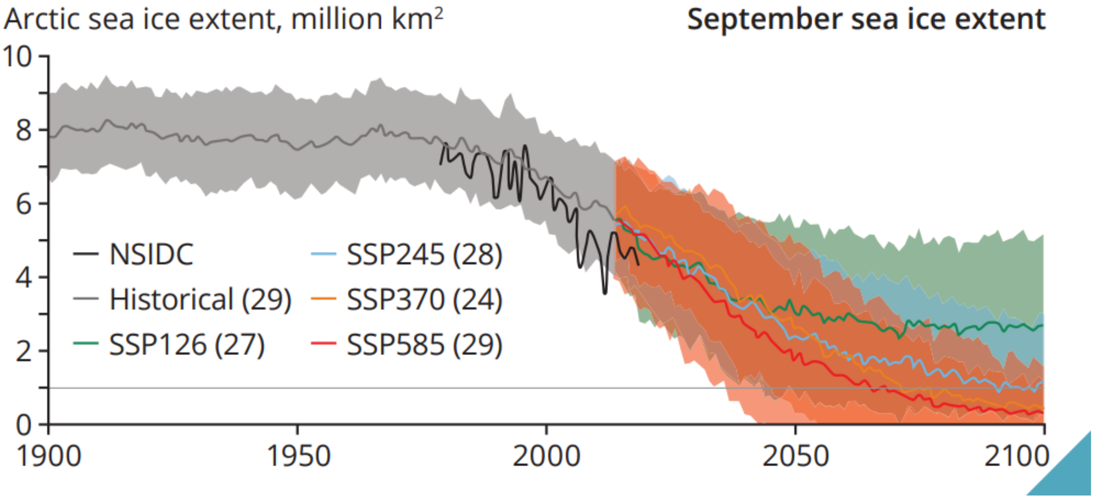


Figure 2.12: Ice-extent forecasting. Source: adapted from (AMAP, 2021)

However, to understand the different futures for Arctic, key developments, forces and processes need to be identified and their relationship, analyzed. A scenario methodology develops around the identification of future trends and key uncertainties that grow from the interaction of certain key 'forces', as explained by Hodgson, 2014. These drivers may develop in either predictable or unpredictable ways. A scenario is not a prediction of the future but rather a hypothetical sequence of events that is helpful in investigating causes and necessary decision points (Quigley et al., 2018).

In Hodgson's study, market motivation is identified as a key force to influence the way that shipping may evolve in the Canadian Arctic. International economic trends, especially the ones driven by a growing global demand for non-renewable resources and expanding international trade, are expected to have important consequences for the scale and configuration of shipping activities in Arctic waters (Hodgson, 2014).

Although the marine transportation industry is considered very complex, when developing scenarios, it is useful to consider every different component that might impact it, in order to better understand possible paths that shipping activity may take into the future.

The health of the world economy is considered to be a central variable responsible for creating demand for marine transportation services. As shipping operates on a derived demand basis, fluctuations in the health of the global economy have a direct effect on the growth and profitability of this industry (Hodgson, 2014).

Regarding demographic changes, projections in the Arctic show a very small population increase, in the range of 1%, until 2055 (Government of Canada, Statistics Canada, 2022b). Cities in the Arctic are indeed becoming more urbanized and multicultural, reflecting its economic structure, where larger shares of population are employed in mining, manufacturing, and the service sector than in agriculture. An important fact that needs to be pointed out, is that energy consumption has risen significantly in the Canadian Arctic in the past decade, and population increase has contributed to this trend (Hodgson, 2014).

Alongside population growth, demand for fresh water and food supplies to different communities in the Arctic are also associated with the rise in energy consumption, contributing to an increase in required shipping traffic.

The use of northern passages for transit of the Arctic may only be considered under certain market conditions, and depending on whether ice breakers are needed, how heightened insurance rates are, and more specifically the weather conditions, southern routes may be more feasible than Northern Arctic routes. Changes to the sea ice conditions may pose threats for the safety and effectiveness of moving goods. Thus, the Arctic may not be seen as a viable route for international traffic at the present but rather for destinational activities only (Hodgson, 2014).

In regard to oil and gas exploration, residents and businesses in the North support the responsible development of our natural resources, and there is currently a moratorium in the Canadian North (Government of Canada, 2022). Mining has also played a large part the Northwest Territories' history and will continue to do so (Government of Northwest Territories, 2020). However, the lack of infrastructure may still be an obstacle as well as climate factors (short shipping seasons, melting permafrost)(Desjardins, 2020). Despite the weakening state of global and Canadian economic growth in recent years, the mining sector is getting reestablished in the Yukon and expanding in Nunavut, as more greenfield mining projects are planned. Also, after being on a declining trend or remaining at a standstill in the latter part of 2018, most metal and mineral prices have started to improve. Nunavut's economy will post solid growth over the near and medium terms thanks to strength in the mining sector (Bernard et al., 2019).

In essence, any decision to use the Arctic for transit purposes need to take into consideration several circumstances. Market factors still constitute important uncertainties for how shipping traffic will develop in the following years.

Forecasting horizon

Developing possible futures requires a feasible time horizon considering data and resources that are available today. The shorter the time horizon of the forecast, the lower the degree of uncertainty and the more accurate the forecast will be. Considering 2030, it's a relatively short-term scenario that can be constructed based on what's available now in terms of ship technology, infrastructure and policies. Although climate change consequences are accelerating year by year, a 10-year period is still short to expect radical changes (Belostotskaya et al., 2021).

Yet, if we think about 2075, the accelerating pace of technological changes, the changing natural environment, and geopolitical dynamics may result in an Arctic quite different from the one we have now. Thus, the gap between the years of 2040- 2050 will likely be a "half-way" point from today's structure and a different future situation. It tends to present features of both periods at once, making this process very creative and complex at the same time (Belostotskaya et al., 2021).

3 Methodology

Given recent increases in Arctic marine traffic, as described by Carter et al. 2017 in section 2.2, it is reasonable to try to anticipate the future traffic picture in the Canadian Arctic, especially since improvements in infrastructure, regulations, traffic services, and environmental or safety response all have long lead times.

With the purpose of understanding the present and possible future conditions of shipping traffic and the underwater noise generated by its activities, this research proposed a representative forecasting process to support the comprehension of future trends and uncertainties associated with the important drivers that might affect shipping activities, and finally, how will technology mitigation means impact ship-generated noise shown in scenario samples of three types of vessels (cargo, tanker and cruise), limited frequency bands and limited assumptions on marine mammals behavior. Future and more detailed works should/could consider modeling sound propagation taking into consideration all ice and water properties for both present and forecasted situations as well as analyzing all areas in the Arctic and all types of vessels in the regions.

Cargo and tanker vessels were chosen due to their considerable size and therefore, significant underwater noise levels emitted, as well as to the fact that shipping traffic in the Arctic largely consists of bulk cargo vessels and tankers transporting natural resources. As for cruise vessels, Arctic tourism is an emerging sector and it is the class of vessel that shows the most significant relationship with the changing of the Arctic conditions (Raspotnik, 2022).

With the purpose of analyzing how the underwater noise impact the marine faune, three species of whales were considered due to their importance to native communities and due to the fact that the acoustic bandwidths used by them overlap with anthropogenic sound sources:

- Bowhead whales: the gentle giants of the Arctic Ocean, they are the only mysticete, or baleen whale, endemic to the region (Darnis et al., 2012) with a population estimated at around 6,000 individuals (DFO, 2017). Bowhead whales stay above the 50 m water depth and their moans are relatively low-frequency tonal sounds that last for about 2.5 seconds and range from 25-900 Hz (Cummings & Holliday, 1987).

- Narwhals: they are seen in Baffin Bay and Davis Strait area throughout the summer months and they are important to traditional Inuit subsistence hunting as well as the economy for the eastern Canadian Arctic (COSEWIC, 2022). Narwhals spend the majority of their time at the surface or above 50 m depths and their buzzes or whistles range from 300 Hz to 10 kHz (Cummings & Holliday, 1987).

- Beluga: highly social odontocetes, these whales are seen in the Baffin Bay area during summer months and have been a concern for scientists as all of the beluga whale populations have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2022) as threatened, endangered or special concern (Government of Canada, 2004). Belugas spend most of their time at the surface waters between 15 and 50 m in depth, producing sounds ranging from 400 Hz to 22 kHz (Lefebvre et al., 2012).

In order to match with the dataset retrieved from JASCO's reports on parameters used to calculate the underwater noise levels and still relate them to the acoustics bands used by mammals, only two frequencies were analyzed in this thesis: 63 and 400 Hz. Detailed explanations on the calculation of underwater noise are presented in section 3.3.

Due to AIS data limitations (see section 3.2) gaps were found in some months of 2019 and 2020 for AIRSS zones 1 and 2, located in the Beaufort Sea. Furthermore, information on shipping traffic in the winter months was very limited, due to a small number of ships during that period. Thus, it was decided to consider the zones and time of year that presented the highest traffic levels: zones 9 and 13 (Lancaster Sound and Baffin Bay) during the summer months (July to September). These zones presented ice-free waters during this time of year and significant shipping activity.

The drivers analyzed herein, and the way they may unfold or interact were essential elements in the development of the process. However, it is important to emphasize the fact that all of them are sources of uncertainty and part of a very complex chain of forces influencing shipping activity, being therefore, not precise when analyzing each driver separately, as done in this project.

Nevertheless, based on an analysis of available historical data and reference to Hodgson's work on exploring plausible futures for marine transportation in the Canadian Arctic (Hodgson, 2014), this process proposes a quantitative review of two key drivers that shaped the progress of shipping activities in the past and might continue to do so within the future: northern population growth and gross domestic product (GDP), i.e., examining the underlying drivers through a basic supply and demand model. According to Hodgson, unpredictability in global population growth, which in turn may cause an increased demand for fresh water and food supplies and the health of the world's economy are considered central variables affecting marine transportation services.

In addition, the process proposes an understanding of possible future scenarios for the Canadian Arctic based on experts' opinions. Interviews were conducted via Microsoft Teams with professionals from community re-supply shippers, cruise and oil/mineral industry sectors, naval engineers and regulators. Questions were posed regarding their opinion on how the shipping traffic volume might develop by 2040 and which technologies are most likely to be adopted when building new vessels or modifying existing ones. As uncertain inputs, the Monte Carlo simulation method was used to calculate possible future values for underwater noise (as further explained in sections 3.1.2 and 3.3) and, thus, determine the relationship between the quantity of ships and technology improvements with noise levels. A sample of the posed questions can be found in Appendix A.1 and A.2.

Regarding the rising concern of the impacts of underwater noise on marine mammals, in order to analyze future sound exposure levels for a possible receiver, considered herein to be in a fixed location both in the water column as well as in the distance range from the ship, sound exposure levels were also retrieved from the calculations. The procedure of having the receiver in a fixed position was adopted in order to simplify the calculation and modeling of a future possible state. Alternatively, randomization of not only the receiver location would need to be modeled, but also sound speed profiles together with the transmission loss model. Further limitation features of this research are presented in the discussion section 5.4.

The process for developing and analyzing future scenarios is presented in Figures 3.1 and 3.2, categorized by the forecasting method used (qualitative and quantitative analysis), wherein shapes colored in grey indicate methods used to achieve a goal, shapes colored in green identify parameters for the future, and shapes in orange indicate parameters for historical and present data. Each of these steps is explained in the following sections.

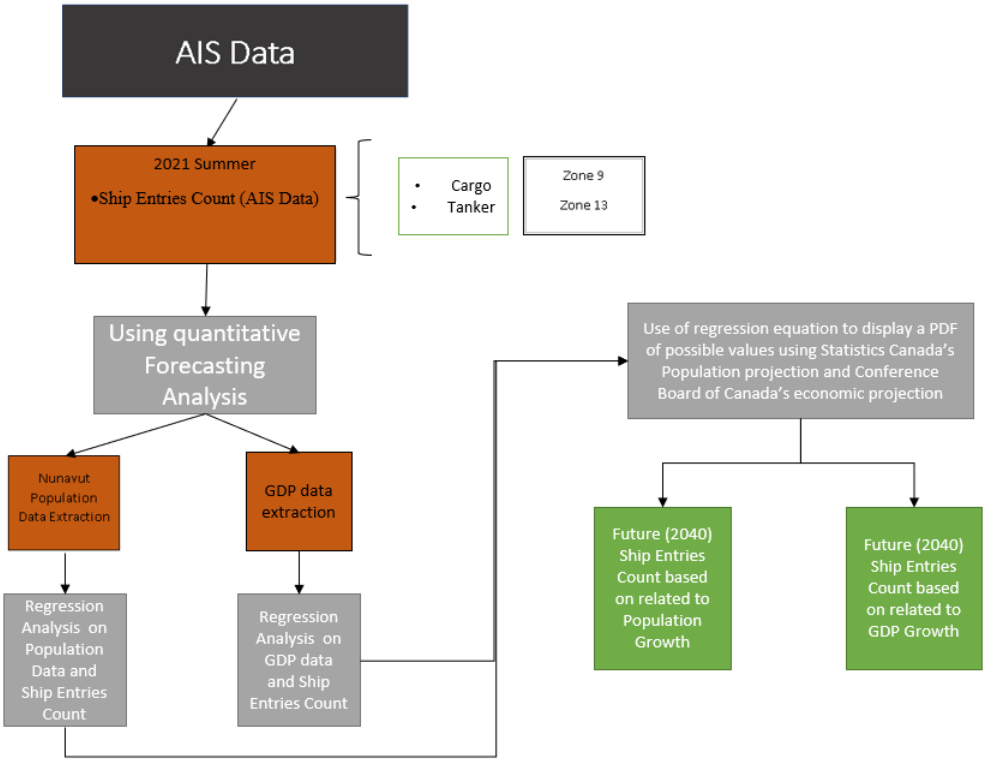


Figure 3.1: Process proposed for developing future scenarios of shipping traffic levels using quantitative method (regression analysis).

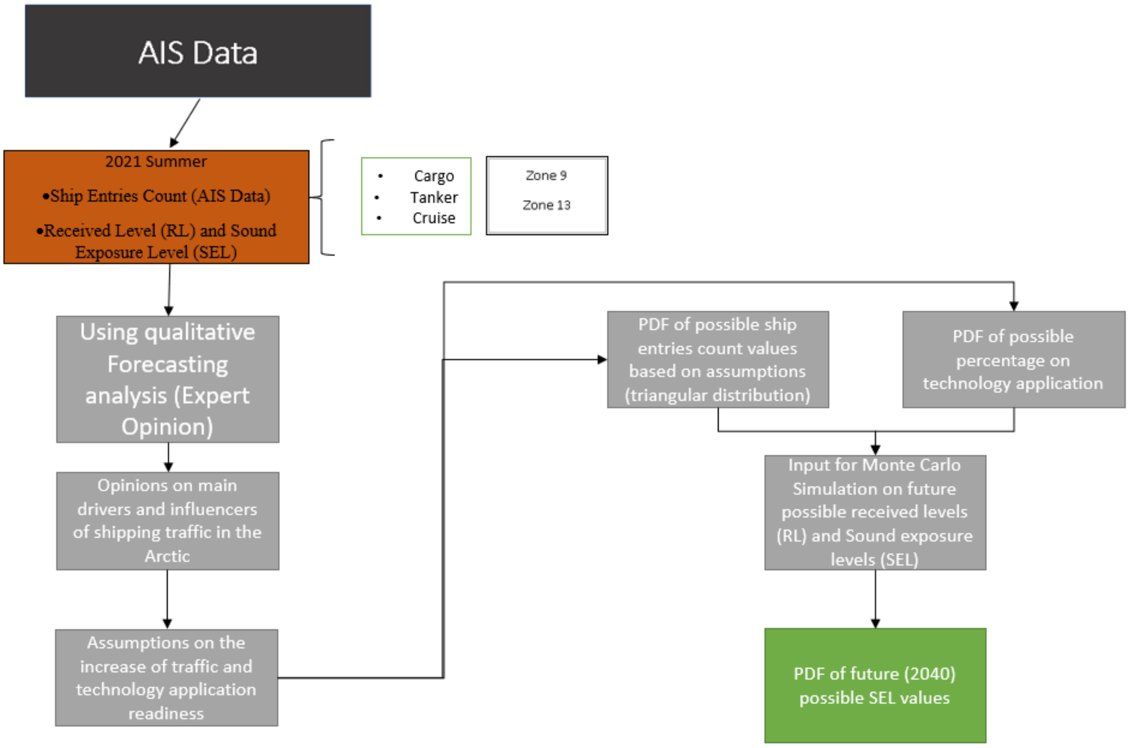


Figure 3.2: Process proposed for developing future scenarios of shipping traffic levels and underwater radiated noise using qualitative analysis (expert opinion).

Methods and Research Question	
Quantitative Analysis	Qualitative Analysis
How will important key drivers influence shipping traffic in the future?	Does an increase in shipping traffic also imply an increase in underwater noise levels?
	What will the underwater sound levels be in 20 years in the Canadian Arctic?
	How are technology improvements and environmental restrictions affecting the levels of underwater noise in the Arctic?

Table 3.1: Relation between methods used to answer research questions.

Table 3.1 shows a linkage between the methodology proposed and the research questions presented in section 1.1

3.1 Data Analysis Methods

3.1.1 Regression Analysis

In order to examine the relationship between two or more variables of interest, in this case, the relation between population numbers or GDP respectively with shipping traffic, the statistical method of linear regression analysis was used, a trend line was observed and its equation was obtained. Regression lines always consider an error term because in reality, independent variables are never precisely perfect predictors of dependent variables (Gallo, 2022).

From the regression analysis, the values of the R-Squared (R^2 or the coefficient of determination) and the p-values were analyzed. The R-squared value shows how well the data fit the regression model. It takes values between 0 and 1, with 0 indicating that the model explains none of the variability of the response data and 1 indicating that the model explains all the variability of the response data around its mean. The p-values in regression help determine whether the relationships that you observe in your sample also exist in the larger population (Taylor, 2022).

A p-value less than 0.05 indicates statistical significance and a greater statistical incompatibility of the data with the null hypothesis, i.e., there is a statistical relationship and significance in the observed variables (Nahm, 2017). The trend line equation is assumed to be linear for all the vessel types and zones.

3.1.2 Monte Carlo Simulation

A Monte Carlo simulation is used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty (Harrison, 2010). The Monte Carlo method acknowledges an issue for any simulation technique: the probability of varying outcomes cannot be firmly pinpointed because of random variable interference. Therefore, a Monte Carlo simulation focuses on constantly repeating random samples (Palisade, 2023).

Monte Carlo simulation takes the independent variable that has uncertainty and assigns it a random value. The model is then run and a result is provided. This process is repeated again and again while assigning many different values to the variable in question. Once the simulation is complete, the results show the decision-maker a range of possible outcomes and the probabilities that they will occur for any choice of action (Palisade, 2023).

On this project, the input variables that presented uncertainty regarding the future situation of underwater noise were: shipping traffic level or quantity of ships, the probability of technological changes in ship design, and the probability of noise reduction using these technologies. Assumptions on how these uncertainties are distributed are discussed in section 4.

3.1.3 What-if Analysis

Later in the results section, further analysis on the possible future values for underwater noise was conducted using the What-If analysis method. What-If Analysis is the process of changing the input values to see how those will affect the outcome. In the case of this project, the values of the probability of technological changes in ship design were modified to much higher levels, envisioning a hypothetical scenario, very different from what was stated by experts. However, with this method, we were able to observe that if a large quantity of ships adopts new underwater noise mitigation technologies, the collective noise emitted by them can significantly drop. Further analysis is shown in section 4.

3.2 Raw Automatic Information System (AIS) vessel tracking data

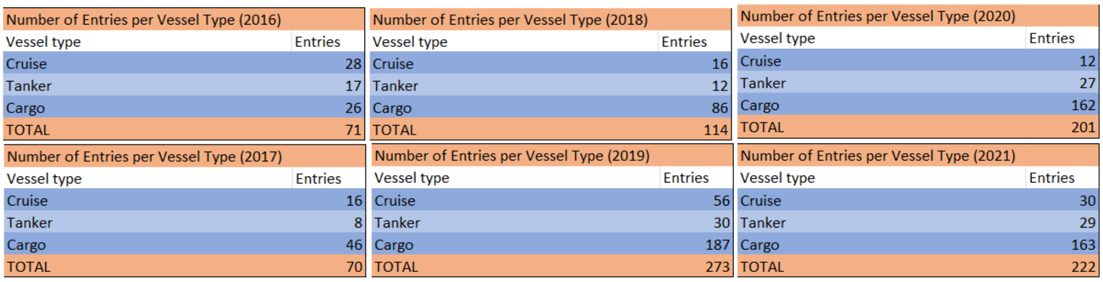
The ship traffic data were retrieved from the raw Automatic Information System (AIS) data and refined by the Marine Environmental Observation Prediction and Response (MEOPAR) network programmers.

The automatic identification system, or AIS was originally developed by IMO (International Maritime Organization) in 2004, and it transmits a ship's position so that other ships are aware of its location (UN Statistics Wiki, 2019). The range of reception can be variable and is dependent on factors including signal propagation conditions, sea state, the height of the transmitting and receiving antenna and the strength of the vessel transmitter. Reception could be as little as 20 nautical miles, or as much as 350 nautical miles for powerful transmissions during appropriate atmospheric conditions. That information transmitted includes the Maritime Mobile Service Identity (MMSI) number, vessel name, destination and cargo type, for example (UN Statistics Wiki, 2019). AIS has been made compulsory for international commercial ships with gross tonnage (GT) of 300 or more tonnes, and all passenger ships regardless of size (UN Statistics Wiki, 2019). Although a powerful tool for vessel localization, it has limitations regarding its transmission, which is further explained in the discussion section.

The AIS dataset used for this research includes ship traffic information from the year 2016 to 2021 and filtered by month. The interval of 5 years was chosen due to limited time and computational constraints as the AIS data was retrieved for all types of vessels and all zones being significantly large. The area of interest was filtered by the AIRSS' boundaries and the trajectories were filtered by vessel type: cargo, passenger and tanker. The resulting data were output in CSV format with each row representing one vessel transit per AIRSS zone, and the associated metadata for the vessel: MMSI number (Maritime Mobile Service Identity) which is a unique nine-digit number for identifying a ship, vessel type, length, draught, gross tonnage, zone transit (with the starting and endpoint of the transit specified by AIRSS zone) and vessel average and maximum speed. Many of these attributes are required for generated noise source level (SL) calculations, notably the length and speed of vessels.

3.2.1 Historical and recent AIS data analysis

From the AIS data collected, the monthly number of unique entries made by each type of vessel, in each area/zone of interest and for each year was calculated. An overview of the summer months' numbers for AIRSS zone 9 and zone 13 is shown in Figures 3.3 and 3.4:



Number of Entries per Vessel Type (2016)	
Vessel type	Entries
Cruise	28
Tanker	17
Cargo	26
TOTAL	71

Number of Entries per Vessel Type (2018)	
Vessel type	Entries
Cruise	16
Tanker	12
Cargo	86
TOTAL	114

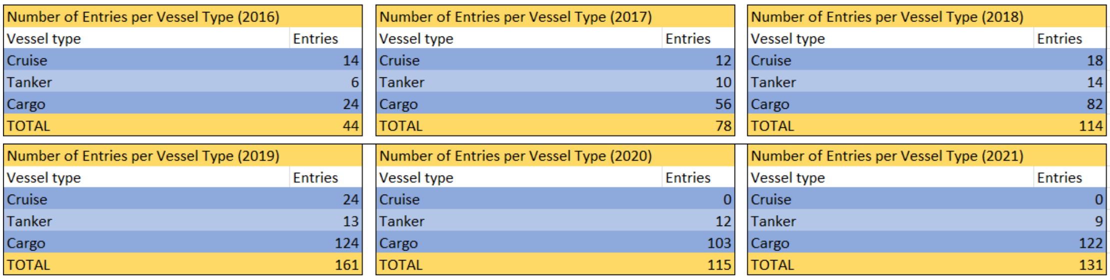
Number of Entries per Vessel Type (2020)	
Vessel type	Entries
Cruise	12
Tanker	27
Cargo	162
TOTAL	201

Number of Entries per Vessel Type (2017)	
Vessel type	Entries
Cruise	16
Tanker	8
Cargo	46
TOTAL	70

Number of Entries per Vessel Type (2019)	
Vessel type	Entries
Cruise	56
Tanker	30
Cargo	187
TOTAL	273

Number of Entries per Vessel Type (2021)	
Vessel type	Entries
Cruise	30
Tanker	29
Cargo	163
TOTAL	222

Figure 3.3: Unique entries made by each vessel type in each year in zone 9



Number of Entries per Vessel Type (2016)	
Vessel type	Entries
Cruise	14
Tanker	6
Cargo	24
TOTAL	44

Number of Entries per Vessel Type (2017)	
Vessel type	Entries
Cruise	12
Tanker	10
Cargo	56
TOTAL	78

Number of Entries per Vessel Type (2018)	
Vessel type	Entries
Cruise	18
Tanker	14
Cargo	82
TOTAL	114

Number of Entries per Vessel Type (2019)	
Vessel type	Entries
Cruise	24
Tanker	13
Cargo	124
TOTAL	161

Number of Entries per Vessel Type (2020)	
Vessel type	Entries
Cruise	0
Tanker	12
Cargo	103
TOTAL	115

Number of Entries per Vessel Type (2021)	
Vessel type	Entries
Cruise	0
Tanker	9
Cargo	122
TOTAL	131

Figure 3.4: Unique entries made by each vessel type in each year in zone 13

3.3 Underwater Noise Calculation Model

3.3.1 Source Level (SL)

The method used for the calculation of the SL was based on the model developed as part of the Joint Monitoring Programme for Ambient Noise in the North Sea (JOMOPANS) project. It validated a widely used reference spectrum model called Research Ambient Noise Directionality noise model (RANDI 3.1) against statistics of monopole (a source which radiates sound equally well in all directions) ship source level measurements from the Vancouver Fraser Port Authority-led Enhancing Cetacean Habitat and Observation (ECHO) Program (MacGillivray & De Jong, 2021). It calculates the ship source level spectrum, in decidecade bands, as a function of noise frequency, vessel speed and length, and AIS ship type.

The purpose of the calculation was to provide an overview of the current underwater radiated noise (URN) within a specific range of frequencies (10 Hz to 10 kHz) (MacGillivray & De Jong, 2021). This range is particularly useful for communication, reproduction and localization (echo-localization) of the three most common species of whales (Beluga, Bowhead and Narwhals) in the Arctic. Future conditions of underwater noise also take into consideration these frequency values, computing what scenarios could look like in a period of twenty years, according to historical correlation analysis and what specialists in the area of Community resupply, Cruise ships and Engineering companies have as a best possible guess for the inputs used in the calculations.

These validation comparisons developed throughout the programme resulted in a new reference spectrum model (the JOMOPANS-ECHO source level model, used herein) that retains the power-law dependence of the source level on vessel speed and length but incorporates class-specific reference speeds and new spectrum coefficients, as information available from AIS is limited (small ships are not required to carry AIS transponders; potential sources of error within the data, as for example, transponders may be switched on or off during a ship's passage) and not easily related to vessel noise emissions, as the speed variance remains a fundamental uncertainty in estimating source levels from AIS information (AIS can provide better information about the presence of ships (GT $>$ 300) or shipping densities)(MacGillivray & De Jong, 2021). The statistical uncertainty (standard deviation of the deviation between model and measurement) in the predicted source level spectra of the new model is estimated to be 6 dB (MacGillivray & De Jong, 2021).

The source level spectral L_{Sf} proposed by JOMOPANS, is a function of sound frequency f (Hz), vessel speed V (kt), vessel length l (ft), and a reference speed per vessel class V_c confirms that there is a correlation between the source level and the ship speed and length, and these two parameters are readily available from ship traffic systems (AIS).

$$L_{S_f}(f, V, L, C) = L_{S_f0}(f, C) + 60\log_{10}(V/V_c)dB + 20\log_{10}(l/l_0)dB \tag{3.1}$$

where,

$$L_{S_f0}(\hat{f}, C) = K - 20\log_{10}(\hat{f}_1)dB - 10\log_{10}((1 - \hat{f}/\hat{f}_1)^2 + D^2)dB \tag{3.2}$$

with, $\hat{f} = (f/f_{ref})$, $\hat{f}_1 = 480Hz(V_{ref}/V_C)$, f_{ref} =1 Hz, $V_{ref} = 1kt$, and $K = 191dB$, $D = 3$ for all classes, except $D_{cruise} = 4$

- V_c is the reference speed for the ship class C (table 3.1)
- $l_0 = 300ft$ is the vessel reference length consisting of a baseline spectrum of an "average ship"

For the cargo vessels (container ships, vehicle carriers, bulkers, tankers), the updated model includes an additional peak in the baseline spectrum below 100 Hz:

$$\begin{aligned} L_{S_f0}(\hat{f} < 100, Cargo) &= K^{LF} - 40\log_{10}(\hat{f}_1^{LF})dB \\ +10\log_{10}(\hat{f})dB - 10\log_{10} &\left(\left(1 - \left(\frac{\hat{f}}{\hat{f}_1^{LF}{}_1}\right)^2\right)^2 + \left(D^{LF}\right)^2\right) \end{aligned} \tag{3.3}$$

with $K^{LF} = 208$ dB and $\hat{f}_1^{LF} = 600$ Hz(V_{ref}/V_{Vc}) and $D^{LF} = 0.8$ for container ships and bulkers) or $D^{LF} = 1.0$ for vehicle carriers and tankers.

The above model expressions are for source power spectral density level. In the final modeling, these are converted to source level in decidecade frequency bands by adding $10\log_{10}(0.231\hat{f})$ dB. A power spectral density is always measured in a 1 Hz band, whereas decidecade bands are a predefined bandwidth that increases with frequency. This way, the power spectral densities within the frequency range of the given decidecade band are summed in linear space and then converted back to a logarithmic scale to result in the decidecade source level.

Vessel Class	**AIS SHIPTYPE ID**	**V_C**	**Cargo**	**D_lo**	**D_hi**
Bulker	70, 75-79 (speed 16 kt)	13.9	TRUE	0.8	3
Containership	71-74 (all speeds); 70, 75-79 (speed >16 kt)	18.0	TRUE	0.8	3
Cruise	60-69 (length >100 m)	17.1	FALSE	1	4
Dredger	33	9.5	FALSE	1	3
Fishing	30	6.4	FALSE	1	3
Government/Research	51,53,55	8.0	FALSE	1	3
Naval	35	11.1	FALSE	1	3
Other	All other type IDs	7.4	FALSE	1	3
Passenger	60-69 (length 100 m)	9.7	FALSE	1	3
Recreational	36,37	10.6	FALSE	1	3
Tanker	80-89	12.4	TRUE	1	3
Tug	31,32,52	3.7	FALSE	1	3
Vehicle Carrier	n/a	15.8	TRUE	1	3

Table 3.2: Parameters for source level calculation according to JOMOPANS proposed model

As an example, the source level PDF for each frequency (63 and 400 Hz) is shown in Figure 3.5 regarding cargo vessels in zone 9. The different outputs relate to the variation in speed and length of the ships that entered the zones of interest.

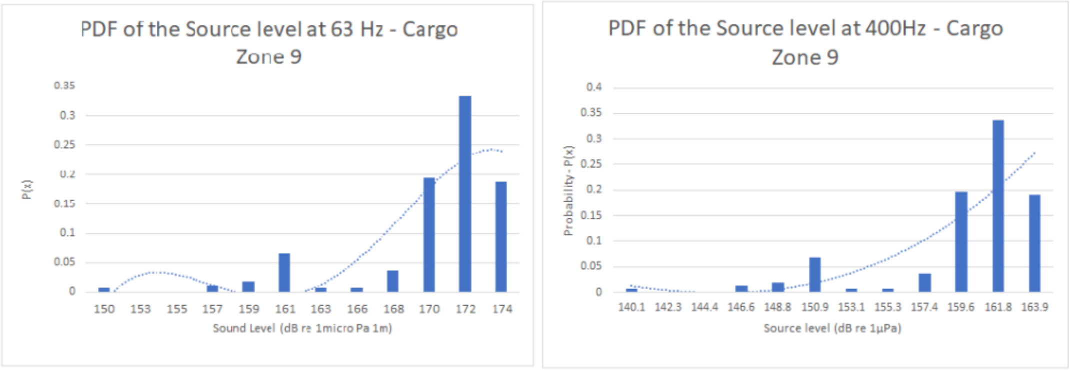


Figure 3.5: Probability distribution function (PDF) of the source levels for cargo vessels that transited through zone 9 boundaries during the summer of 2021.

The relation between sound level generated, the length and the speed of a vessel is here shown in the 3D chart in Figure 3.6. We can observe that the higher the speed or the length, the higher the SL.

3.3.2 Transmission Loss

Following the steps for the application of the simplified sonar equation ($RL = SL - TL$), the model used for the acoustic propagation loss values was JASCO's Parabolic Equation (PE). PE models are often employed for low-frequency solutions when high computation speed is required. Some of the features of the JASCO model include fast execution time, range-dependent model and full-wave (time domain) capability as long-range propagation can lead to pulse distortion.

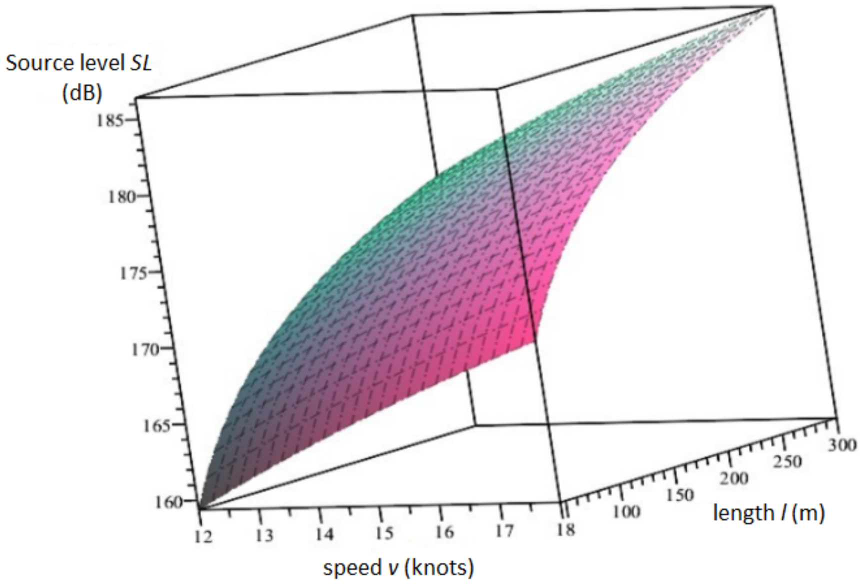


Figure 3.6: Relationship between Sound Level (axis z), length (l) and speed (v) variables

The propagation loss values consider the bathymetry, a sound speed profile, the source depth (or draught of the ship) and the location of the receiver (whale) in the water column (Hines et al., 2020). In order to simplify the complexity of propagation calculations, a fixed depth of 50m for a whale location was employed.

The minimum distance at which a ship's noise would disturb a whale was based on the range of variability of responses of marine mammals, and the minimum distance that a ship can get to a whale was based on Fisheries and Oceans Canada's regulations. According to Finley 1990, at distances of up to 50 km from icebreakers, or other operating ships, beluga whales respond with a suite of behavioral reactions (Finley et al., 1991). According to Canadian laws, keeping a distance of 400m away from suspected whale locations is required based on Canada's Marine Mammal Regulations. The distance ranges are illustrated in Figure 3.7.

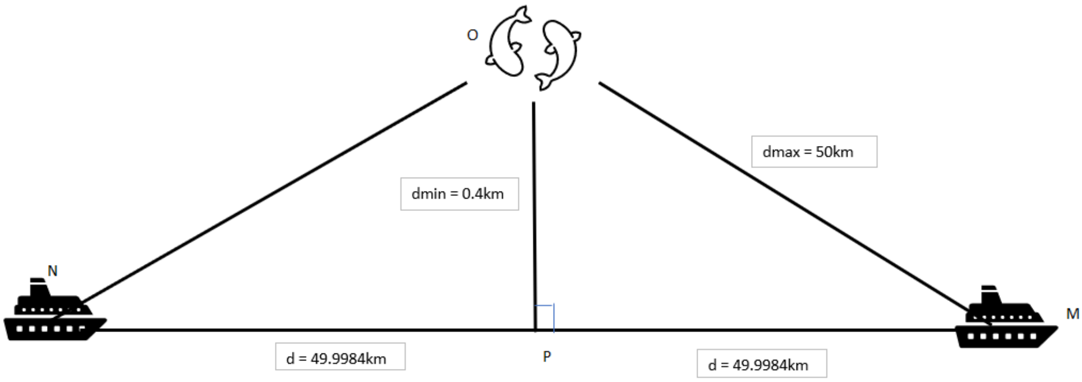


Figure 3.7: Simulation of the vessel transit through an area with a located whale

From this picture, the whale's position was considered to be fixed on the point O while the ship navigates from M to N, or vice versa. The values of d_{min} and d_{max} were already determined by the literature and the value of d was calculated through the Pythagorean theorem.

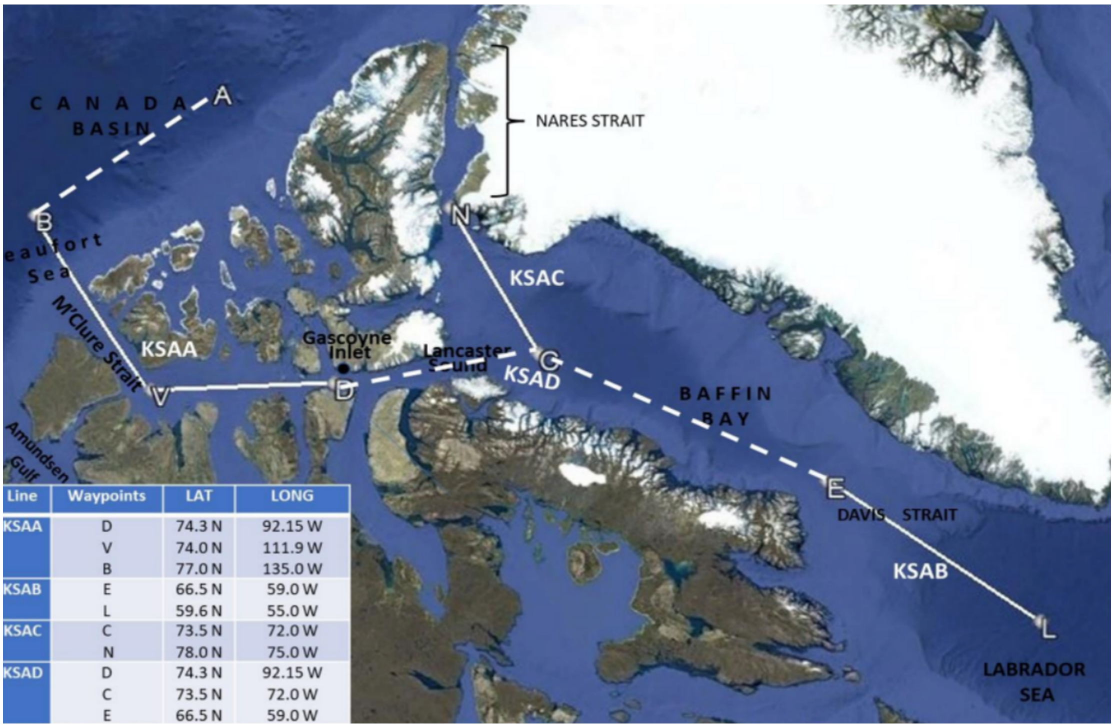
Another variable that is considered for the TL calculation is the frequency of the sound wave emitted at the source. For an analysis of the impacts on the three species of whales, the model was run at 400 Hz and 63Hz respectively for each of the three whale species. The value of 63 Hz was chosen because of the audible thresholds assumed for the Bowhead (Bowhead hearing thresholds are primarily focused in these lower octaves) and communication behaviors are focused on the lower frequency spectrum, specifically from 25 to 200Hz (Richardson et al., 1995). As for the value of 400Hz, all these whale types produce communication and social vocalizations at this frequency (Giesbrecht, 2018).

The model developed by JASCO analyzed the current situation of noise propagation for the year 2020 together with a projection for the year 2040. This modeling investigation of the projected changes to sonar performance in the Canadian Arctic is part of a contract with the Defence Research and Development Canada (DRDC). The results provided information that helped in guiding the development of improved Arctic surveillance (Hines et al., 2020).

The source levels and propagation loss results were analyzed in the following areas according to Figure 3.5:

- Line D–C Lancaster Sound – Baffin Bay: corresponds to AIRSS zone number 13 and presents ice-free conditions in summer.
- Line E–C Davis Strait – Baffin Bay: corresponds to AIRSS zone number 9 and presents ice-free over the entire line in the summer.

The model developed by JASCO also takes into consideration the direction of sound propagation. For this research, in the Lancaster Sound area, the values were employed assuming the ship's position at point D (direction to C), and in the Baffin Bay area, the position for the ship was assumed to be at C (direction to E) (see Figure 3.8).



Line	Waypoints	LAT	LONG
KSAA	D	74.3 N	92.15 W
	V	74.0 N	111.9 W
	B	77.0 N	135.0 W
KSAB	E	66.5 N	59.0 W
	L	59.6 N	55.0 W
KSAC	C	73.5 N	72.0 W
	N	78.0 N	75.0 W
KSAD	D	74.3 N	92.15 W
	C	73.5 N	72.0 W
	E	66.5 N	59.0 W

Figure 3.8: Areas of study from Arctic Acoustic Propagation Projections to 2040 (Hines et al., 2020)

3.3.3 Received Level

The received level was then calculated through the simplified Sonar equation ($RL = SL - TL$). Due to the large amount of AIS unique vessel data, the average value of speed was used for each vessel type during the summer months and within the different areas (zone 9 and 13). With the SL being considered a fixed value for each vessel, as it is dependent on the vessel length and speed and sound frequency, the values of TL varied while the ship transited from point M to N, since the line MO decreases its length, and consequently, the RL values also varied (see Figure 3.8)

The transmission loss values from the JASCO model showed a small variance when fixing the position of the receiver in water column, as a result of the limitation of the representative process here proposed. As an example, Figure 3.9 shows the slight variance throughout the distance range.

3.3.4 Sound Exposure Level (SEL)

Once the RL was calculated through the SONAR equation ($RL = SL - TL$), its values were used to estimate the Sound exposure level (SEL). The SEL is defined as the time integral, over the duration of the exposure, of the instantaneous sound pressure-squared. For the purpose of this model, the RL values were interpreted as the average instantaneous RL for the entirety of the region (distance range), as the attenuation is small due to limitations on the process here proposed. With the transit distance already calculated (D) and the vessel speed taken as the average of each vessel class in that zone

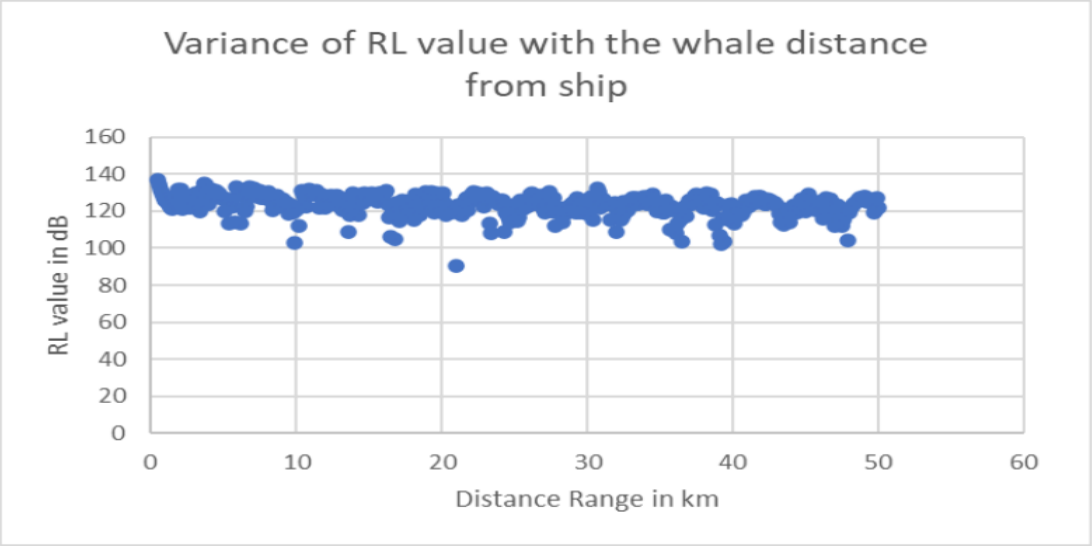


Figure 3.9: Received Level relation to the distance range between the source of sound and receiver (whale), for one vessel of length 142 m transiting from A to D in an average speed of 12.85 knots.

(V), the transit time for each vessel category was then determined (T). Subsequently, as a parameter to calculate the SEL, the time dependent intensity level (TdB) was computed $(TdB = 10\log_{10}(T/1))$ and used on the following calculation $(SEL = RL + TdB)$.

It is important to understand that when $T = 1$, the SEL is treated as an instantaneous $RL(Tdb = 0)$. Thus, taking the RL value as an average is equal to interpreting it as an average instantaneous RL for the entire trajectory.

Nevertheless, in order to make a relation between the sound levels and the number of vessels, the values of sound level exposure (SEL) were added altogether for all the ships of a given type within each area for the years of 2021 and 2040, respectively.

3.4 Nunavut's Population Data Analysis

Population is very closely linked to the economic development of a society. How the population is growing and changing directly affects the type and distribution of transportation demand.

Of all Canadian Arctic activities giving rise to marine transportation demand, community resupply is the most predictable as an operation, which will continue to generate a growing need for northern shipping activities (Hodgson, 2014). However, predicting future re-supply levels depends on many uncertain parameters (as in all forecasting), driven by unpredictability in population growth, the future economic situation and geopolitical scenarios.

Nevertheless, the process of this research proposed a correlation analysis between shipping traffic and population numbers for the Nunavut territory, as shown in Figure 3.10 to correspond with the Baffin Bay and Lancaster Sound Areas.

The population numbers were retrieved from Statistics Canada's census, from 2016

Figure 3.10: Provinces, territories, provincial and territorial capitals in Canada, highlighting the areas of study for this research. Source: Copyright On the World Map (2021)

and 2021. Nunavut's population has grown by 914 people between 2016 and 2021, as noted by Statistics Canada in its 2021 Census Profile for Nunavut. Figure 3.11 shows Nunavut's growth rate over the last 20 years.

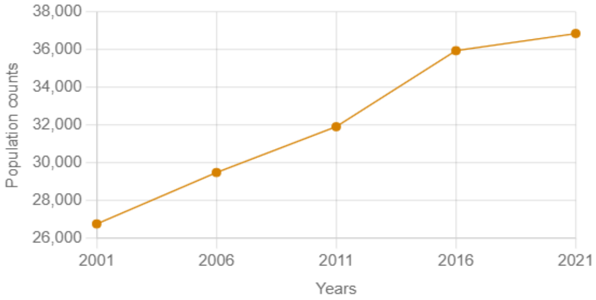


Figure 3.11: Population in the last 20 years in Nunavut

As the population census is only made every five years, for the purpose of this research, an assumption of constant growth of the population throughout the years of 2016 and 2021 was made, so we could relate it to the shipping traffic in the same period.

It is important to understand that the data are showing an upward movement for the entire period illustrated in Figure 3.11.

3.4.1 Population Scenarios Projections

Statistics Canada recently released a study about population projections for Canada, provinces and territories, from 2021 to 2068 (Government of Canada, Statistics Canada, 2022b). These projections are based on assumptions that consider the most recent trends relating to components of population growth, particularly fertility, mortality, immigration, emigration and inter-provincial migration.

Selection of Scenarios

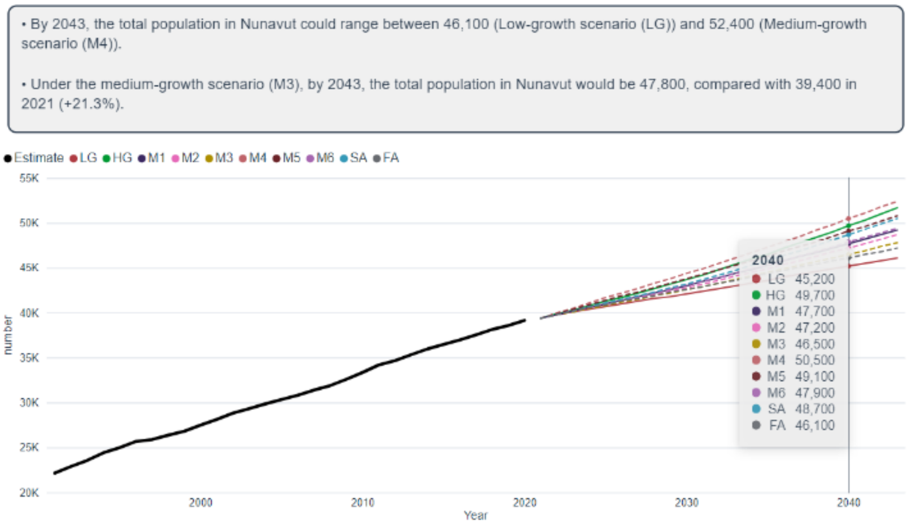
The purpose of having multiple projection scenarios is to reflect the uncertainty associated with the future, and they are built by combining several assumptions regarding the future evolution of each of the components of population growth. In that regard, Statistics Canada developed three different kinds of scenarios related to future population growth: low, medium and high growth scenarios. For the medium growth scenario, six of them were developed based on assumptions reflecting different internal migration patterns observed in the past. Each scenario puts forward a separate assumption to reflect the volatility of this component. For this research, only one medium scenario was chosen.

Statistics Canada's low-growth (LG) and high-growth (HG) scenarios bring together assumptions that are consistent with either lower or higher population growth than in the medium-growth scenarios at the Canadian level. For example, assumptions that entail high fertility, low mortality, high immigration, low emigration and high numbers of non-permanent residents are the foundation of the high-growth scenario (Government of Canada, Statistics Canada, 2022b). An example of the medium scenario analyzed in this project is shown in Figure 3.12.

The projections for the provinces and territories include an additional component compared to the projections for Canada as a whole: inter-provincial migration. According to the projection scenarios, provinces and territories would experience an increase in population between 2021 and 2043, which falls exactly into our period for the research.

Due to limited time, this project only analyzed one medium-growth (M3) scenario together with the low and high-growth ones. According to M3, international migration would be the main driver of population growth in Canada, along with other factors: the immigration rate reaches 0.83% in 2042/2043 and remains constant thereafter; the annual number of non-permanent residents reaches 1,795,800 in 2043 and remains constant thereafter; the net emigration rate reaches 0.15% in 2042/2043 and remains constant thereafter (Government of Canada, Statistics Canada, 2022b).

As cited in section 3.4, an assumption of constant growth of the population between the years 2016 to 2021 was made, so we could relate it to the shipping traffic in the same period for which we had AIS data available. This way, a regression analysis was performed using the Data Analytics Tool from Microsoft Excel, in order to find a correlation between ship traffic and population data and the R-squared value and p-value were



- By 2043, the total population in Nunavut could range between 46,100 (Low-growth scenario (LG)) and 52,400 (Medium-growth scenario (M4)).

- Under the medium-growth scenario (M3), by 2043, the total population in Nunavut would be 47,800, compared with 39,400 in 2021 (+21.3%).

Figure 3.12: Growth of the Canadian population according to medium-growth scenario M3. Under the medium-growth scenario (M3), by 2040, the total population in Nunavut would be 46,500, compared to 36,858 in 2021 (Government of Canada, Statistics Canada, 2022b)

retrieved. Later, the two series of data were plotted and the linear trend line equation was calculated, being the best-fit straight line that is used with simple linear data sets. A trend line is most reliable when its R-squared value is at or near 1, which is confirmed in section 4.

In the equations, ship entries (into a zone) are displayed as the dependent variable Y and the population numbers as the independent variables. Cruise ships did not show any kind of statistical relation with population growth, and were, thus not considered for this part of the methodology.

Afterwards, the values projected by Statistics Canada regarding the population growth scenario were used as parameters for the creation of random numbers (10,000 samples) using a triangular probability distribution: the low (45,200), medium (46,500) and high (49,700) growth value were used as a minimum, most likely, and maximum values, respectively (Figure 3.13). From these random values used here as the independent variables, the number of possible ship entries was calculated using the regression equation and displayed in a probability distribution function (PDF). Results are further shown in section 4.

3.5 Gross Domestic Product (GDP)

As stated by Hodgson 2014, there is a close correlation between shipping activity, merchandise trade and gross domestic product (GDP), stated here as the health of the economy as well.

Being an industry operated on a derived demand basis, this project also analyzed whether there was any correlation between the number of entries by each vessel type and the expenditure-based gross domestic product of the province of Nunavut (i.e., final,

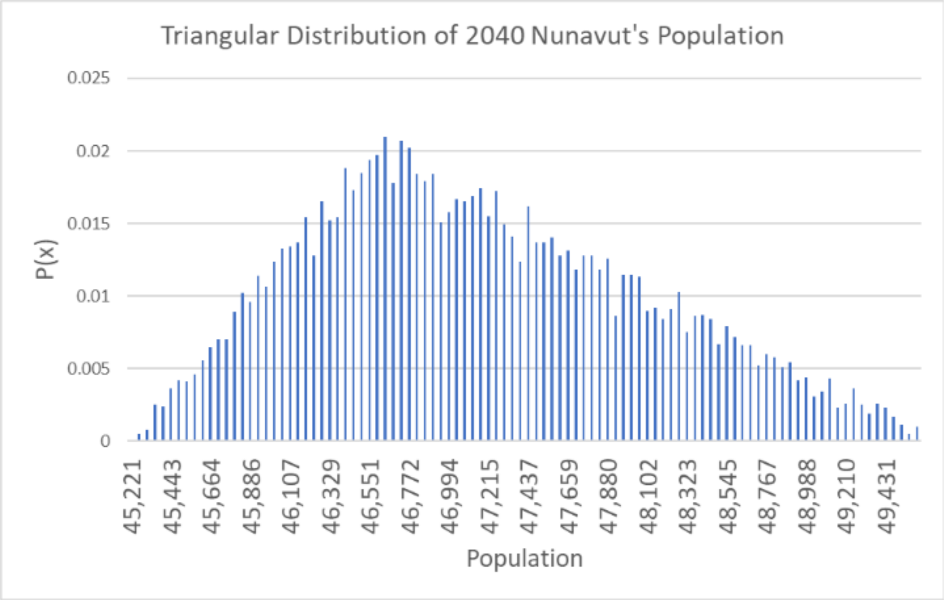


Figure 3.13: Using the minimum, most likely and maximum values of Statistics Canada's population projection, 10,000 random values were generated using a triangular distribution calculation and displayed in a histogram chart. As observed, most likely values, according to scenario M3 are in the range of 46,100 to 47,400 people.

purchases of the goods and services produced in a given period). Figure 3.14 shows the evolution of the numbers from the year of 2000 until 2021.

Although the GDP trend observed in Figure 3.14 has a low rate of increase, it is apparent that during the given period, there is a growth on the final consumption expenditure. In such a manner, the same regression analysis methodology as the one used with population numbers was done for cargo and tanker vessels using GDP data as the independent variable, in each zone, in order to examine the relationship between these two variables. An assumption of constant growth of the GDP in between the years of 2016 and 2021 was made, so we could relate it to the shipping traffic in the same period for which we had AIS data available, a regression analysis was performed in order to find a correlation between ship traffic and GDP data and the R-value and p-value were retrieved. Subsequently, the two series of data were plotted and the linear trend line equation was calculated: ship entries are displayed as the dependent variable Y and the GDP data, as the independent variables.

Again, cruise ship traffic levels did not show any kind of statistical relation with GDP data, and, thus, not considered either.

3.5.1 Economic Projections

In 2019, the Conference Board of Canada released a report highlighting the key drivers of the economy of Nunavut, Northwest Territories and Yukon, as well as building forecasts on key economic indicators until 2040 (Bernard et al., 2019). The GDP value at basic prices (values do not include taxes and subsidies on products) for the year of 2040 was collected, yielding 3,787 in millions as the most likely value and maximum and minimum

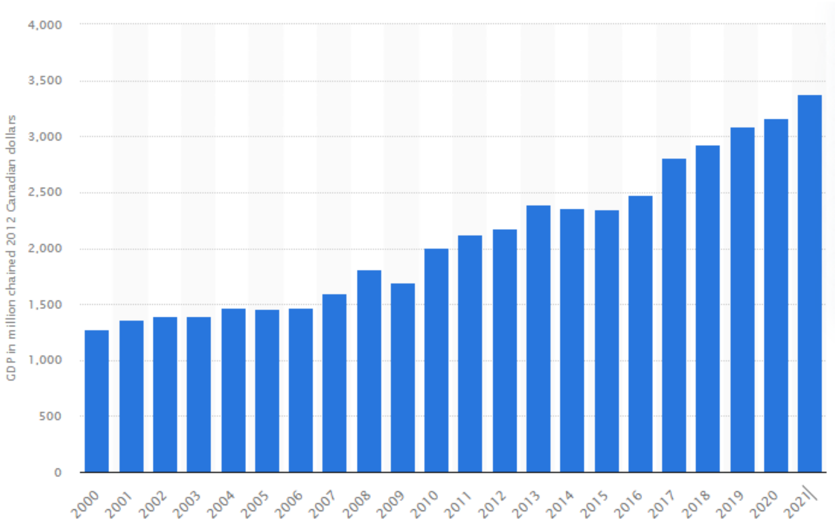


Figure 3.14: Gross domestic product of Nunavut, Canada from 2000 to 2021 (Government of Canada, Statistics Canada, 2022)

of 4,048 and 3,357, respectively (Canadian Dollars). The last two values are the upper and lower limit of the forecast interval (20 years) modeled by the Conference Board of Canada. In this manner, a triangular distribution (with 10,000 samples) of possible values was calculated and displayed in a PDF, shown in Figure 3.15.

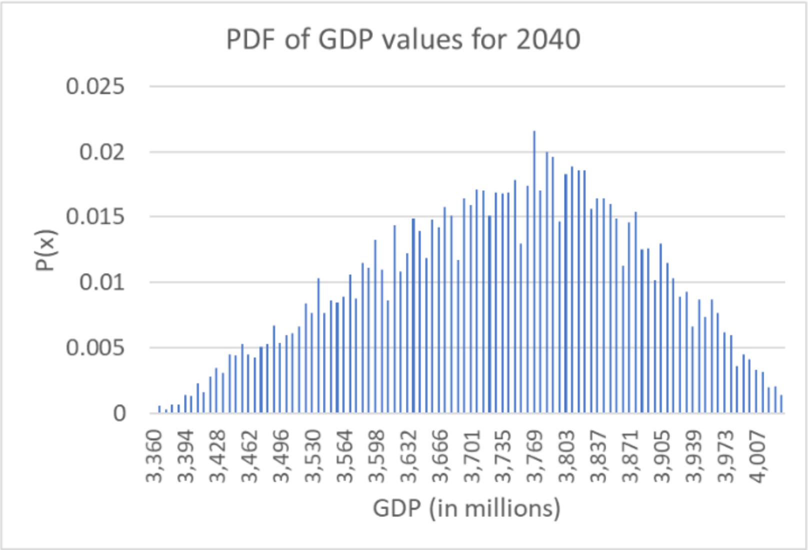


Figure 3.15: Probability Distribution Function of GDP values based on projections made by The Conference Board of Canada for the year of 2040. Most likely values for future GDP lie between 3,701 and 3,837 millions (Canadian Dollars)

From these random values used here as the independent variables, the number of possible ship entries was calculated using the regression equation and displayed in a probability distribution function (PDF). Results are further shown in section 4.

3.6 Expert Opinion

Expert opinion was used in this research as an instrument to create possible scenarios related to future shipping traffic levels, specified ship characteristics, and, consequently, underwater noise levels. Interviews were conducted through Microsoft Teams, with a duration of approximately one hour each.

For this method, we interviewed four underwater noise expert, two ship technology experts, three maritime transportation experts from Transport Canada, three experts from bulk cargo companies, one whale behavior expert, and three experts from cruise expedition companies. The specialists were asked about their opinion on how they think the future maritime traffic would evolve, the most important drivers affecting their activities, how new technologies are most likely to be implemented, and how they would affect the underwater noise problem.

Subsequently, reasonable assumptions regarding a percentage of increase or decrease of shipping traffic levels were made, as well as the percentage of the future fleet to apply new technology mitigation measures. Some interviewees were able to give some numerical estimates on the parameters under discussion, which was used as the most likely value within a triangular distribution. Then, values of the underwater noise generated by the vessels, along with the exposure levels for whales to the sound, were also calculated using a Monte Carlo simulation, as the inputs here given by experts were treated as probability distribution functions. Here, for future values, the same assumptions as before (i.e. current values) were used: whales are found in a fixed depth of 50m and the distance range navigated by a ship is the same as Figure 3.7.

Summary of assumptions

The assumptions considered for this project are herein summarized in Tables 3.3 to 3.6 and further developed in the Results sections:

Ships' navigation characteristics
Average speed considered for each kind of vessel (cargo, tanker and cruise) in each zone
Constant speed considered in the navigation line M-N (Figure 3.7)
Cargo and tanker analyzed as a group (similar length and speed)
Speed and length will not differ from today's fleet

Table 3.3: Ships' navigation characteristics.

Noise calculation
TL values retrieved from modelling investigation made by JASCO (Hines et al., 2020)
RL values for each vessel assumed to be the average RL values for the entire navigation trajectory M-N (Figure 3.7)
Noise calculated only for two frequencies (63 Hz and 400 Hz)
SEL calculated in order to consider the time exposure level of the whales to the noise
Constant values used for the time dependent intensity level (TdB) as speed values were considered constant for each vessel type

Table 3.4: Noise calculation assumptions.

Technology improvements
Values for dB reduction based on expert opinion, using the VARD (2019) report for the parameters
Reduction values distributed in a PDF based on maximum, minimum and most likely values
Reduction of noise subtracted from the source level of each vessel
Considered technologies to be used in the Arctic's climate conditions only
One technology improvement considered for each vessel type group: propeller cap turbines and diesel electric machinery

Table 3.5: Technology improvement assumptions.

Population and GDP data
Constant and linear growth between census years (every five years) was considered for the regression analysis
Assumed a relationship between each of these two parameters and cargo/tanker traffic as a whole
Linear relationship between these parameters and shipping activity
Extrapolation into the future assumed a continued relationship between these parameters and shipping traffic data

Table 3.6: Population and GDP data assumptions.

4 Results

4.1 Population Data Regression Analysis

As stated in the Methodology Section, Statistics Canada developed projections for low, medium and high growth scenarios for the population of Nunavut in the year 2040 (45.2, 46.5 and 49.7 in thousands, respectively). These three values were used as inputs for a triangular distribution (Figure 3.13), from which 10,000 values were generated and used to calculate the number of ship entries following the regression equation of each zone and ship type. Cruise ships did not show any kind of statistical relation with population growth, and were, thus, not considered for this part of the methodology (see Figure 4.1).

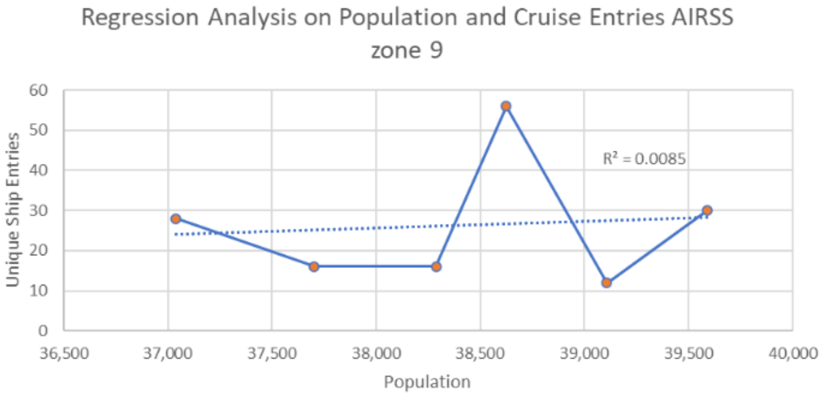
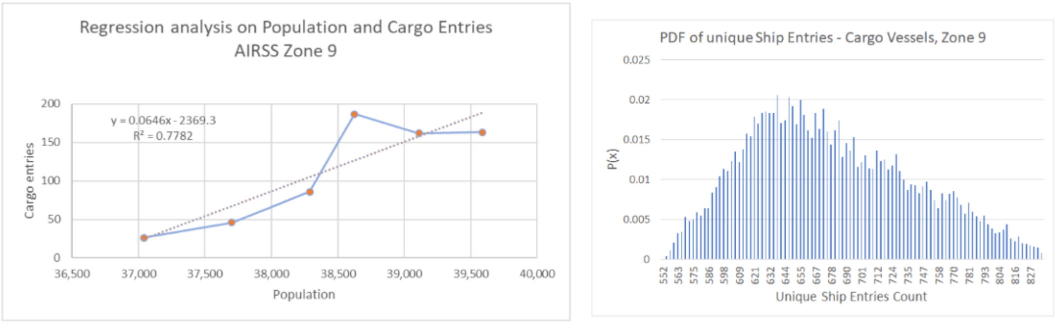


Figure 4.1: Regression analysis between population data and Cruise vessel unique entries. We can observe a value of 0.0085 for the R-squared, indicating that the cruise ship count does not generally follow the movements of population growth.

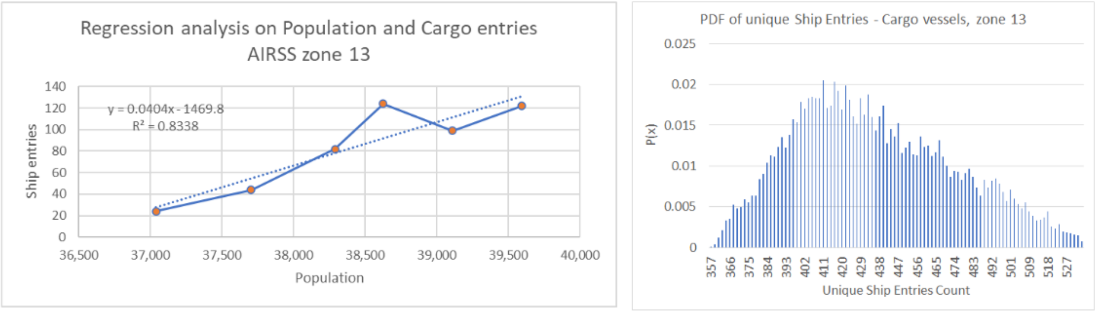
The results for each zone and vessel type are displayed in Figures 4.2 to Figure 4.5, demonstrating how this key driver, herein analyzed alone, could suggest a relationship with ship traffic.



(a)

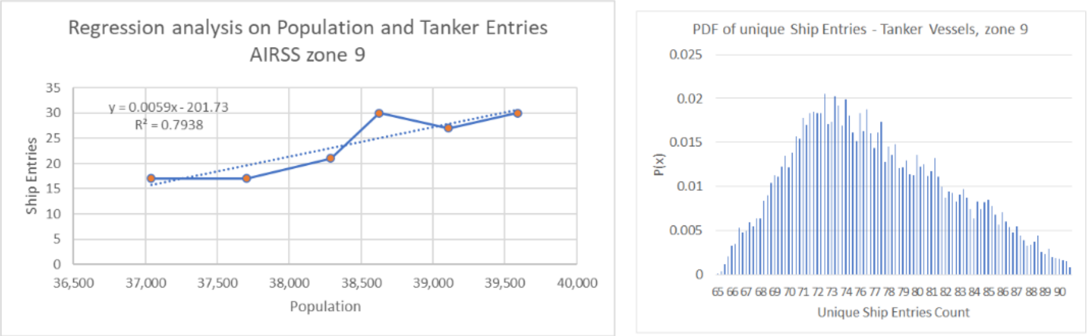
(b)

Figure 4.2: **(a)** Regression analysis on population and unique cargo ship entries in zone 9. **(b)** PDF of ship entries in zone 9 for cargo vessels, in relation to population numbers.



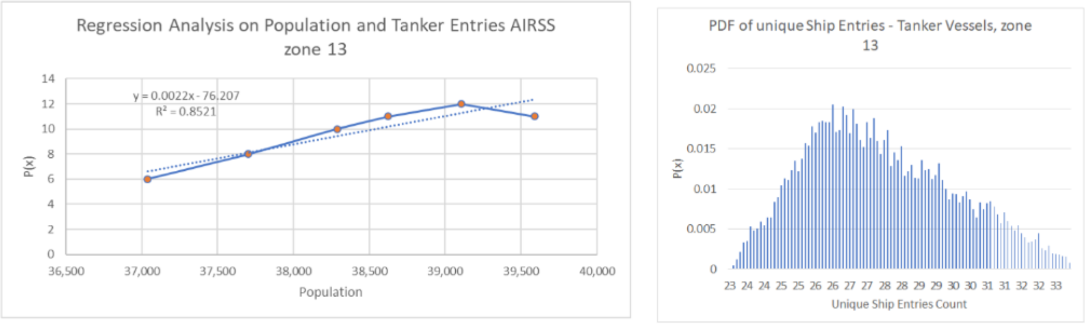
(a) (b)

Figure 4.3: **(a)** Regression analysis on population and unique cargo ship entries in zone 13. **(b)** PDF of ship entries in zone 13 for cargo vessels, in relation to population numbers.



(a) (b)

Figure 4.4: **(a)** Regression analysis on population and unique tanker ship entries in zone 9. **(b)** PDF of ship entries in zone 9 for tanker vessels, in relation to population numbers.



(a) (b)

Figure 4.5: **(a)** Regression analysis on population and unique tanker ship entries in zone 13. **(b)** PDF of ship entries in zone 13 for tanker vessels, in relation to population numbers.

From all the charts we observe a high level of correlation between ship traffic volume and population growth (R^2 value), which allowed us to apply the trend line equations to obtain possible future values for ship quantity. Also, we could observe that:

- Cargo - zone 9: highest probabilities of occurrence lie around 630 to 700 entries, while the current number for 2021, according to AIS data extraction, is 163;

- Cargo - zone 13: highest probabilities of occurrence lie around 420 and 450 entries, while the current number for 2021, according to AIS data extraction, is 122;
- Tanker - zone 9: highest probabilities of occurrence lie around 73 to 76 entries, while the current number for 2021, according to AIS data extraction, is 30;
- Tanker - zone 13: highest probabilities of occurrence lie around 27 to 28 entries, while the current number for 2021, according to AIS data extraction, is 11;

Tables 4.1 and 4.2 shows the summary of the regression analysis parameter for each zone and ship type.

Zone 9	Cargo	Tanker	Cruise
R-squared value	0.793	0.793	0.0085
p-value	0.0173	0.0171	0.86

Table 4.1: Statistics summary for regression analysis on zone 9.

Zone 13	Cargo	Tanker
R-squared value	0.83	0.85
p-value	0.01	0.008

Table 4.2: Statistics summary for regression analysis on zone 13.

4.2 GDP data Regression analysis

When developing a regression analysis to understand the relationship between the gross domestic product (GDP) of the territory of Nunavut and the number of ships entering areas 9 and 13, a positive relationship could be observed for tanker and cargo vessels versus GDP respectively, in both areas. However, cruise ship statistics did not show the same result. From Figure 4.6, we can observe a value of 0.0216 for the R-squared, indicating that the cruise ship count does not generally follow the movements of population growth.

As a tourism activity, it is reasonable to think that relating the GDP of the territory of the destination of cruise ship traffic is not a direct driver of such activity.

As stated before, a significant value for the R-squared is generally above 0.7, however, this is not a hard rule and will depend on the specific analysis. Nonetheless, for this project, it was the only parameter taken into consideration to relate GDP with shipping traffic as GDP is only a rough indicator of society's standard of living.

Considering the GDP as a relevant factor for northern shipping traffic volume, the same procedure as the population data analysis was applied to demonstrate how this key driver, herein analyzed alone, could suggest a relationship with ship traffic. For the GDP case, we used the economic projections from the Conference Board of Canada. A triangular distribution of the independent value of the regression equation (GDP in

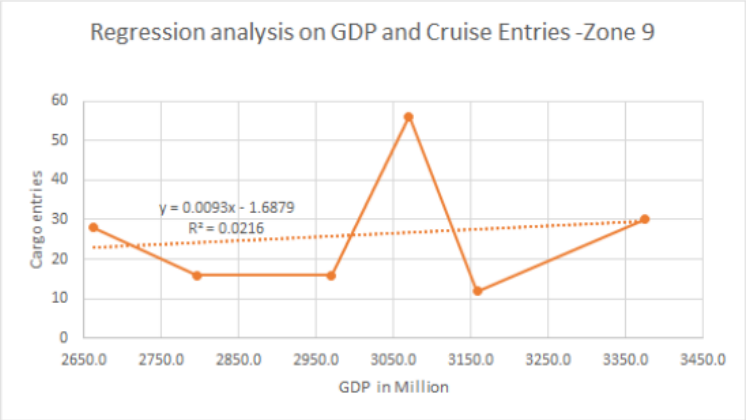
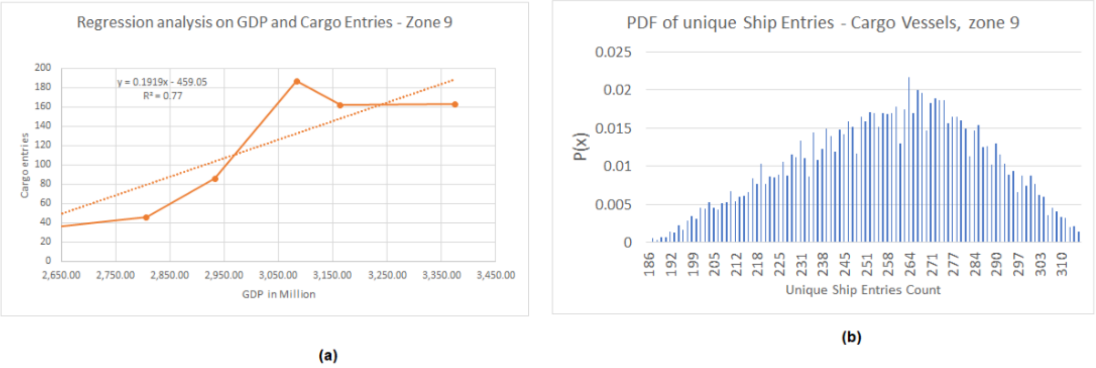


Figure 4.6: Regression analysis between GDP data and Cruise vessel unique entries. We can observe a value of 0.0216 for the R-squared, indicating that the cruise ship count does not generally follow the movements of population growth.

millions of dollars) was developed based on the three values mentioned before: 3,787 for the most likely, 4,048 for the maximum and 3,357 for the minimum value. Once again, a sample of 10,000 values was generated and for each one of them, the regression equation was applied in order to obtain the value for the count of ship entries. Then, a PDF was generated for the most likely values of ship traffic in 2040. From Figure 4.7 to Figure 4.10 we observe the regression analysis between the two datasets and the trend line equation and the correspondent R-value in part (a) of each figure, and the PDF with the values of the Y variable (unique ship entries) when applying the sample of the GDP distribution to the equation shown in part (b) of each figure.



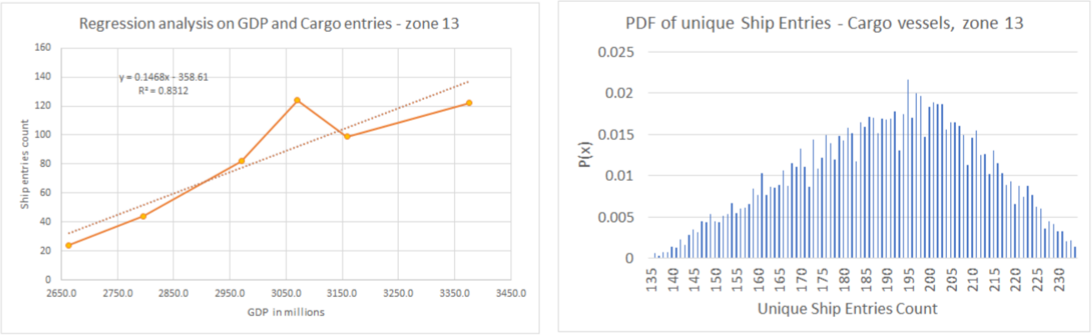
(a)

(b)

Figure 4.7: **(a)** Regression analysis on GDP and unique cargo ship entries in zone 9. **(b)** PDF of ship entries in zone 9 for cargo vessels, in relation to GDP numbers.

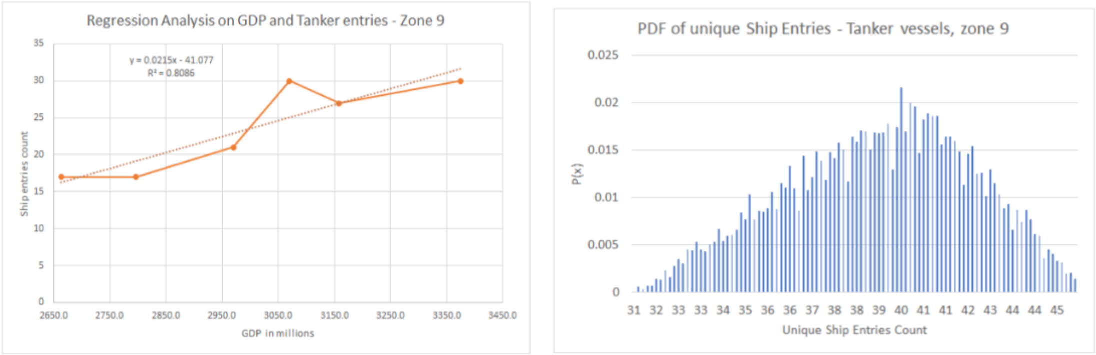
4.3 Experts Insights

Interviews were conducted with experts from different areas of the shipping traffic industry (bulk cargo companies), namely Transport Canada, naval engineers and noise expert scientists. During our discussions, we asked our interviewees about the main drivers influencing maritime activities, how they think the future of northern shipping



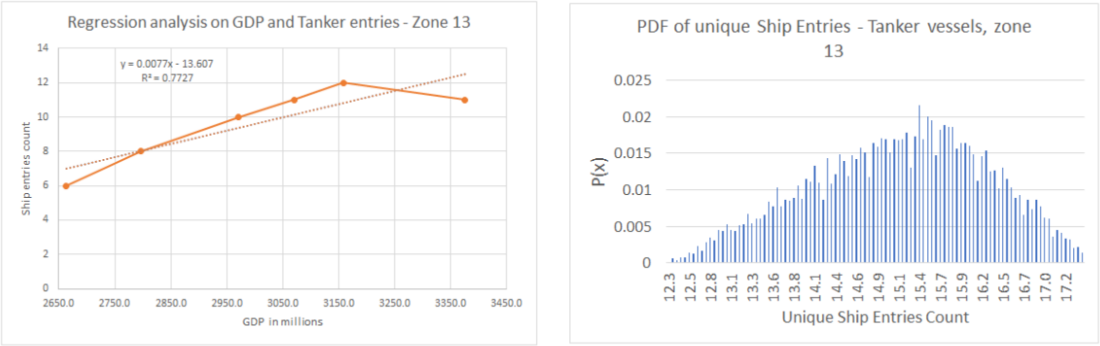
(a) **(b)**

Figure 4.8: **(a)** Regression analysis on GDP and unique cargo ship entries in zone 13. **(b)** PDF of ship entries in zone 13 for cargo vessels, in relation to GDP numbers.



(a) **(b)**

Figure 4.9: **(a)** Regression analysis on GDP and unique tanker ship entries in zone 9. **(b)** PDF of ship entries in zone 9 for tanker vessels, in relation to GDP numbers.



(a) **(b)**

Figure 4.10: **(a)** Regression analysis on GDP and unique tanker ship entries in zone 13. **(b)** PDF of ship entries in zone 13 for tanker vessels, in relation to GDP numbers. For this case in specific, as ship entries' integer numbers did not significantly vary throughout the distribution, one decimal place was left for distinction.

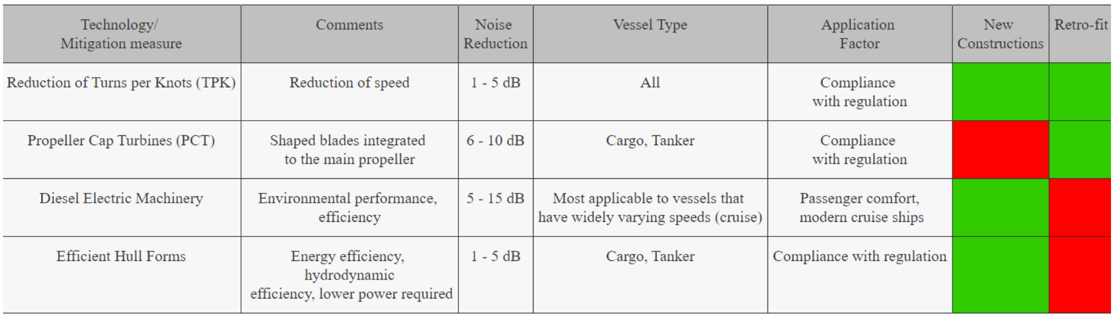
would evolve, and how are companies are adapting to new ship technologies and regulations imposed by for environmental reasons. This section is, then, divided into each topic and a summary of how the future was analyzed is stated at the end.

4.3.1 Technology Changes in the Ship-Building Industry

There is considerable scope to make new ships quieter than existing ships in the fleet (Williams et al., 2019). Improved propellers (e.g., Contracted Loaded Tip or CLT propellers) can be incorporated into the design or added as a retrofit without requiring modifications to the hull. Even so, given the complexity of ship design and their construction, it is important to assess the probability of some technological changes that may be implemented in the future by ship owners.

Hence, taking the VARD report (2019) for the parameters (which introduces a review of means of mitigating underwater noise from ships), eight technology improvements were examined based on their technology readiness level (TRL) and the cost-benefit parameter. Four technology improvements were ultimately selected and inspected during the interview with ship technology experts. They were asked about their opinion on how likely these features were to be implemented and what would the noise reduction be.

Figure 4.11 summarizes an overview of noise-related ship technologies that would have the greatest chance of application in the next 10 years, according to experts. Even though four improvements are herein cited, only two technologies were assessed (one for cargo and tanker vessels and one for cruise vessels), due to limited time.



Technology/ Mitigation measure	Comments	Noise Reduction	Vessel Type	Application Factor	New Constructions	Retro-fit
Reduction of Turns per Knots (TPK)	Reduction of speed	1 - 5 dB	All	Compliance with regulation	🟩	🟩
Propeller Cap Turbines (PCT)	Shaped blades integrated to the main propeller	6 - 10 dB	Cargo, Tanker	Compliance with regulation	🟥	🟩
Diesel Electric Machinery	Environmental performance, efficiency	5 - 15 dB	Most applicable to vessels that have widely varying speeds (cruise)	Passenger comfort, modern cruise ships	🟩	🟥
Efficient Hull Forms	Energy efficiency, hydrodynamic efficiency, lower power required	1 - 5 dB	Cargo, Tanker	Compliance with regulation	🟩	🟥

Figure 4.11: Shipping design technologies (noise-related) that are most likely to be implemented in the future. Red cells mean that the technology does not apply to that category. (Vard Marine Inc. et al., 2019)

Reduction of Turns per Knot (TPK)

Reducing the number of propeller turns per knot reduces the speed of the flow at the tips of the blades and, consequently, the speed and power of the vessel altogether. For the Arctic situation, in areas of higher ice coverage, even if the ship is classified as the right class for that area (section 2.2.1 - AIRSS zones), it may still need ice breaker vessel escort, increasing the intensity of underwater noise emitted, since, compared to other vessels, icebreakers generate higher and more variable noise levels from propeller cavitation due to the episodic nature of breaking ice, which often involves maneuvers such as backing-and-ramming into the ice (Roth et al., 2013).

However, assuming a summer season free of ice, as stated by JASCO's report on acoustic forecasting (Hines et al., 2020), and that, according to specialists, given that there is a regulated trend of decrease of ship speed in designated habitat areas, we analyze this technological mitigation process for all kinds of vessels, estimating the noise reduction to be calculated through a triangular distribution, estimating values to be between 1 and 5 dB with a most likely value of 3 dB. Due to limited time, this technology improvement was not modelled in the Monte Carlo Simulations, however an analysis on speed reduction was done for the Baffinland area, shown in section 4.3.3.

Propeller Cap Turbines (PCT)

Aside from a good cost-benefit ratio, the propeller cap turbine is easily designed for retrofit and the relatively low cost can be recovered quickly. With the application of shaped blades, energy savings are achieved over a wide operating range of ship speed and draft/trim conditions. For this approach, noise reduction was calculated through a triangular distribution, estimating values to be between 6 and 10dB, with a most likely value of 7dB. According to specialists, the application is limited to cargo and tanker vessels only.

Diesel-Electric Machinery

Almost all new ships feature a diesel-electric propulsion mechanism. As a very efficient system, they allow the main engines to operate near the most efficient speed, regardless of the vessel speed. With this application, electricity is carried from generators to switchboards, through passageways, public rooms, crew and passenger cabins, relating more significantly to cruise ships as well as producing a great benefit for those. Thus, for this technology application, only cruise vessel sound levels were taken into consideration. Furthermore, according to specialists, it is not likely for bigger bulk cargo vessels to implement this technology. The most likely value for reduction, as estimated by specialists, was 10 dB, with a high of 15 and a low of 5 dB.

Efficient Hull Forms

According to specialists, this improvement has been taken seriously by shipbuilding companies as they manage to keep pace with regulations imposed by international marine bodies. Recently, better hull forms have been observed in an increasing number of cargo and tanker vessels. With a focus on the hydrodynamics of the vessel, an efficient hull form allows for a better utilization of the engine's energy and thus, less power is required for transiting. A most likely value for sound reduction, according to specialists, was considered as 2 dB for this approach, with a low value of 1 dB and a high value of 5dB. Due to limited time this technology improvement was not modelled in the Monte Carlo Simulations.

4.3.2 Cruise Ship Activity

We interviewed the consulting director from Quark Expeditions, a cruise company pioneering new types of expeditions into the Polar Regions for over 30 years now and two specialists from AECO, an international association for expedition cruise operators operating in the Arctic and others with interest in this industry.

During the interview, Quark confirmed that it is reasonable to think that there will be significant changes in the cruise shipping traffic system twenty years from now. They affirmed that people should recognize that cruise growth can be a positive economic factor if done right, respecting the environment, and most of all, the local communities. Warmer northern waters, as a consequence of climate change, will be easier to navigate, as cruise ships, especially expedition cruise vessels, present a higher flexibility when it comes to exploring new routes.

From AECO, the specialists stated that there will be an increase in the traffic in the Canadian north over the coming years, however, it is very complex to predict it. A decrease is not expected, as new restrictions and regulations are put in place for the European part of the Arctic which might drive additional tourist traffic to the Canadian Arctic.

According to them, the main driver in the last few decades for an increase in cruise ship traffic was people's curiosity to see landscapes they never saw before and enjoy a comfortable trip. This driver might still apply in the future, along with the safety criteria offered by new cruise vessels: all cruise ships must be equipped with safety gear and tracking equipment, cruise crews go through a rigorous training in every aspect of passenger safety, and passengers have now even their health monitored.

The ice-melting process has indeed facilitated the trips of cruises to the Arctic. Nonetheless, there are many parameters affecting/limiting cruise shipping in the north and some of the key elements are related to regulations imposed by the federal or provincial government, the increasing concern of how this economic activity might affect local communities: permits are required everywhere a ship might navigate or dock and the impact on residents, particularly Indigenous Peoples, can be harmful – housing shortages, inflated property values, infringement on property and food resources, and more.

Fuel prices are another driver of great uncertainty, especially because of global geopolitical tensions. However, cruise trips have always been expensive, so not accessible to all the population, and increased costs due to fuel may not deter many potential passengers.

The focus of new technologies for cruise ships has been on GHG emissions and improved wastewater treatment. Ship-quieting technologies still present a big trade-off between energy efficiency and noise generated and are not planned to be ready for at least 10 years from now.

The interviewees' best estimates are that regulations will still continue to limit their cruise activities in the Canadian north, yet a gradual increase is expected in the next years, maybe doubling the fleet quantity by 2040.

4.3.3 Cargo and Tanker Shipping Activity

We interviewed a conservation scientist with a research focus on the Arctic underwater acoustic environment, and even though he does not work within any maritime shipping industry, he was able to give significant insights on how traffic might evolve in the next decades.

According to him, considering bio-acoustic concepts, a smaller interval between ship transits leads to fewer behavior disturbances among the whales. A longer duration of a single disturbance event is biologically less harmful than multiple shorter disturbances throughout the day. He also stated that behavioral disturbance of whales might be just as consequential as hearing damage.

This is the reason why some companies are approaching areas of high biodiversity and some marine protected areas (MPA) using ship convoys. Grouping the ships into convoys dramatically changes the temporal distribution of ship noise over the day and night and increases quiet periods. Finally, he discussed the main drivers for the future of shipping traffic. According to him, in the last few decades, the biggest jumps seen in maritime traffic in the Canadian north came from the discovery of new mines, contributing to the great economic development of the region.

Another specialist interviewed by us was an employee from FEDNAV, Canada's largest bulk shipping company. During our discussion, we focused on understanding how the traffic might evolve in the next decades, taking into consideration drivers that were already analyzed here (and found to have a statistical relationship with vessel traffic) and others that influenced significantly their activity, historical events from their own company and the interviewee's expertise on the subject.

AIRSS zone 13 was the main point of discussion on the interview with FEDNAV, considering that it leads to one of the richest iron ore deposits in the world: Baffinland mine. With a current permit for 4.2 million MTPY (metric tons per year), Baffinland is looking to increase its exports to 12 million MTPY and has expressed interest in further increasing exports to 30 MTPY by 2030, as a long-term goal.

Consequently, it was confirmed that it is reasonable to think that there will be significant changes in the traffic system (volume) 20 years from now as, in order to export additional products, Baffinland will need to increase the size and number of vessels servicing the mine as well as extend the shipping season beyond open water season (WWF Arctic, 2016).

According to the interviewee, these are the main factors that may affect their fleet traffic up in the Arctic:

1. new mines might be discovered; however, it is not very likely to happen within two decades and an increase would not be significant;

2. regulations regarding permission to transport a higher volume of goods might be authorized by Canada's government;

3. unpredictability of the Arctic operating conditions.

Regarding point 2, Baffinland mines already find itself on the second phase of negotiation with the Government of Canada and the Nunavut Impact Review Board (NIRB) for permission to transport up to 12 MT from the recent volume of 4.2 million MT (which has not yet been attained) and according to their opinion, if this keeps happening, it will potentially double the number of ship entries in the area for the next five years and probably reach three times the current level in 2040.

Noise pollution from ships is amplified by some environmental factors such as the bathymetry of the ocean, the type of sediment, the sound speed profile of the region and sea surface features (Farcas et al., 2016). Also, shallow cold waters have been shown by Farcas et al. 2016 to propagate sound much further, impacting marine life on a larger scale. Therefore, this suggests that similar results may occur in Milne Inlet (Cucinelli, 2020), shown in figure 4.13. Furthermore, this area of interest coincides with the proposed NMCA Tallurutiup Imanga, an area of high importance for conservation due to its high ecological and cultural value, being internationally recognized as one of the most significant ecological areas in the world (Cucinelli, 2020).

Among Baffinland's measures to reduce anthropogenic noise, a voluntary speed reduction took place in 2021, in which vessels transiting within the Eclipse Sound are restricted to a maximum speed of 9 knots compared to their previous 14 knots requirement (the critical ship speed threshold above which strikes on marine mammals have a higher potential to occur, especially with bowhead whales as they spend a considerable more amount of time at the surface feeding) (Baffinland, 2019). For many ships, a 1kt reduction in speed leads to a 1dB reduction in broadband source level (Veirs et al., 2016). JASCO Applied Sciences conducted studies in which they mapped the underwater noise pollution in Eclipse Sound and a comparison was made between vessels traveling at 14 knots versus 9 knots. The result shows a significant decrease (Figure 4.12).

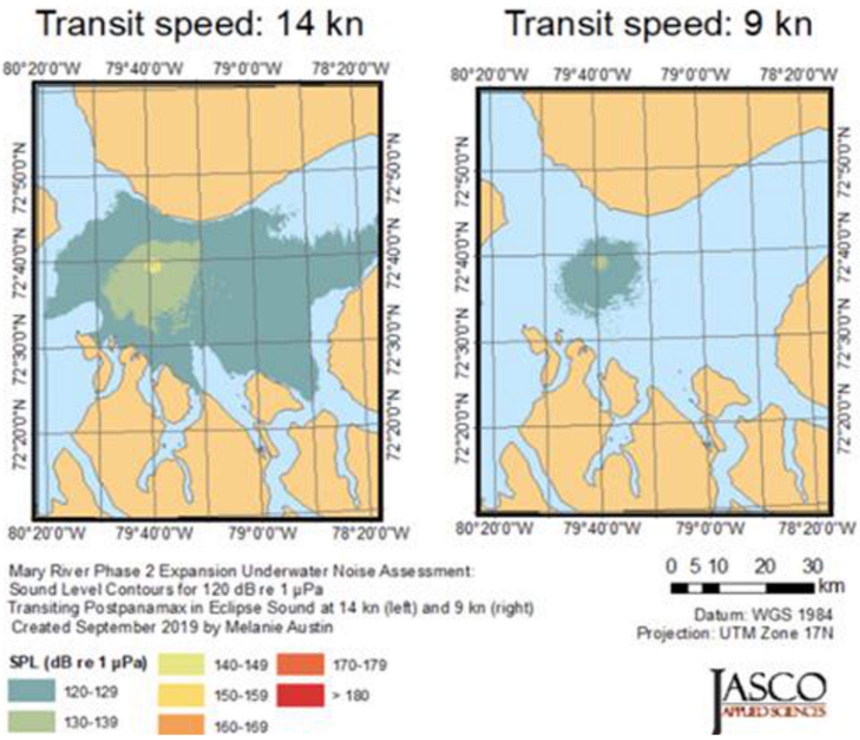


Figure 4.12: Underwater noise assessment in the Eclipse sound regarding transit speed at 14 and 9 knots. Source: adapted from (Zykov et al., 2010)

As a special case of this research, a separate analysis was done regarding Baffinland. The Baffinland shipping route runs from the port in Milne Inlet (Bruce Head/Koluktoo Bay region) through Eclipse Sound, Pond Inlet, and out to Baffin Bay (Figure 4.13). The route from Milne Inlet to Baffin Bay ranges in depth from 5m to 1300m. From the AIS data extracted by MEOPAR for this research, it is possible to observe the navigational path taken by the vessels (Figure 4.14) and that approximately 70% of the vessels that entered zone 13 went through the strait towards Baffinland.

Figure 4.13: Baffinland shipping route through Eclipse Sound until Milne Inlet.

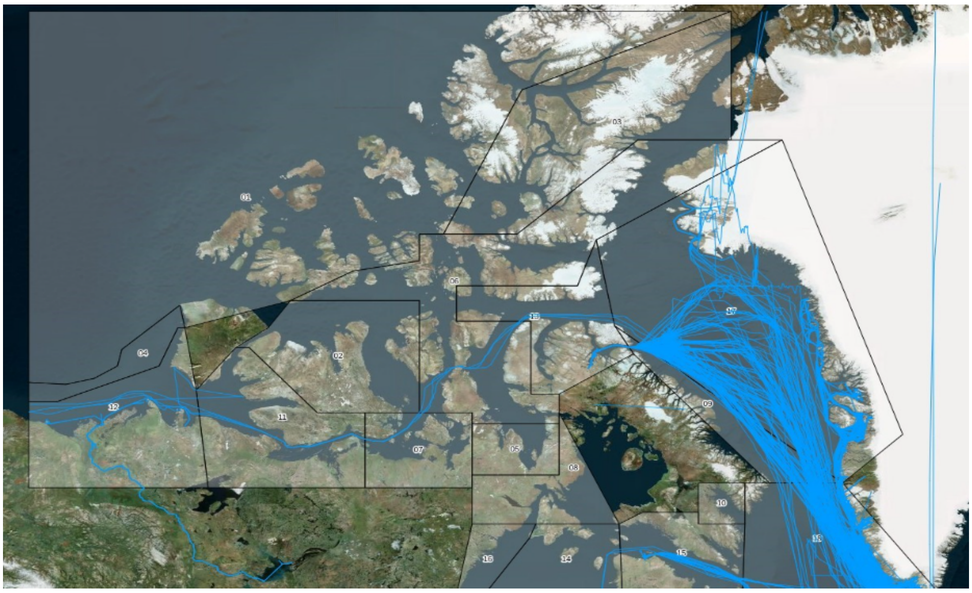


Figure 4.14: Cargo traffic density for the month of September in 2021 (AIS data). The numbers shown in each zone refer to the AIRSS zone, explained in section 2.2.1, with a focus on zone 13, related to the same region as Baffinland. The density map shows the distribution of cargo vessels based on the instantaneous number of vessels per unit area, such as a square kilometre or a square degree, for example.

Hence, a calculation on exposure levels in the Baffinland area of interest was done, along with comparisons between present and future possible values according to FEDNAV's expert opinion, emphasizing the impacts on underwater noise values when vessels slow down to 9 knots. For this study, it is supposed that:

- the total quantity of ships transiting through zone 13 would triple by 2040;
- 70% of the vessels entering zone 13 would still go to Baffinland mine;
- their speed in the area is 9 knots;
- the length of the new ships would not differ from the current fleet;
- for simplification purposes, a possible receptor (whale) is also at a fixed depth in the water column (50m) and the distance range is the same as calculations shown in section 3.4.2.

According to JASCO's report on projections of acoustic propagation in 2040, an ice-free period of several months in Baffin Bay allows for warming of the surface layer by 2 to 4°C in summer and, consequently a change in the sound speed profile (Figure 4.15), modifying also the values of the TL in the area. However, analyzing the transmission loss data, the changes in the TL were insignificant for our purposes. The interview with a sound expert also confirmed that the transmission loss values would not change much.

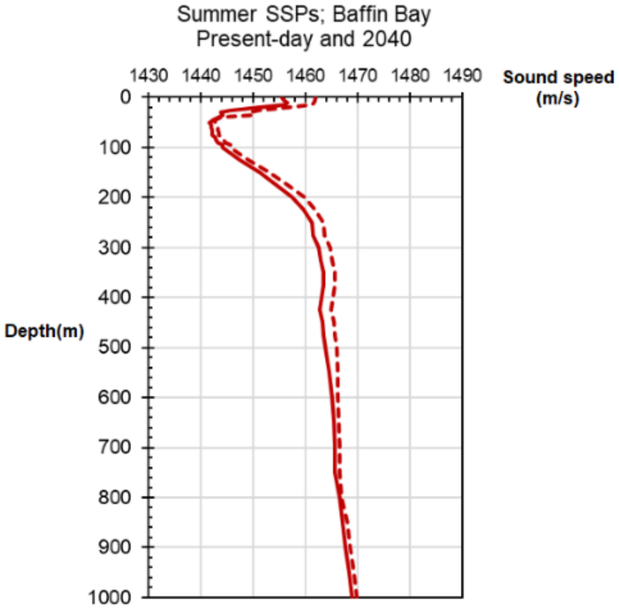


Figure 4.15: The dashed lines represent sound speed profiles (SSPs) where expected warming and freshening in the water column and shoaling of the mixed layer over the next two decades are accounted for. A longer ice-free summer will result in a warmer summer mixed layer by 2040 and thus a stronger sound speed maximum at the surface (Hines et al., 2020)

Considering all the parameters listed previously and analyzing cargo traffic data, Figure 4.16 shows a comparison between PDFs for what future sound exposure levels near Baffinland might look like when ships travel at 12.87 knots (average for cargo vessels on zone 13 in 2021) and when they travel at 9 knots, for both frequency values of 63Hz and 400Hz.

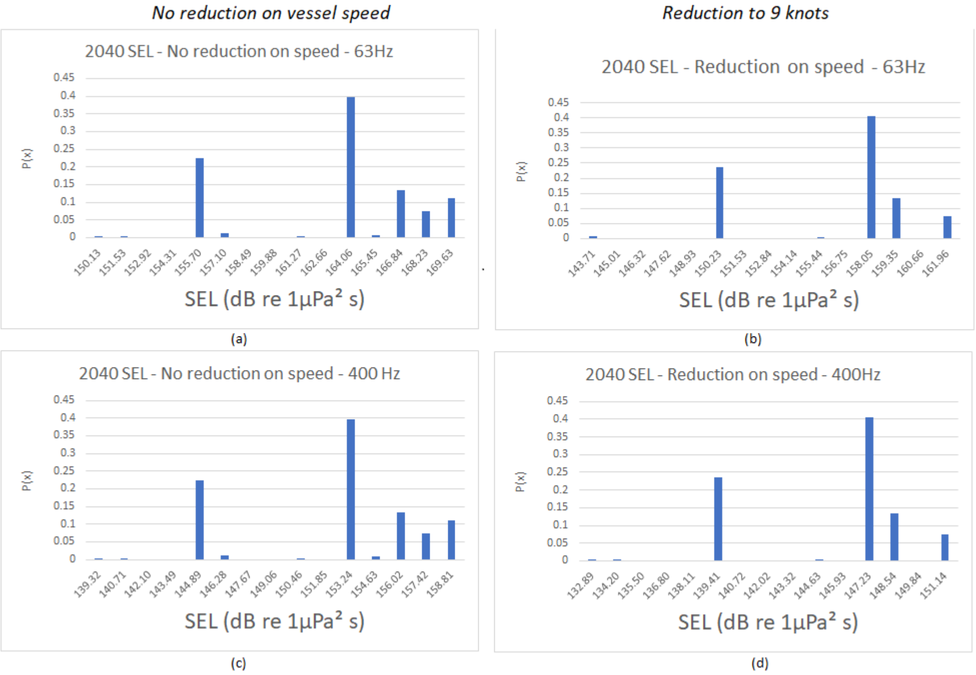


Figure 4.16: Comparison between PDFs for suture sound exposure levels when reducing the speed to 9 knots.

Cumulative SEL (dB)	No Reduction on speed		Reduction on Speed	
	Current	Future State	Current	Future State
63 Hz	185	190	177	182
400 Hz	175	180	166	171

Table 4.3: Comparison between current and future cumulative sound exposure level values (dB) when cargo and tankers would slow down their speed to 9 knots in the Baffin Land area and when speed was maintained its actual values from outside the area.

From Table 4.3, we can observe the significant drop in the underwater noise generated by vessels when they reduce their speed to 9 knots and how the speed parameter is important when calculating the sound generated, as the length and class of the ships remained the same. Comparing the future state situation, in which the quantity of ships would increase by three times the current value, we can observe that, for 63 Hz, the value dropped from 190 dB ($1.15 \cdot 10^7 W/m^2$) to 182 dB ($1.58 \cdot 10^6 W/m^2$) (difference of $9.92 \cdot 10^6 W/m^2$) and for 400 Hz, the value dropped from 180 dB ($10^6 W/m^2$) to 171 dB ($1.25 \cdot 10^5 W/m^2$) (difference of $8.75 \cdot 10^5 W/m^2$) As a logarithmic scale, we can observe how significant the drop on the energy value is, when converted to W/m^2.

4.4 Modelling parametric estimates and outputs

After presenting the main points of discussion deriving from the literature review and interviews, the principal drivers and constraints for the shipping activity in the Arctic were carefully considered and the assumptions for future increases in the traffic and future technologies to be implemented are presented in this section. With changes in values for future activity in the northern zones, the cumulative SEL values of each ship type in each zone were calculated and compared with current values. This measure allows us to show how the summed value for all SELs from all ships varies depending on the number of vessels.

A triangular probability distribution was used to assess the future values of ship numbers: a lower and upper limit together with a most likely value. This distribution was chosen because of limited sample data and the distribution is also vaguely known.

The parametric estimates are presented in Tables 4.4 and 4.5.

Cargo/Tanker	Future Fleet % Related to Current
Lower Limit	200%
Most Likely	300%
Upper Limit	330%

Table 4.4: Assumptions on the future percentage of Cargo and Tanker Vessels related to current values, based on expert opinion.

Cruise	Future Fleet % Related to Current
Lower Limit	100%
Most Likely	200%
Upper Limit	300%

Table 4.5: Assumptions on the future percentage of Cruise Vessels related to current values, based on experts' opinions.

Regarding the technologies to be implemented for each vessel type, after discussing with experts, the most likely to be implemented on cargo/tanker vessels are the propeller cap turbines and on cruise ships, the diesel-electric machinery. For this project, technology improvements' effects were only analyzed separately and no scenario was developed taking into consideration two technology features applied together. A deeper study should be done, in order to evaluate the final noise levels when two technology improvements are applied at once.

Therefore, we also assumed possible values of the percentage of the future fleet of each vessel type to apply a specific underwater noise mitigation technology. As well as the assumption for the increase in shipping traffic, interviewees were asked about the most likely value of these percentages, which was then used to shape a triangular distribution.

Subsequently, this same distribution was used as an input for the Monte Carlo simulation, used to calculate the SEL, as well as the cumulative (here referred to as the addition of all individual ship noise sources) SEL. The PDF of the percentage of the future fleet to apply the measures was used in conjunction with the most likely value of the technology noise reduction (also a PDF) (section 4.3.1).

Cruise ships were assessed to have a most likely value of 20% of the total fleet adopting the new technology by 2040 and for cargo and tanker 10% of the total fleet. The values are shown in Tables 4.6 and 4.7.

Cargo/Tanker	Percentage of total future cruise fleet to apply technology mitigation means
Lower Limit	7%
Most Likely	10%
Upper Limit	14%

Table 4.6: Percentage of total future cargo and tanker fleet to apply technology mitigation means

Cruise	Percentage of total future cruise fleet to apply technology mitigation means
Lower Limit	10%
Most Likely	20%
Upper Limit	30%

Table 4.7: Percentage of total future cruise fleet to apply technology mitigation means

Consequently, the simulations were done for each AIRSS zone (9 and 13) and frequency (63 Hz and 400 Hz). For ease of reference, current values for each frequency, zone, and vessel type are summarized in Figure 4.21, separated into tables, representing the statistics of individual and cumulative values of SEL.

The PDF charts (Figure 4.17 to Figure 4.20) show how the current individual SEL values are distributed.

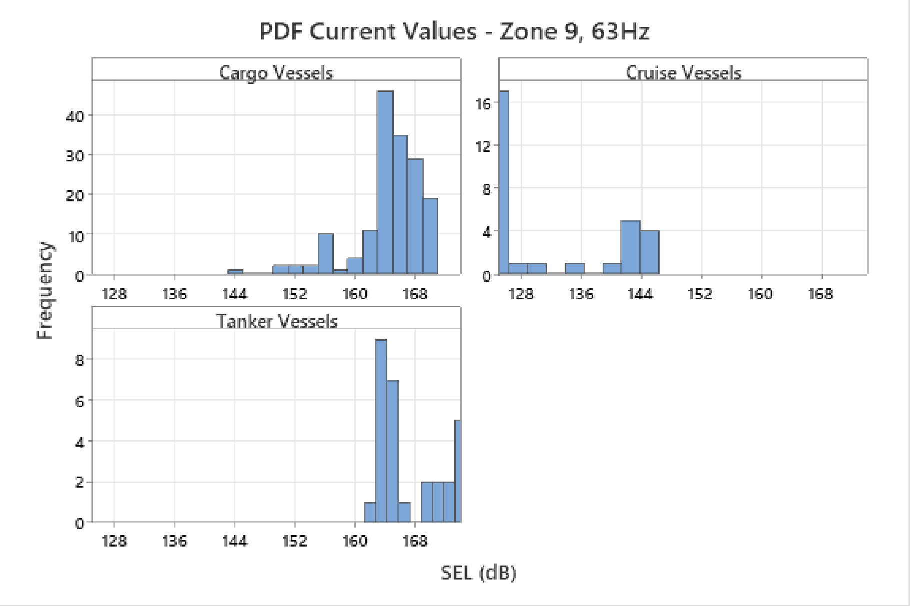


Figure 4.17: PDF Current Values - Zone 9, 63Hz

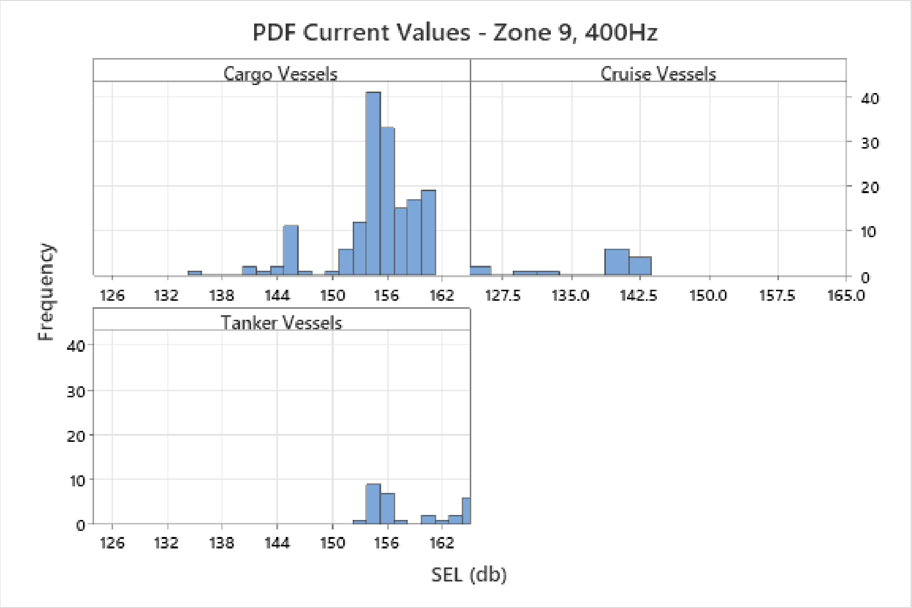


Figure 4.18: PDF Current Values - Zone 9, 400Hz

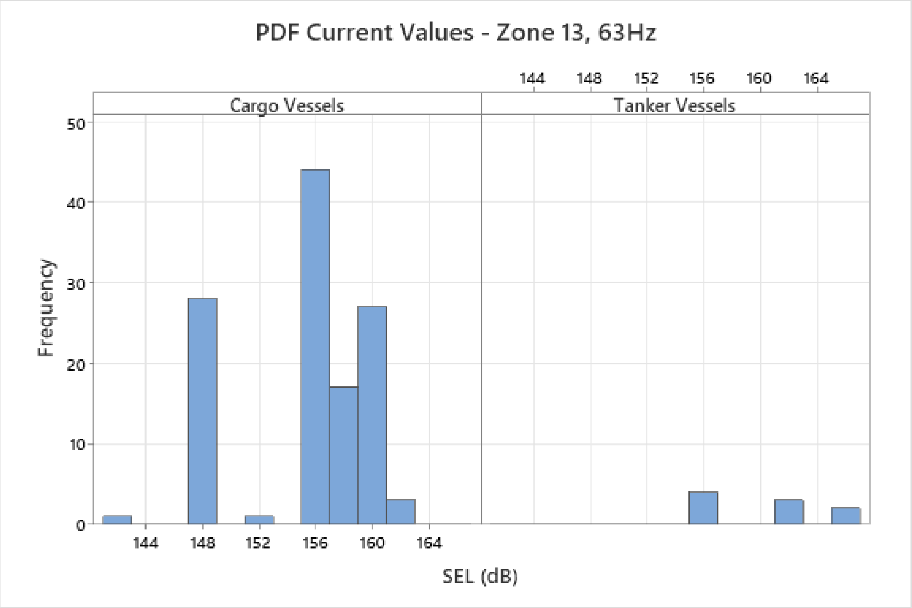


Figure 4.19: PDF Current Values - Zone 13, 63Hz

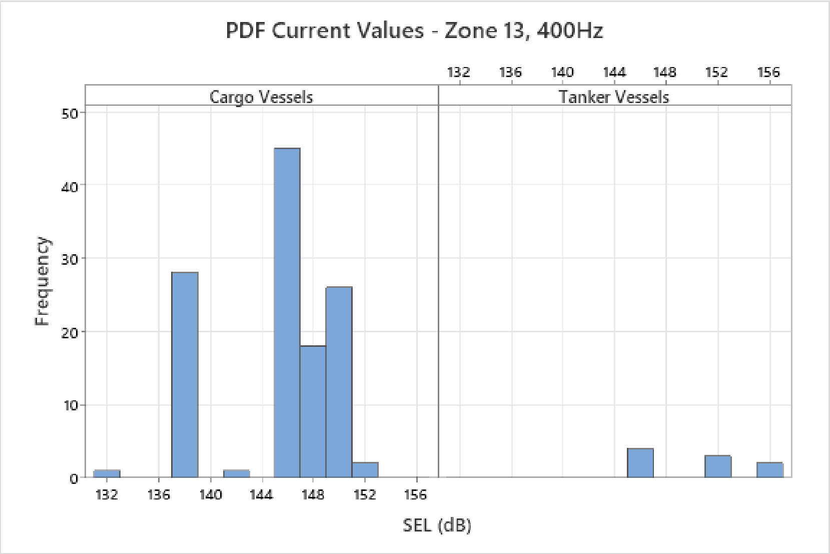
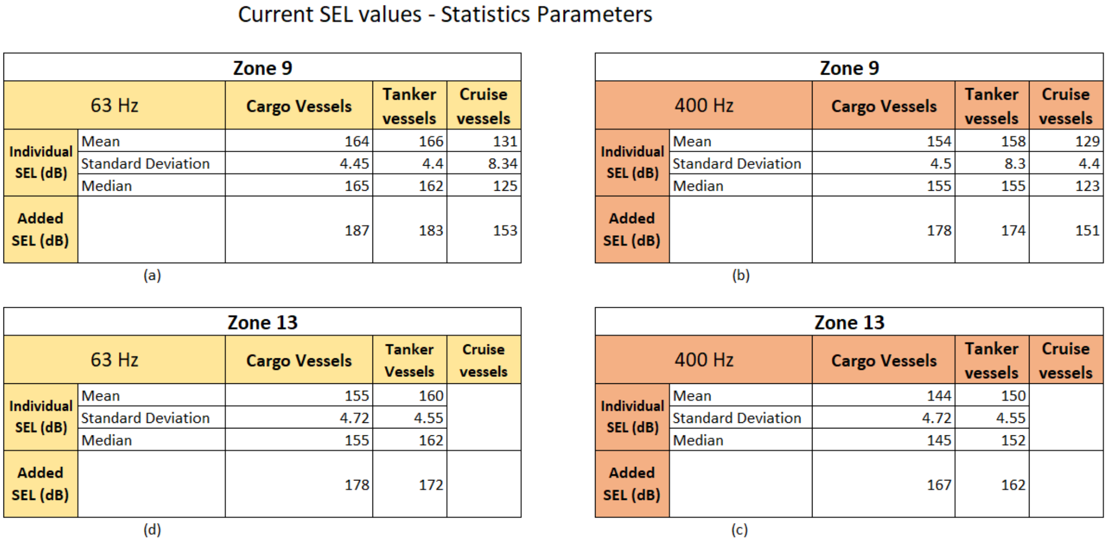


Figure 4.20: PDF Current Values - Zone 13, 400Hz



Current SEL values - Statistics Parameters

Zone 9				
63 Hz		Cargo Vessels	Tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	164	166	131
	Standard Deviation	4.45	4.4	8.34
	Median	165	162	125
Added SEL (dB)		187	183	153

(a)

Zone 9				
400 Hz		Cargo Vessels	Tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	154	158	129
	Standard Deviation	4.5	8.3	4.4
	Median	155	155	123
Added SEL (dB)		178	174	151

(b)

Zone 13				
63 Hz		Cargo Vessels	Tanker Vessels	Cruise vessels
Individual SEL (dB)	Mean	155	160	
	Standard Deviation	4.72	4.55	
	Median	155	162	
Added SEL (dB)		178	172	

(d)

Zone 13				
400 Hz		Cargo Vessels	Tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	144	150	
	Standard Deviation	4.72	4.55	
	Median	145	152	
Added SEL (dB)		167	162	

(c)

Figure 4.21: Summary of Current Values' Statistics Parameters

From section 4.4.1 to section 4.4.4, the results of the Monte Carlo simulation of the individual and cumulative (added) SEL values are displayed for each zone, frequency, and vessel type, allowing a comparison with values shown in Figures 4.17 to Figure 4.20. In addition, Figure 4.30 shows a summary of the Monte Carlo simulation statistics values, divided into four tables (a) to (d), regarding each zone and frequency.

4.4.1 Future Simulations - Zone 9 - 63 Hz

Individual SEL Values

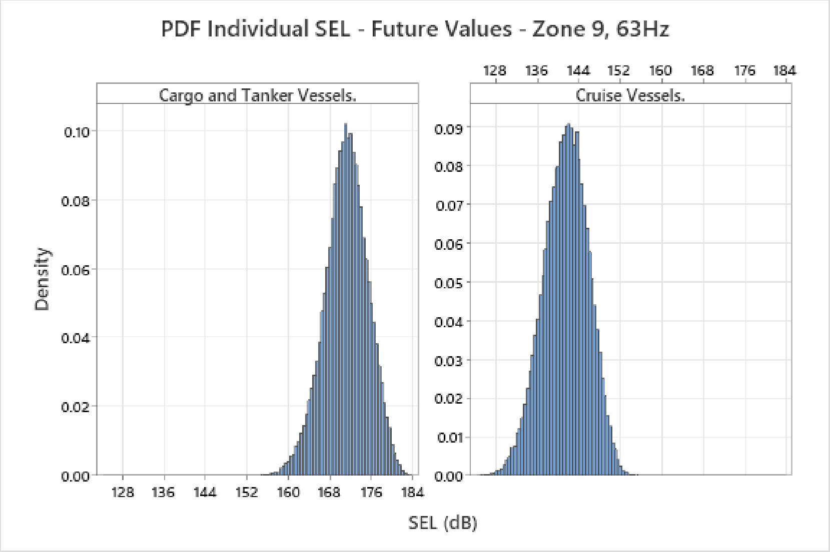


Figure 4.22: PDF of individual future SEL values - Zone 9, 63Hz

Cumulative (added) SEL Values

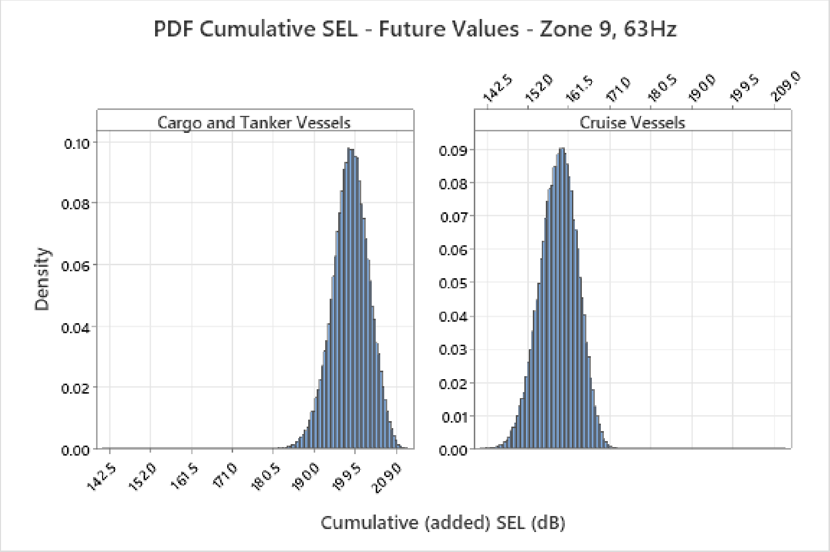


Figure 4.23: PDF of cumulative (added) future SEL values - Zone 9, 63Hz

4.4.2 Future Simulation - Zone 9 - 400 Hz

Individual SEL Values

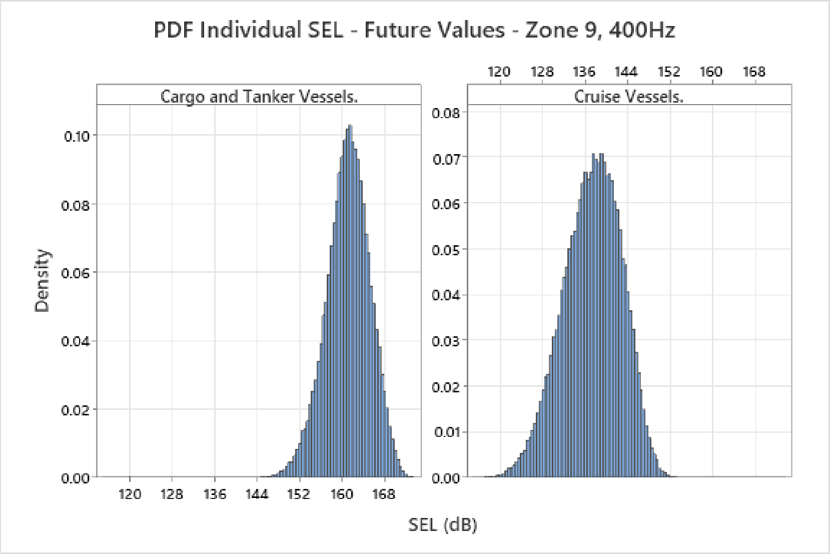


Figure 4.24: PDF of individual future SEL values - Zone 9, 400Hz

Cumulative (added) SEL Values

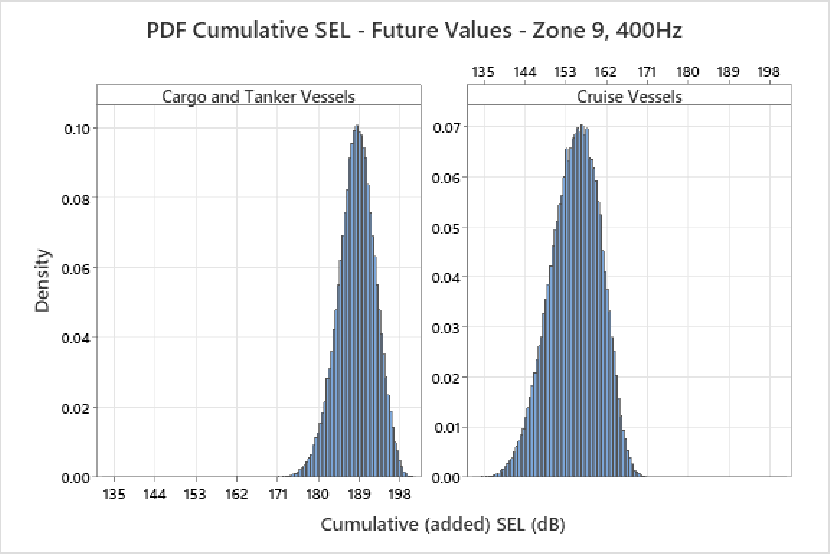


Figure 4.25: PDF of cumulative (added) future SEL values - Zone 9, 400Hz

4.4.3 Future Simulation - Zone 13 - 63 Hz

Individual SEL Values

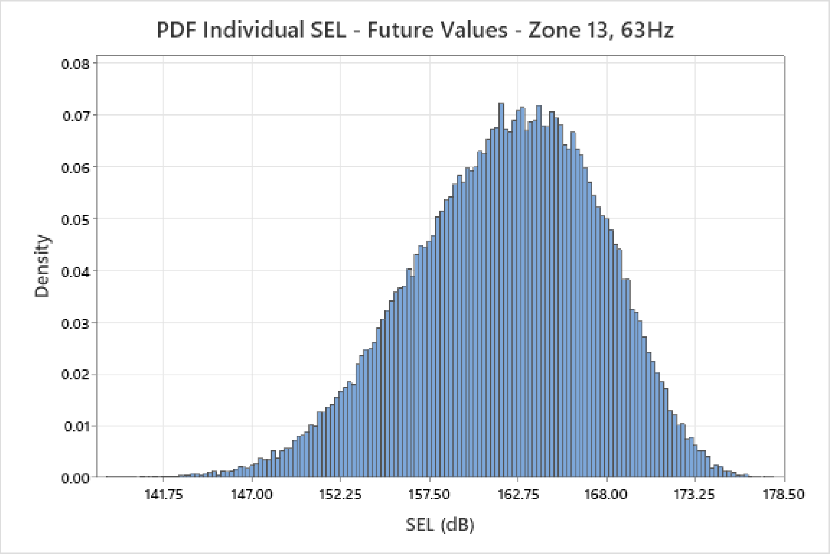


Figure 4.26: PDF of individual future SEL values - Zone 13, 63Hz

Cumulative (added) SEL Values

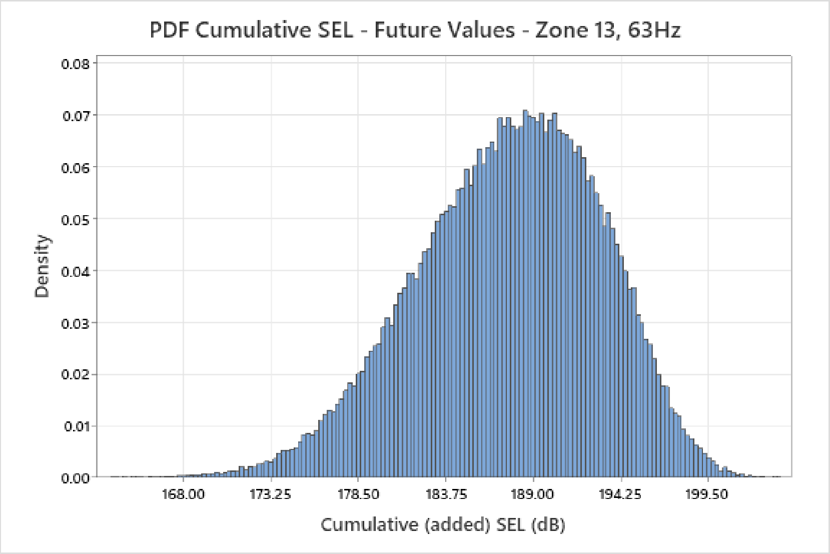


Figure 4.27: PDF of cumulative future SEL values - Zone 13, 63Hz

4.4.4 Future Simulation - Zone 13 - 400 Hz

Individual SEL Values

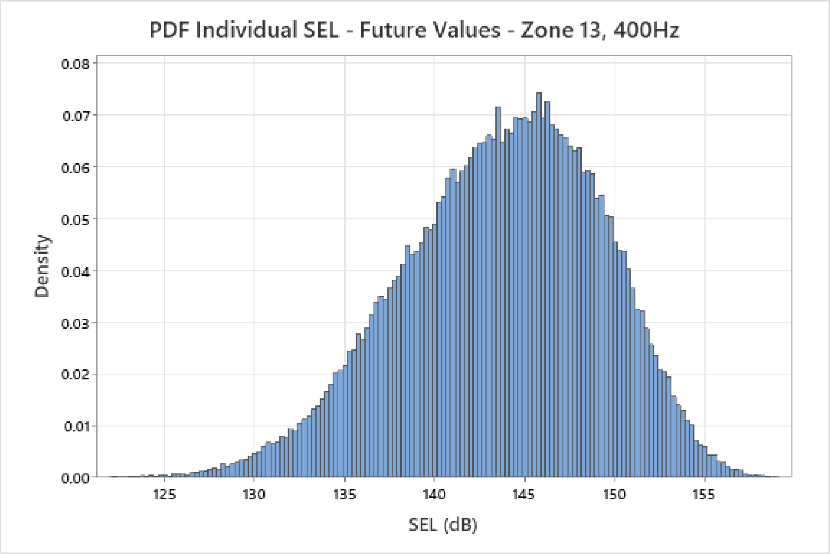


Figure 4.28: PDF of individual future SEL values - Zone 13, 400Hz

Cumulative (added) SEL Values

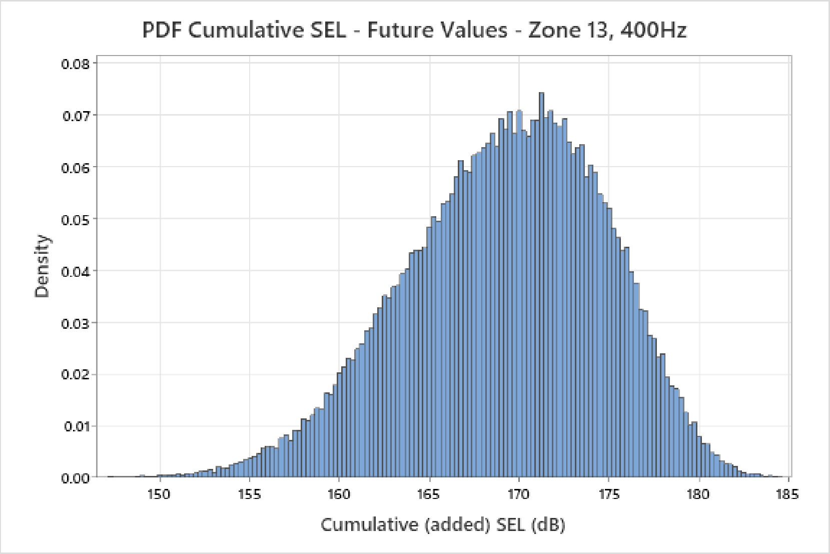
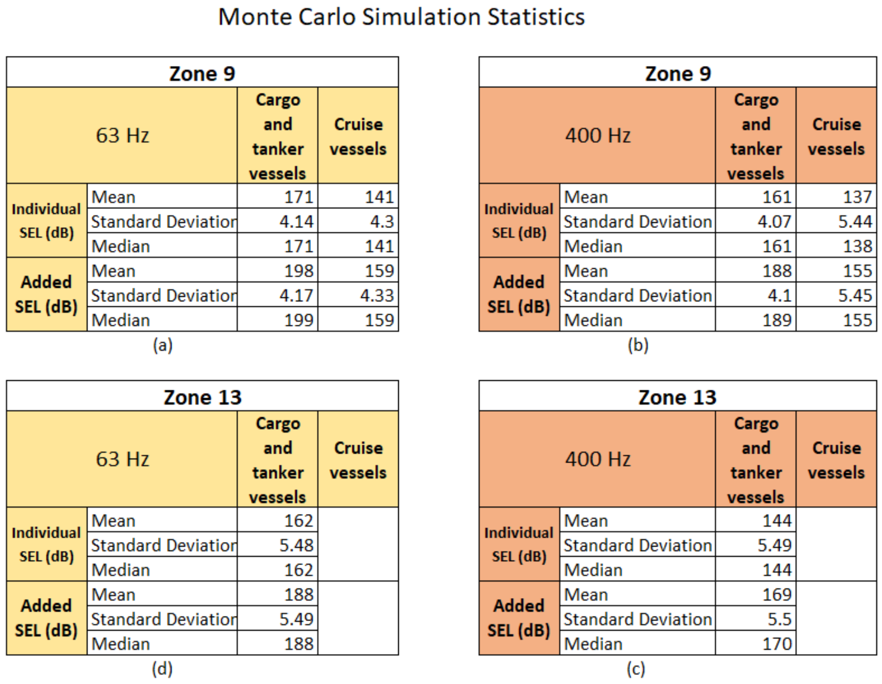


Figure 4.29: PDF of cumulative future SEL values - Zone 13, 400Hz

Summary Results



Monte Carlo Simulation Statistics

Zone 9			
63 Hz		Cargo and tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	171	141
	Standard Deviatior	4.14	4.3
	Median	171	141
Added SEL (dB)	Mean	198	159
	Standard Deviatior	4.17	4.33
	Median	199	159

(a)

Zone 9			
400 Hz		Cargo and tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	161	137
	Standard Deviation	4.07	5.44
	Median	161	138
Added SEL (dB)	Mean	188	155
	Standard Deviation	4.1	5.45
	Median	189	155

(b)

Zone 13			
63 Hz		Cargo and tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	162	
	Standard Deviatior	5.48	
	Median	162	
Added SEL (dB)	Mean	188	
	Standard Deviatior	5.49	
	Median	188	

(d)

Zone 13			
400 Hz		Cargo and tanker vessels	Cruise vessels
Individual SEL (dB)	Mean	144	
	Standard Deviation	5.49	
	Median	144	
Added SEL (dB)	Mean	169	
	Standard Deviation	5.5	
	Median	170	

(c)

Figure 4.30: Summary of Future Estimated values

4.5 What-if Analysis

In order to better understand the impact of using new shipping technology, as the estimated values for the futures show relatively low changes relative to the present, we used the statistical tool of what-if analysis, to compare different scenarios and their potential outcomes.

Thus, we changed the parameters of the percentage of the total fleet to apply technology mitigation means in each vessel type segment. Questions were devised in order to draw different possible futures:

- What if not only 20% of the total cruise fleet, but 50% of it applied underwater noise mitigation design processes or technologies in the next 20 years?
- What if not only 10% of cargo and tanker fleet, but at least 40% of it applied underwater noise mitigation design processes or technologies in the next 20 years?

The same technologies (i.e., diesel-electric machinery for cruise ships and propeller cap turbines for cargo and tanker ships) were also herein considered. With these parameters being taken into consideration, Monte Carlo simulations were completed, and the PDFs (Figure 4.31 to Figure 4.38) and summary results (Figure 4.39) are shown in the following section.

4.5.1 Future Simulation - What- if Analysis - Zone 9 - 63 Hz

Individual SEL

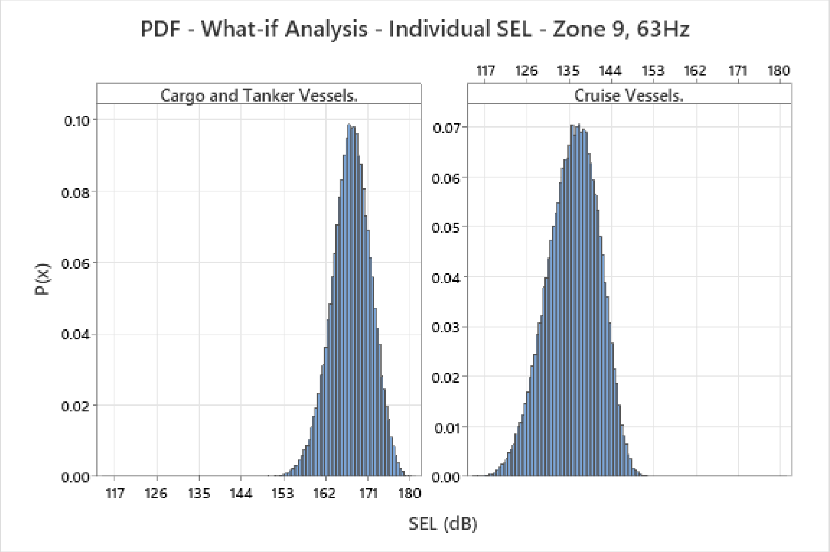


Figure 4.31: PDF of individual SEL values - Zone 9, 63Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

Cumulative (added) SEL

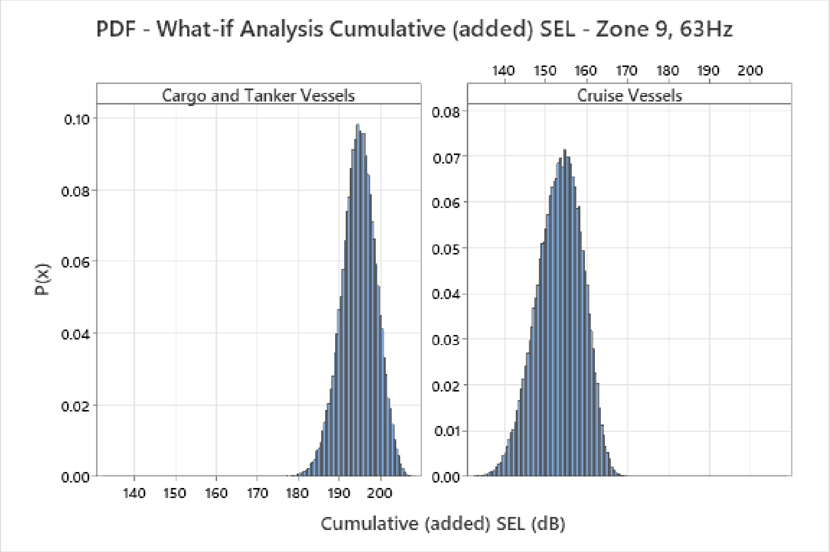


Figure 4.32: PDF of cumulative (added) SEL values - Zone 9, 63Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

4.5.2 Future Simulation - What- if Analysis - Zone 9 - 400 Hz

Individual SEL

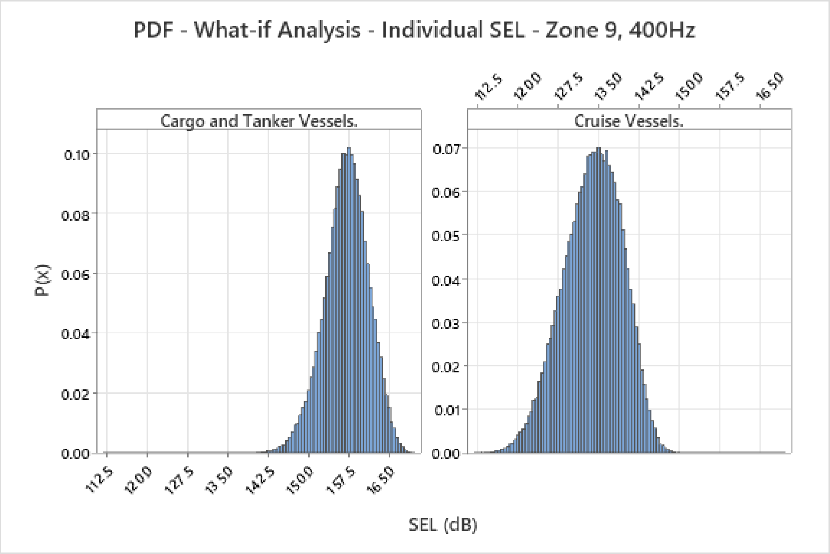


Figure 4.33: PDF of individual SEL values - Zone 9, 400Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

Cumulative (added) SEL

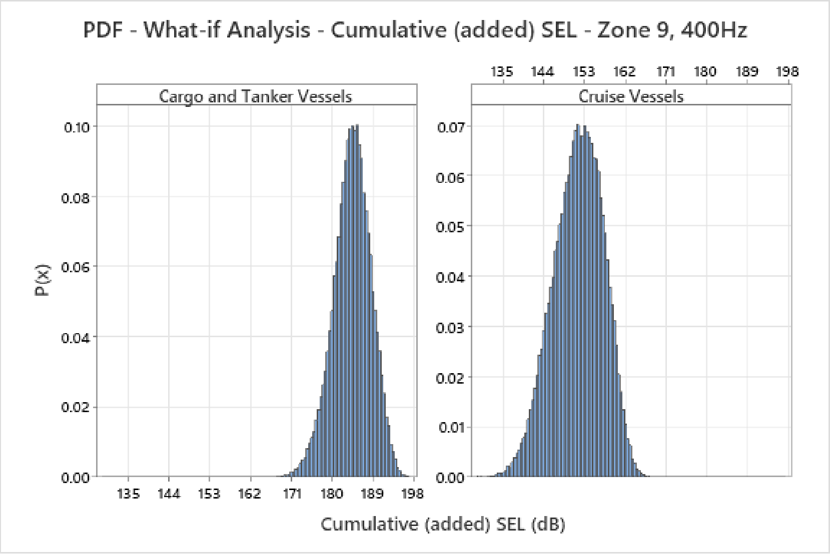


Figure 4.34: PDF of cumulative (added) SEL values - Zone 9, 400Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

4.5.3 Future Simulation - What- if Analysis - Zone 13 - 63 Hz

Individual SEL

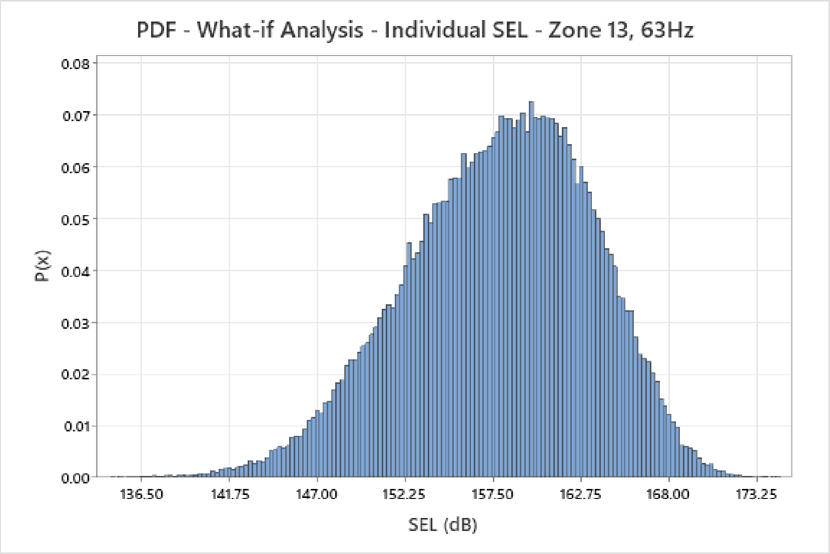


Figure 4.35: PDF of individual SEL values - Zone 13, 63Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

Cumulative (added) SEL

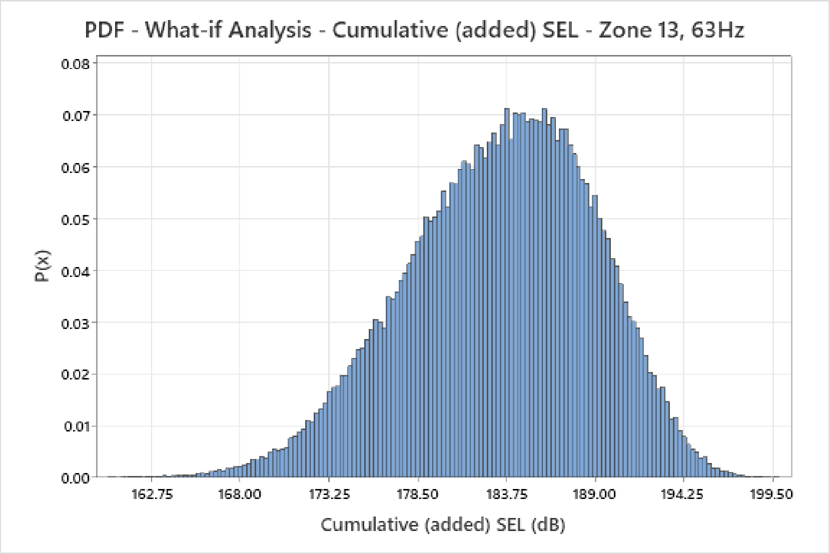


Figure 4.36: PDF of cumulative (added) SEL values - Zone 13, 63Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

4.5.4 Future Simulation - What- if Analysis - Zone 13 - 400 Hz

Individual SEL

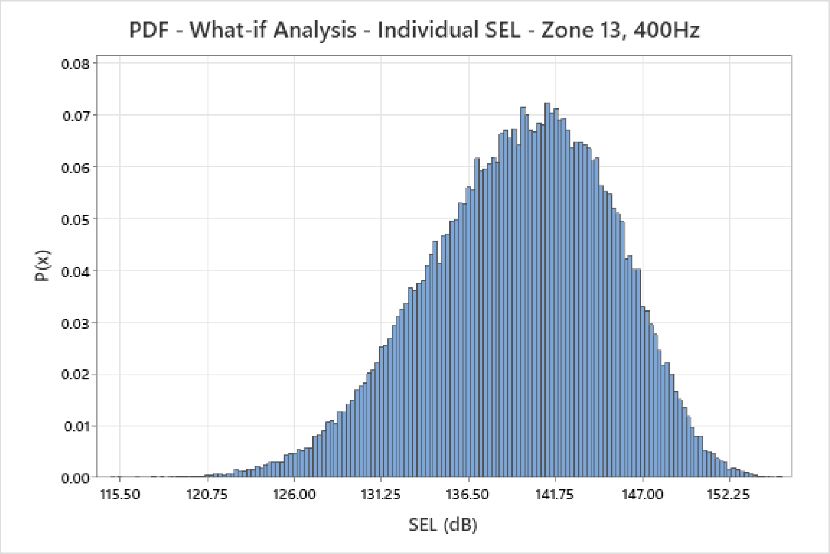


Figure 4.37: PDF of individual SEL values - Zone 13, 400Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

Cumulative (added) SEL

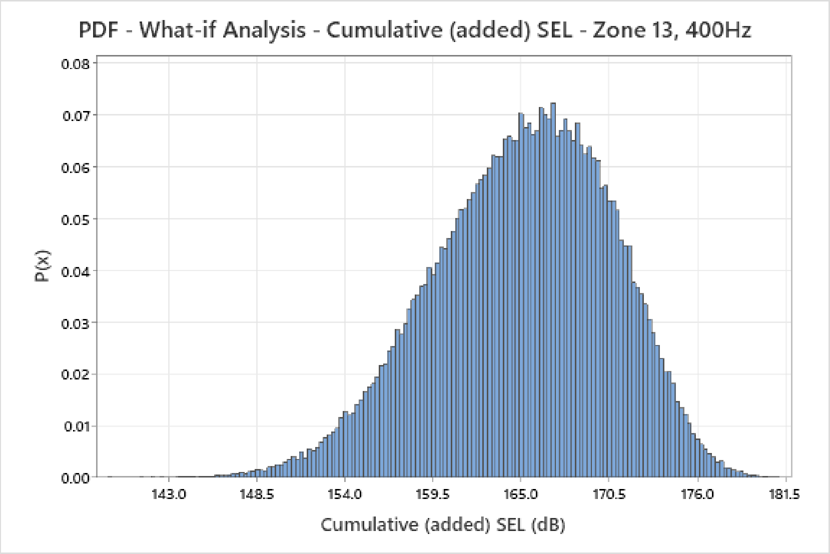
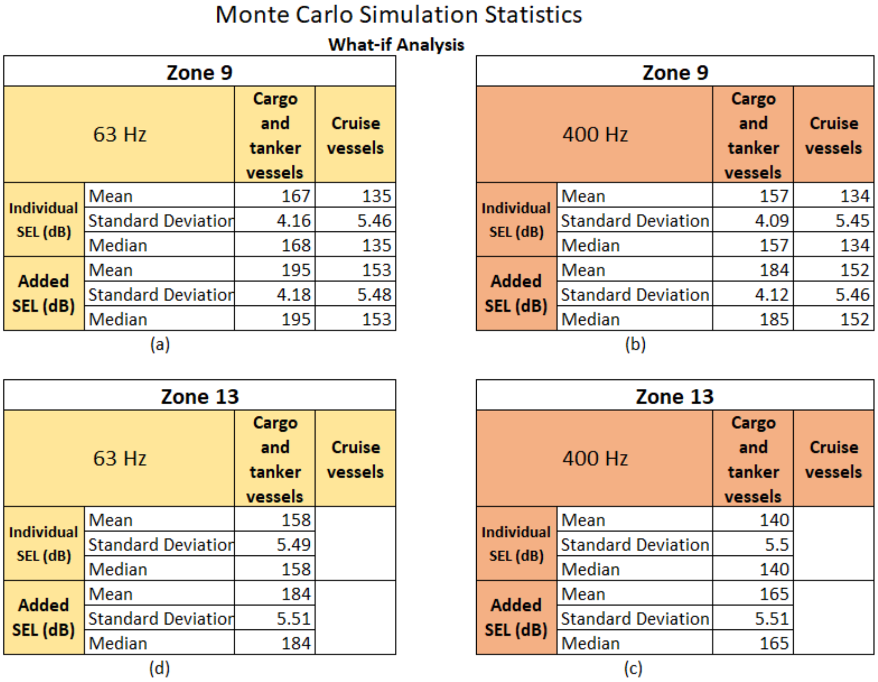


Figure 4.38: PDF of cumulative (added) SEL values - Zone 13, 400Hz - Most likely value for the percentage of future cruise fleet to apply new technologies: 50% and most likely value for the percentage of future cargo and tanker fleet to apply new technologies: 40%

Summary Results



Monte Carlo Simulation Statistics

What-if Analysis

Zone 9			
63 Hz		**Cargo and tanker vessels**	**Cruise vessels**
Individual SEL (dB)	Mean	167	135
	Standard Deviation	4.16	5.46
	Median	168	135
Added SEL (dB)	Mean	195	153
	Standard Deviation	4.18	5.48
	Median	195	153

(a)

Zone 9			
400 Hz		**Cargo and tanker vessels**	**Cruise vessels**
Individual SEL (dB)	Mean	157	134
	Standard Deviation	4.09	5.45
	Median	157	134
Added SEL (dB)	Mean	184	152
	Standard Deviation	4.12	5.46
	Median	185	152

(b)

Zone 13			
63 Hz		**Cargo and tanker vessels**	**Cruise vessels**
Individual SEL (dB)	Mean	158	
	Standard Deviation	5.49	
	Median	158	
Added SEL (dB)	Mean	184	
	Standard Deviation	5.51	
	Median	184	

(d)

Zone 13			
400 Hz		**Cargo and tanker vessels**	**Cruise vessels**
Individual SEL (dB)	Mean	140	
	Standard Deviation	5.5	
	Median	140	
Added SEL (dB)	Mean	165	
	Standard Deviation	5.51	
	Median	165	

(c)

Figure 4.39: Summary of What-if Analysis Results

5 Discussion

5.1 Results: discussion and comparison

This study assessed possible scenarios regarding the Canadian Arctic's future shipping traffic situation together with an evaluation on how underwater noise emitted by different types of vessels have the potential to cause harm to whales and other marine mammals. The use of the Monte Carlo method is justified by the uncertainties around the inputs provided for the calculation of individual and cumulative (added) SEL: future ship quantity, probability of the future fleet to apply technology mitigation means, and the probability of source level reduction.

The PDFs shown in the results section indicates a range of possible values as outputs and the probability associated with each of them. The output distribution is composed of a range of combinations of the inputs' uncertainties.

From the calculations, the highest intensities of sound level SL were observed to be in the low-frequency range, with a peak in between 25 and 70 Hz, as commercial ships produce underwater noise primarily at low frequencies (below 500Hz), caused especially by propeller cavitation. As an example, Figure 5.1 shows how the SL value varies within the frequency range, for a ship navigating at 12.87 knots and with a length of 179 m.

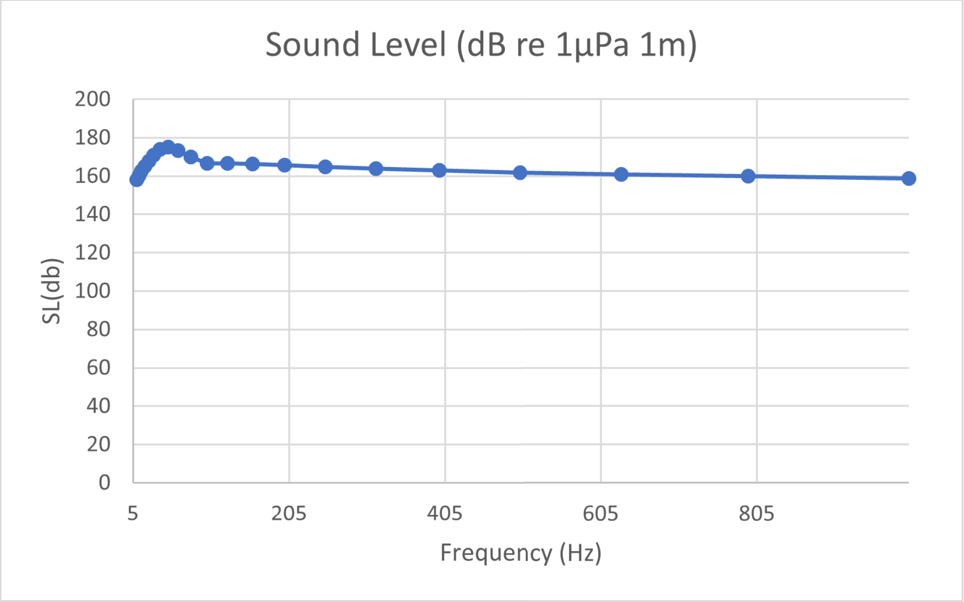


Figure 5.1: Variation of SL within a frequency range from 10 Hz to approximately 1000 Hz, for a ship navigating at 12.87 knots, with a measured length of 179m. A peak is observed between 25 and 70 Hz.

As seen in equation 3.1 and Figure 3.6, sound level is directly proportional to the length and speed of the vessel and this relation is shown in Figures 5.2 and 5.3 for the frequency of 63 Hz for a cargo vessel when fixing one parameter at a time.

Regarding the regression analysis made between shipping traffic and either GDP

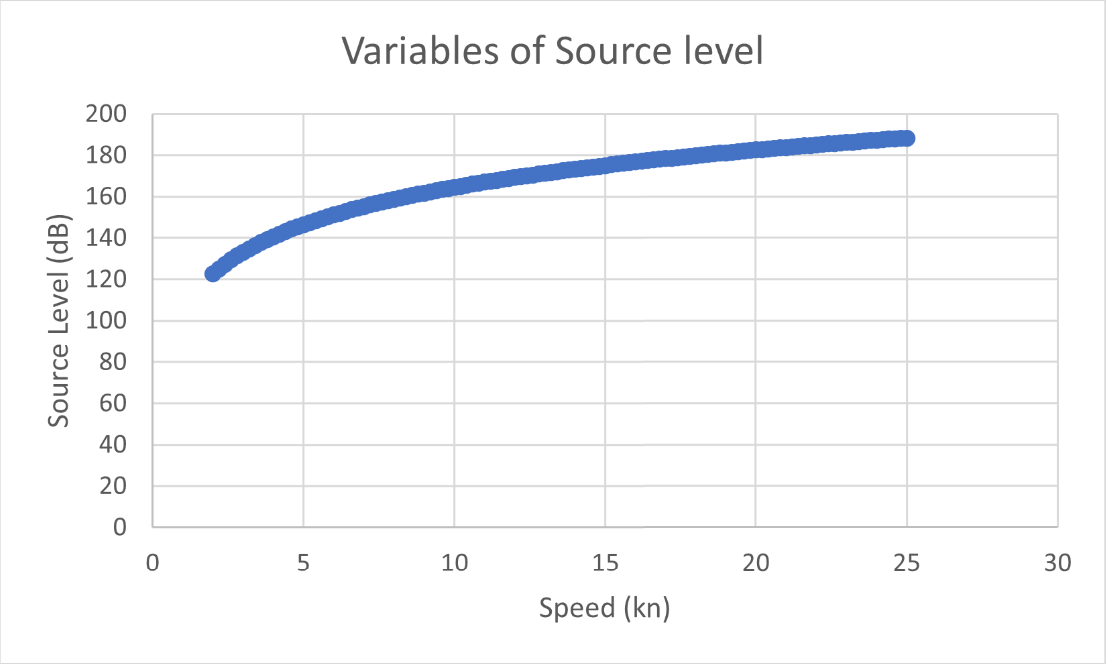


Figure 5.2: Increase of SL (dB) with the increase of ship speed in knots.

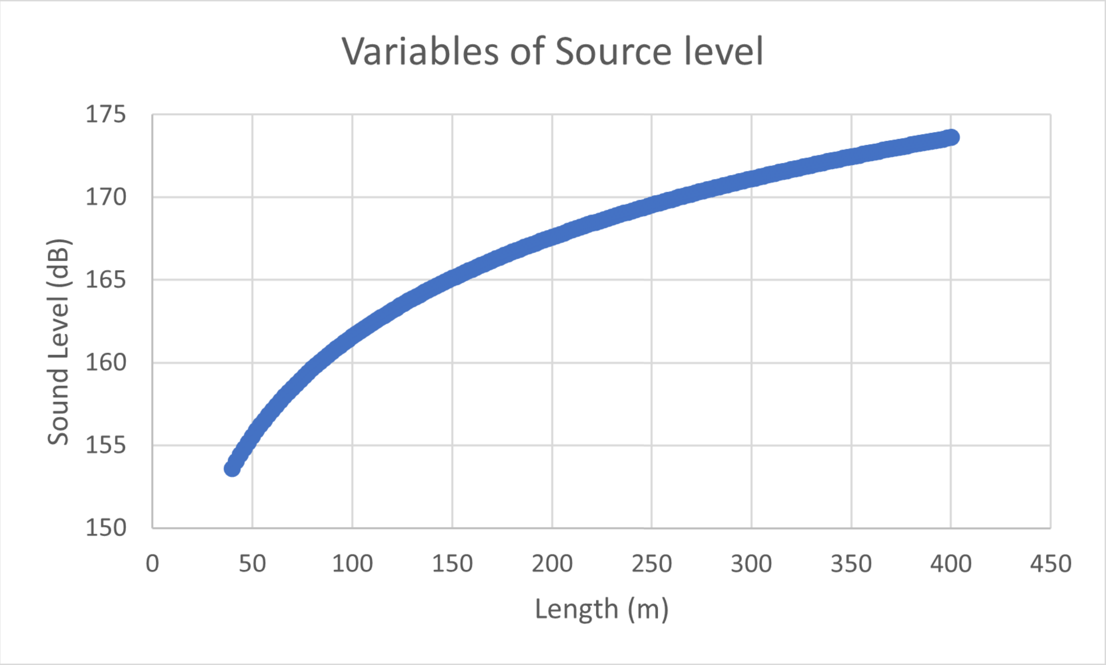


Figure 5.3: Increase of SL (dB) with the increase of ship length in meters.

or population historical data, results showed a significant difference from what experts assume might happen in the future (section 4.4), and therefore, it is worth discussing some points.

With regard to the GDP case, as shipping operates on a demand basis, fluctuations in the health of the economy can have a direct impact on the growth of this industry. Thus the dependence of this economic sector on the health of the economy represents a vital uncertainty for the development of any scenario (Hodgson et al., 2014). Hodgson et al. 2014 even cite other factors that influence the demand for marine transport such as the price of fuel oil and the impact of political events for example. However, these parameters are driven by different uncertainties and should not be analyzed separately.

As for the population aspect, while its growth may cause an expansion in demands for resources, it is seen as another parameter driven by unpredictability and affected by other uncertainties such as the availability of natural resources to local communities as well as non-renewable resources, driving the demand for energy consumption, for example. Thus, a deeper and more detailed study considering all drivers and constraints should be able to result in more realistic future scenarios.

Another limitation of the regressions was the availability of only 5 years of historical data and the extrapolation into 20 years in the future, assuming a constant relationship between the variables. Again, this relationship can be substantially changed driven by unpredictability in both population and GDP numbers.

Nevertheless, the results from the regression analysis, although limited, showed that there is a relationship between these two parameters and shipping traffic, as it is a demand-driven industry (Hodgson et al., 2014).

In addition, as stated in section 4.2, GDP data is only a rough indicator of society's standard of living (it does not even measure crucial aspects of the economy such as its sustainability). Deeper research on geopolitical factors, natural resources availability and technological changes, for example, would better predict a society's economic performance.

Regarding the measure (added SEL) used to relate quantity of ships with sound exposure levels, a noticeable increase in the cumulative sound exposure level for the future values was demonstrated from section 4.4.1 to section 4.5.4, as an increase of the ship entries was estimated for all types of vessels, and therefore, the cumulative SEL would add up to higher levels than currently (Figure 5.4).

From the results, we could clearly see that for both frequencies, zones and for the three types of vessels, cumulative sound exposure levels (SEL) will increase significantly in the future.

As a representative process of forecasting noise levels, this project did not take into consideration all types of vessels transiting through the region in the period considered. Therefore, it is not possible to conclude which type of vessel could cause greater impacts. Nonetheless, it was clear during the study, that cargo and tanker vessels are responsible for higher underwater noise generated, as their length measures are significantly greater than cruise ships (an average of 183 m length for cargo and tankers and an average of 139 m length for cruise vessels).

The percentage of ships applying quieting technologies, along with the associated low expected decrease in the sound generated, did not create a significant difference. The fact that not many ships will adopt technology mitigation features was explained by experts that technology implementation, especially in retro-fit processes, demands a large budget from companies, and the design and construction of new fleets and, consequently, substituting the old vessels, take time, not fitting into our forecasting horizon.

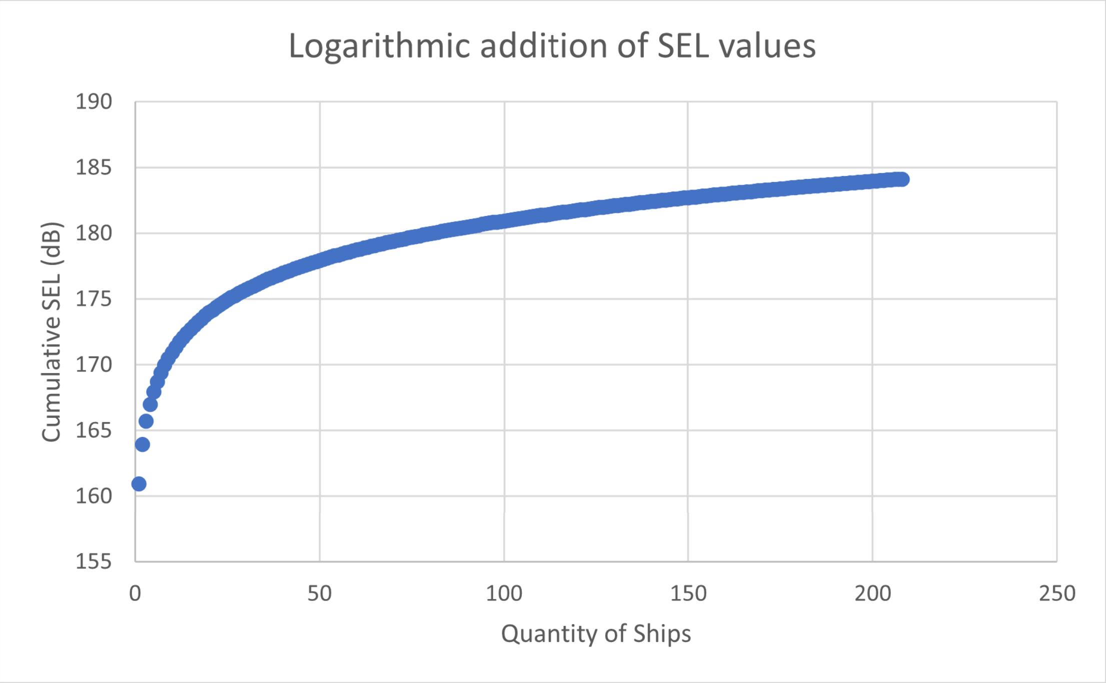


Figure 5.4: Increase of cumulative SEL values with the increase of ship number

Yet, the what-if analysis allowed us to change the percentage of ships applying underwater mitigation features while maintaining the same quantity of ships, confirming that the technologies can, indeed, decrease the sound level within an area.

As for the Baffinland area, the reduction of the average speed to 9 knots made a great difference compared to values whereby the speed was the same as the current average. Results can be seen in section 4.3.3.

5.1.1 Effects on the Received and Sound Exposure Levels

Over the past decade, ship traffic in the Canadian Arctic has increased by more than 25%, a phenomenon that is expected to continue in the coming years (Dawson et al 2018). Furthermore, the consequences to marine faune of the noise produced by larger vessels in the lower-frequency band have prompted multiple environmental bodies to reduce commercial shipping's contribution to ambient noise within 20 to 30 years (Wade et al., 2010).

Within the five years of the summer shipping season analyzed herein (2016-2021), for the vessel types of cargo, tanker and cruise, 58% of entries in the studied zones were made by vessels over 100m in length. All the calculated sound levels (SL) from these larger vessels were above 110 dB in both frequencies observed (63 and 400Hz). However, when analyzing both present and future (probability distribution) values and following the National Oceanic and Atmospheric Administration (NOAA) Report on Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing, no ships produced individual SEL values (which take into consideration the cumulative sound level over time) above the threshold (179 and 178 dB for low and medium frequency cetaceans, respectively) (NOAA - National Oceanic and Atmospheric Administration &

U.S. Department of Commerce, 2018).

An exception was seen in the future values of zone 9, 63 Hz (Figure 4.22), where the tail end of the distribution chart shows possible values (although with a very low associated probability) that exceed the threshold. Again, the PDFs generated by Monte Carlo simulations show a range of possible values for the output as inputs are entered as uncertainties. This can be explained by a random combination of inputs characterized by: low probability of technology application by the future fleet and low probability of reduction in the source level by the technology applied.

Consequently, it is worth discussing why these values did not reach the TTS threshold, and why this study might not be entirely representative of the potential impacts that vessel noise could bring to the marine fauna.

When the values for the SL were calculated, for the purpose of simplification, the speed considered was the average speed for each kind of vessel in each month. Consequently, ships that were positioned in docking areas decreased the final average speed of that month, given the way that the AIS data are captured. Since speed is a factor that plays a significant role in the SL calculation, this ultimately influences the RLs and SELs.

As explained in section 3.3.1, Table 3.1 provides the applied conversion between the ship type identification (ID) in the AIS data set and vessel class. However, the AIS types 'Passenger' (ID = 60–69) and 'Cargo' (I = 70–79) do not provide clear identification of larger and faster vessels such as container ships (which do not navigate in the Canadian Arctic) and cruise vessels. Therefore, these vessel classes are tentatively identified by ship length, observed mean speed and, as defined by AIS, a hazard class (the nature of a physical or health hazard, e.g., flammable solid and acute toxicity), leading to possible errors in the exact source level.

Furthermore, the recommended application of the weighted SEL cumulative metric from NOAA is for individual activities or sources and a specified accumulation period is needed, and generally, a 24-hour period is considered. It is not intended for accumulating sound exposure from multiple activities occurring within the same area or over the same time period nor to estimate the impacts of those multiple exposures to an animal occurring over various spatial or temporal scales. Current data available for deriving thresholds using this metric are based on exposure to only a single source and may not be appropriate for situations where exposure to multiple sources is occurring.

According to Gervaise et al. 2012, the noise radiated by a fleet with different ships may, in fact, generate cumulative SELs that exceed the threshold values proposed by NOAA (Gervaise et al., 2012). When inspecting the results of cumulative future values, i.e., adding together all the SEL values for the different ship types, most portions of the probability distribution values (see section 4.4 and 4.5) exceeded the temporary threshold shift (179 and 178 dB for low-frequency and medium-frequency cetaceans, respectively) as well as the permanent threshold shift (199 and 198, for low and medium frequency cetaceans, respectively) for some areas and frequencies, even though NOAA suggests the use of the metric only for individual sources. There is a need for a more appropriate metric to be re-evaluated for the application of exposure from multiple activities occurring in space and time.

Aside from the noise generated by vessels, natural ambient noise was not considered herein, although it is not so consequential in low-frequency ranges. In the mid-frequency band (500Hz to 25kHz), ambient noise is primarily due to sea-surface agitation: breaking waves, spray, bubble formation and collapse, and rainfall. For high-frequency band (>25kHz) ambient noise is essentially generated by ice noise (when breaking or interacting with sea waves) (Cook et al., 2020).

Another factor to highlight is the parameters used for the assessment of the transmission loss values (TL) and, consequently, the RLs and SELs, namely the distance from the source of the noise to the receiver. The depth of the whale in the water column was considered to be fixed, while the ship transited through the distance range. Certainly, this is not the reality. It is almost impossible to consider that whales will remain immobile for the period of approximately three hours (the minimum amount of time spent for the analyzed vessels to navigate through the distance range).

The reason why SEL was calculated for this study is that NOAA considers the onset of the TTS to occur when either the RL or SEL values exceed the threshold. Since the RL was considered as the intensity heard at one second of exposure (TdB = 0), it can be taken as the minimum theoretical SEL value for a specific SL, and the SEL calculated for the whole trajectory as the maximum theoretical value. Being a logarithmic measure, SEL increases significantly after one second of exposure. As an example, a SEL value can increase to almost 7dB (6.98) after 5 seconds of exposure (see Table 5.1 and Figure 5.5).

t (sec)	**TdB (dB)**
1	0
2	3.01
3	4.77
4	6.02
5	6.98

Table 5.1: Increase of time dependent sound levels with time in seconds.

One important point to also be taken into consideration is the fact that ships are not well-defined punctual noise sources. Aside from the main sound source (propeller cavitation), the noise also emanates from secondary sources such as engines, generators, pumps, hydraulics, and dampers.

5.2 Noise Propagation Model Limitations

In order to understand the projected changes to sonar performance in the Canadian Arctic by 2040, the Parabolic Equation Approximation model from JASCO Applied Sciences' project was used, providing information that will help guide development of improved Arctic surveillance. Although the objective of the JASCO study was to examine SONAR performance under future conditions, it is also useful for ship noise projections.

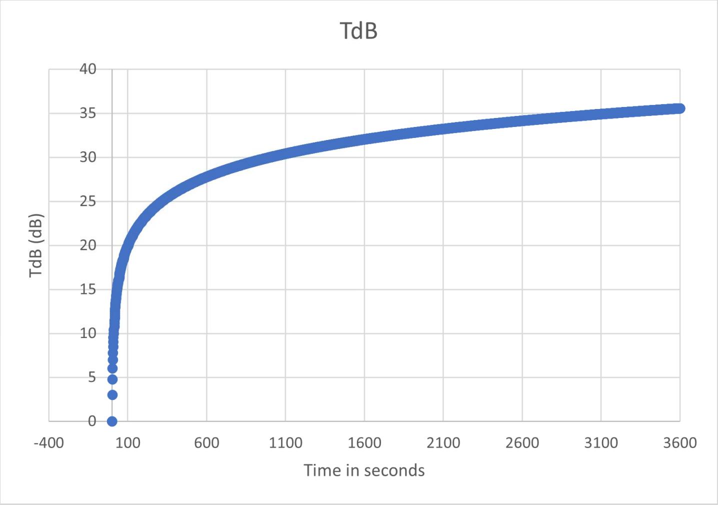


Figure 5.5: As a logarithmic scale, TdB increases significantly after one hour (3600 seconds) of exposure. For this study, the maximum time exposure was 4.196 hours (cargo vessels in zone 9) and, thus, a TdB value increase of 41.79 dB related to the instantaneous RL (t=1s).

However, any limitations in their model will also translate into limitations for shipping noise forecasting.

No simulation model is flawless and there is always space for improvement. Regarding this model, some limitations were presented:

- The propagation modeling was limited to single site-to-site lines, while performing an additional number of radials would provide more accurate results;

- With the ice cover in the Arctic becoming partial, it is not known whether the relative location of the ice cover and the sonar will impact sonar performance, or if it will simply scale as a percent of the ice cover along the track. Simulations of propagation modeling for various percentages and relative positions of ice cover could be run to examine this;

- Being a very sensitive ecosystem, an environmental review to identify locations of sensitivity would be valuable information to feed into decisions about hardware deployment sites.

Prediction of future situations involves a great number of possible scenarios, which are never fulfilled at once. Additional inputs on the cryoacoustic, geoacoustic and bathymetry of the Arctic could show different outputs, as for example, modeling with different ice-arch positions and with different season duration for full-cover winter, partial spring and fall, and fully open summer. Thus, there is a great variety of ways to assess a modeling simulation, and in order to reduce uncertainty and cover a wide range of scenarios, simulations should be run under different approaches.

5.3 Data quality

Data quality is always a concern for every research study, or the information we are analyzing would not fulfill its intended purpose. The AIS database might present some limitations: information is not easily related to vessel noise; it may not be accurate; vessels may deactivate their transponder or lose their connectivity; in congested areas, the time between observations may increase due to interference; so, coverage can always be a problem to consider. Also, as it is a dynamic data, it constantly changes as the vessel moves and known errors in marine GPS are, for example, propagation errors that arise due to signals from satellites slowing down as they pass through different layers of the atmosphere and multi-path errors, caused by signals from the satellites not taking a direct path to the receiver and influence the distance being calculated.

AIS also has manual information entered by the crew of each vessel, as the vessel destination. Thus, this can naturally lead to erroneous data input, sometimes not updating in a timely manner and, consequently, failing to update the navigational status when entering or leaving the port.

Another problem, which happens surprisingly often, stated by MEOPAR programmers was that some entries were found with multiple transceivers sending info for the same MMSI, which are globally unique radio identification numbers for ships assigned by flag state authorities.

For this specific research, gaps were found in part of the initial years of 2016 to 2018, and for 2019 only data from July were available. In this regard, it is expected to have discrepancies regarding the real number of entries for each kind of vessel and, therefore, discrepancies in the sound level exposure calculated.

An important fact to point out is the effect that COVID-19 had on shipping volumes. From Figures 3.3 and 3.4, it is possible to observe a small decrease for cargo and tanker vessels, and a significant decrease for cruise ships, which at the time, ceased their activity completely. This fact could be treated as an outlier in our data set which can possibly distort statistical analyses. However, due to limited data on historical AIS retrieved through MEOPAR and due to the fact that cruise ships were not considered for the quantitative analysis, these values were not deleted.

5.4 Methodology Limitations

As stated in section 3, the process developed herein to predict future possible scenarios for the Canadian Arctic is supported by the comprehension of the various drivers and key forces affecting shipping activities and how they may unfold and interact between them. For that reason, it is important to assert that they are all sources of uncertainty and globally complex, i.e, their impact is not amenable to adjustment or mitigation through measures developed and applied exclusively within an Arctic context (Hodgson, 2014). The complexity of the drivers and trends makes it impossible to apply standard forecast methodologies, such as a time series for example.

Through identification of trends and critical uncertainties that drive Arctic shipping activities, this methodology used insights from experts and assumptions based on historical data. As stated before, due to time constraints, experts' opinions were collected from a limited number of industry contacts, creating possible tunnel-vision for their assumptions by focusing on trends within their own industry, generating a possibility of biased opinions towards what they might think it is better for their company, or what they want for the company.

5.5 Suitability of the process for decision makers and government bodies

The process developed in this study helps to better understand the potential risks from underwater noise created through shipping activity in order to provide governments and entities with a more comprehensive knowledge of shipping traffic effects and assist decision processes about new technologies to be developed, sustainable economic models to be created and most importantly the preservation of marine life.

The Government of Canada implemented in 2017 Canada's Oceans Protection Plan to ensure that commercial shipping is taking place in a way that is safe for mariners and that protects and sustains the economic, environmental, and social elements. One of the main points from the plan is the implementation of a real-time whale detection system in specific areas of the species' habitat to alert mariners of the presence of whales. However, underwater noise is not yet generally regulated under Canadian law or international law, therefore it is important that companies and stakeholders comply with options that were already implemented (voluntary guidelines (IMO, 2014)) in order to maintain safety guidelines (Transport Canada, 2020).

However, as ongoing studies are better assessing the effects of underwater noise in mammals, including showing that behavioral changes can be as dangerous as hearing loss (Halliday et al., 2018), and also studies have shown that the cumulative noise generated by a fleet may, in fact, exceed the threshold values proposed by NOAA, government bodies and institutions could consider the possibility of improvements in the Polar Code, as already stated by WWF, 2022. Making IMO 2014's guideline mandatory and better categorizing vessels according to their ability to withstand sea ice are examples of improvements to fill gaps found in current regulations.

While financial feasibility is a very important aspect for the maritime industry when applying new ship design technologies (as stated by VARD report)(Vard Marine Inc. et al., 2019), developing a code of conduct when transiting through National Marine Conservation Areas (NMCA) could help mitigate the spatial problem. Actions to be followed include reducing the speed of the vessel in such areas and maintaining a minimum distance from most whales.

5.6 Answers to the research questions

Answering the proposed questions in section 1.1, even though a correlation between historical data is apparent, results showed a significant difference with what experts assume will happen, concluding that analyzing one factor at a time and separately is not sufficient, and a deeper analysis should be done studying how all the drivers also relate and influence each other. The probability distribution functions for the individual SEL values for each zone and frequency showed a range of possible values for future underwater noise levels, considering what the experts assumed might happen, and the comparison between level of traffic and the cumulative (added) SEL values showed that an increase in shipping traffic numbers can imply an increase in underwater noise levels. The what-if analysis allowed us to understand how technology improvements in the shipbuilding industry together with voluntary slow down zones can affect underwater noise levels generated by ships. With a greater percentage of sound-abating technology to be implemented in the total future fleet, results showed an approximate reduction of 4dB in the mean of the cumulative (added) SEL. The speed reduction analysis made in Baffinland's case also reinforces the significance of the speed parameter on sound generated by vessels.

5.7 Suggestions for future research

This study put in place a process for analyzing possible future scenarios of maritime shipping traffic in the Arctic and, consequently, the underwater noise generated by the vessels. The outcomes of this work can provide governments and other entities a more comprehensive knowledge of shipping traffic effects to improve the plannings around the use of marine protected areas. However, since the proposed process analyses different, complex and unpredictable drivers such as shipping technology developments, trends in population growth, and trends in sea ice extension, more dedicated research is needed for how each of these elements influence each other before affecting the maritime traffic demand. An analysis of only one driver at a time, as done in this project, may not be enough to predict future scenarios, as each element does not act alone and it is very difficult for us to understand the implications of the confluence of these variables. Geopolitical factors, together with oil and gas prices are also essential parameters for the increase or decrease of this activity.

In order to better relate the traffic of re-supply vessels with population growth, a more detailed filtering can be done from the AIS system, examining the type of cargo and destination details, for example, so a more reliable relationship and forecast could be explored.

Further research should also focus on how the results can be applied to the policy-making process and identifying risk mitigation initiatives to reduce the impacts of not only underwater noise on marine mammals, but other stressors such as vessel strikes and oil discharges.

A future study can also include spatial and temporal modeling of underwater noise propagation along with a better estimation of the whales, and ice coverage location, offering possibilities to lower the uncertainties related to the current study. JASCO has already initiated such a study, in which a transmission loss projection for 2040 was estimated through a Parabolic Equation. This way, the impacts of noise on whales' behavior and physiology would be better understood. An extension from the JASCO modelling investigation would be to assess noise levels in other AIRSS zones that were shown to be more affected by projected transmission loss changes during winter months (Beaufort Sea, for example, referring to zone 1 from the AIRSS division).

One more improvement to the model when analyzing winter months would be an assessment of the noise levels generated by icebreakers when in activity. If a reduction in vessel speed becomes mandatory, vessels will likely need icebreaker escorts and the noise levels could be even higher.

6 Conclusion

As shown by the literature and historical data analysis, shipping traffic in the Arctic has increased significantly over the past decades, and it is likely to continue to do so into the future, as demonstrated by what experts in the community resupply, mining, and cruise industries estimated as future scenarios for the maritime traffic in the Canadian Arctic. Even though the analysis of some key influences for the shipping activity (population growth and GDP values) did not show a correspondence with what experts estimated, they should not be ignored, but studied in conjunction with other drivers, as for example, geopolitical factors, oil and gas prices, and regulations' limitations.

With the increase in the Arctic's maritime traffic, ship noise levels are rising concomitantly. As shown by the results, the values of the cumulative sound exposure levels (added altogether) are higher than the current ones, confirming that, despite all limitations imposed by the methodology, an increase in the shipping traffic also implies an increase in underwater generated noise.

Even though results did not show a great significance on noise reduction even given the possible mitigation means suggested by experts, the what-if analysis confirmed that, if a higher percentage of ships comply with these measures, the underwater noise level can notably decrease. Similar studies were done by Cook et al., 2020 for predictions of shipping noise in a range-dependent environment as well as by Giesbrecht, 2018 in which a probabilistic model was developed to calculate sound exposure levels from various types of vessels in the Tallurutiup Imanga National Marine Conservation Area (TINMCA). Nonetheless, this project adds the forecasting aspect to this subject using Monte Carlo simulation outputs for how these noise levels may evolve into the future, according to expert opinion so as to support a better utilization of marine protected areas while still contributing for a sustainable growth of the Arctic's economy.

In spite of the fact that the SLs, RLs and SELs herein calculated did not exceed the TTS threshold, this does not mean that marine mammals are not impacted by vessel noise. On the contrary, recent studies already showed a change of behavior for some species. In order to precisely understand and predict vessel noise risks to these three species more research is needed, especially when it comes to behavior and physiological changes.

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A Interviews' questions

All interviews are meant to solicit expert opinions that will help inform our maritime shipping forecasts and scenarios in the Canadian Arctic. However, the specific questions are geared to the expertise of the specific interviewee.

A.1 Northern Resupply companies

- Is it reasonable to think that there will be significant changes in the traffic system (volume) 20 years from now?
- Has the community re-supply activity seen a change in demand in the past decades? If so, can we relate the increase/decrease in demand with population growth and/or economic growth in the north (GDP)?
- Are there any other drivers/factors that significantly influence your activity?
- Are new ships being acquired recently, or are there any plans for fleet upgrade or renewal over the next 2 decades?
- If new ships are being acquired, do we have an increase in the fleet quantity (number of ships) or do we have an increase in the vessel size? (or both)

A.2 Cruise Industries

- Is it reasonable to think that there will be significant changes in the cruise shipping traffic system 20 years from now?
- What do you think was the main driver(s) for the increase in the traffic of cruise ships in the last decades?
- What are the main drivers that you think will influence the demand for arctic cruise ships in the future?
- Are arctic cruise trips becoming more affordable or more expensive (generally)?
- What factors are most important to analyze when trying to estimate the future fleet size?
- Has the ice-melting process facilitated the trips of cruise ships in the Arctic, as climate changing consequences are allowing new routes to be explored?
- Has the Arctic developed, in the last years, as a touristic destination (notwithstanding the COVID hiatus)? Do you think it will continue to do so?

- Do you think current regulations, especially regarding northern Indigenous communities and/or increasing environmental protection, will lead to a limit in cruise trips?
- How is cruise shipping technology changing to comply with regulations regarding pollution?