# Acoustic Modelling to Inform Policies: Mitigating Vessel Noise Impacts on Arctic Cetaceans Within the Tallurutiup Imanga National Marine Conservation Area

By

*Emma E. Giesbrecht*

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Vessel traffic throughout the Canadian Arctic has tripled over the past 20 years and is not expected to decline. With the recent announcement of the Tallurutiup Imanga National Marine Conservation Area (TINMCA), the three endemic Arctic cetacean species are protected from hydrocarbon development, but vessel traffic is still permitted. To understand the potential impacts shipping noise could have on cetaceans within the TINMCA boundaries, a probabilistic model was developed for each term in a simplified sonar equation. The received (RL) and sound exposure levels (SEL) were calculated using a probability distribution of source levels (SL) derived from four years of ship traffic data. The calculated SLs, RLs and SELs did not reach levels that could result in temporary hearing loss, termed as temporary threshold shift limits, which are set out by the National Oceanic and Atmospheric Administration. Due to limited studies conducted on these three cetacean populations it cannot be assumed that they are not impacted or disturbed by vessel noise. Modelling the spread of underwater noise from the vessels transiting through the TINMCA helps develop spatial and vessel management tools. These tools can be used to mitigate the risks associated with vessel noise and the three charismatic Arctic cetaceans.

*Keywords:* Arctic; cetaceans; beluga; narwhal; bowhead; underwater noise; acoustic modelling; Tallurutiup Imanga; NMCA; RL; SEL; impacts

# Glossary of Acronyms

AIS: Automatic Information System

ATBA: Areas To Be Avoided

dB: decibels

COSEWIC: Committee on the Status of Endangered Wildlife in Canada

EHABB: Eastern High Arctic-Baffin Bay (Beluga population)

ECWG: Eastern Canada-West Greenland (Bowhead population)

Hz: Hertz

IIBA: Inuit Impacts and Benefits Agreement

IMO: International Maritime Organization

IUCN: International Union for Conservation of Nature

kHz: kilohertz

MEOPAR: Marine Environmental Observation Prediction and Response

MMSI: Maritime Mobile Service Identity

NOAA: National Oceanic and Atmospheric Administration (United States)

NWP: Northwest Passage

NMCA: National Marine Conservation Area

NWMB: Nunavut Wildlife Management Board

RL: received level

SARA: Species at Risk Act

SEL: sound exposure level

SL: source level

SSL: synthetic source level

SPL: sound pressure level

SVP: sound velocity profile

TL: transmission loss

TTS: temporary threshold shift

TINMCA: Tallurutiup Imanga National Marine Conservation Area

# Glossary of Terms

Acoustic Intensity: The measured energy of a sound wave per second over a unit area, or Watts/m$^2$. Often converted to a logarithmic compression of values (decibels) with a reference level of acoustic pressure. In underwater environments, the intensity is measured in dB re 1 μPa (Perry, 1998).

Acoustic masking: The reduction of an animal's ability to detect biologically important sounds in the presence of noise. It may affect their communication, energy budget, behaviours and fitness, and thus their survival (Chen et al., 2017).

Acoustic pressure: The change in pressure due to the presence of sound, and the disturbance by the movement of sound can result in a force being exerted on a medium (Nolet, 2017).

Ambient sound: Natural background noises that are often generated through large ocean processes such as waves, wind, sediment movements, and rain (Willis, 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 & Stern, 2008).

Anthropogenic noise: Noise produced by human activities, such as shipping, mineral and hydrocarbon exploration and production, and construction (Erbe, 2012).

Broadband: Used as a reference to a sound signal that involves acoustic energy across a wide range of frequencies (DOSITS, 2017a).

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).

Frequency: The number of wave cycles per second, and the reciprocal of the time for which the wave repeats itself, measured in Hertz (Hz) (Bradley & Stern, 2008).

Received Level: The resulting energy of a sound signal or wave as 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 & Stern, 2008).

Reflection: When a sound wave bounces off an object/surface/barrier (Bradley & Stern, 2008).

Refraction: The ‘bending’ of sound waves towards regions of slower speeds, as dominated by the sound velocity profile (Farcas, Thompson, & Merchant, 2016).

Scattering Attenuation: When energy waves are caused to depart from a straight path due to imperfections in the medium. Can occur from a rough boundary (see reflection) or by particles suspended in the propagation medium. The change in direction causes an apparent weakening of the sound wave, as a fraction of the energy is no longer travelling to its intended target (Bradley & Stern, 2008).

Source Level: The intensities of sound waves produced from sources, measured as if the receiver was 1 m from the sound source. Often summarized into a broadband sound pressure level across some range of frequencies (Roth et al., 2013).

Sound: A mechanical disturbance that moves through a medium, such as water or air, by causing an increase or decrease in pressure over time at a fixed point in space; or over space, at a fixed moment in time. Sound travels as a compressional, or longitudinal wave through a medium (Bradley & Stern, 2008).

Sound exposure level: A measure of energy that takes into account both the received level and the duration of exposure (DOSITS, 2017c).

Sound pressure level: The sum of sound pressure within some band of frequencies, measured in dB re 1 µPa at 1 m in liquid mediums (DOSITS, 2017a).

Sound velocity profile: The speed of sound at various depths in the ocean, as influenced by temperature, salinity and pressure. Variations in the sound velocity profile help predict the path of sound travel through the water column (Bradley & Stern, 2008).

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, & Ménard, 2012).

Transmission Loss: The amount of energy intensity reduction in a sound signal, between the source and the receiver. It is often affected by absorption, reflection, refraction, scattering and reverberation (Bradley & Stern, 2008).

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There are a few people who I would like to thank and acknowledge for helping me complete this graduate project. First, thank you to my two supervisors, David Barclay and Ron Pelot, who have shown supreme patience for my many days of struggles and confusion. Thank you for believing that I could do this, and for helping me almost every step of the way. I would also like to thank Jenna Hare and Andrea Mast, for sitting with me and talking me through my MATLAB battles. What often took me days to figure out took you two only minutes, but the help I received from you both has been invaluable. I would also like to thank my family and friends for listening to unintelligible rants and cries over the phone, and telling me that I got myself into this and the only way to get out was to finish. So thank you for the tough love, it was much needed. And finally, I would like to dedicate this to 'Mater' with the hopes that this proves why I was unable to be home the last couple of months. Thank you all who have helped me and supported me these past few months, and a special thanks to WWF-Canada, specifically the Arctic division where I gained valuable information and experience.

# Chapter 1: Introduction

## 1.1 Tallurutiup Imanga

In the early 17th century on one of the first expeditions to try and find the fabled Northwest Passage (NWP) William Baffin, a British explorer, named a body of water after one of his financial supporters, Sir James Lancaster (Encyclopaedia Britannica, 2018). Lancaster Sound, located between Baffin Island and Devon Island, was initially thought to be a large ocean inlet and a dead-end, and for over 200 years thwarted many expeditions to find the route that led to the Pacific (Giamo, 2018). Although the British claimed that they had discovered, and thus owned this body of water, in reality this marine space was used for thousands of years by the Inuit, the indigenous peoples of the north (Mckenna, Savikataaq, & Akeeagok, 2017). The communities surrounding the body of water named the region Tallurutiup Imanga in Inuktitut; Tallurut for Devon Island and its rock formations resembling the tattooed chin of a woman, and Imanga meaning a body of water that surrounds an area (QIA, 2017). Tallurutiup Imanga ensured the cultural survival of the Inuit, and still plays a pivotal role in their daily lives, as it provides the food, materials and shelter needed to survive and thrive in such an extreme environment (Mckenna et al., 2017).

Tallurutiup Imanga has been identified as a 'super' ecological and biological significant marine area by the International Union for Conservation of Nature (IUCN), as this area provides nutrients and habitats for various Arctic micro and megafauna (Kenchington et al., 2011). In the winter months, the currents and bathymetry of the area generate highly productive nutrient upwelling sites, creating polynyas or ice-free zones. Polynyas provide critical feeding grounds for non-migratory seabirds and marine mammals such as polar bears (*Ursus maritimus*), ringed seals (*Pusa hispida*) and walrus (*Odobenus rosmarus*) (Clayden, Arsenault, Kidd, O'Driscoll, & Mallory, 2015). It is estimated that upwards of one million seabirds, over two thousand polar bears and five hundred walruses congregate in this region, feeding on the abundant marine life the area provides (Matley, Crawford, & Dick, 2012; Nunavut Wildlife Management Board, 2016; R. E. A. Stewart, Born, Dunn, Koski, & Ryan, 2014). In the spring and summer seasons, the nutrient rich surface waters spread further into the eastern regions of the High Arctic, attracting even larger aggregations of migratory seabirds and fish (Jones & Coote, 1980). Large charismatic megafauna can also be seen in the region, such as the three endemic Arctic cetaceans: the bowhead (*Balaena mysteicetus*), narwhal (*Monodon Monoceros*), and beluga (*Delphinapterus lencas*) whales (Cosens & Dueck, 1991; Heide-Jørgensen, Laidre, et al., 2003; Taylor, Laake, Mcloughlin, Cluff, & Messier, 2008). This 'ecological engine' of the Eastern Arctic has been important for Inuit culture for thousands of years and is also considered one of the last functionally pristine ecosystems in the world, leading Inuit communities to demand the protection of this area since the early 1970's (QIA, 2017).

In August of 2017, the Government of Canada, in partnership with the Qikqtani Inuit Association and the Government of Nunavut, announced the boundaries for the Tallurutiup Imanga National Marine Conservation Area (TINMCA), creating the largest protected area in the country (Figure 1; Frizzell, 2017; Kylie, 2017). Tallurutiup Imanga alone covers 40,000 km$^2$ of marine space, but the boundaries for the TINMCA were

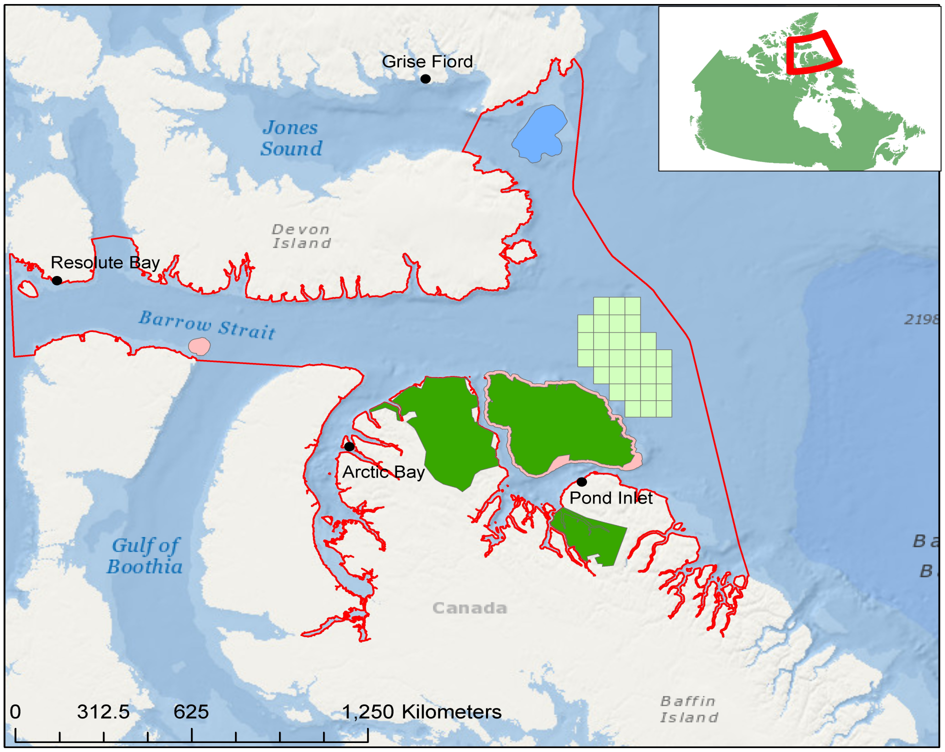

*Figure 1. The location of the Tallurutiup Imanga National Marine Conservation Area and surrounding communities. Combined with Sirmilik National Park (green), Prince Leopold and Bylot Island Migratory Bird Sanctuaries (pink), and the Nirjutiqavvik National Wildlife Area (blue), the total area that is protected combines to 131,000 km$^2$. The light green polygon in the eastern portion of the NMCA was the oil and gas exploration licenses that were gifted to Parks Canada (Data from WWF Canada and DFO).*

expanded to 110,000 $km^2$, covering areas previously prevented from receiving the protection of the TINMCA designation due to hydrocarbon exploration licenses. Furthermore, TINMCA adjoins the already established Sirmilik National Park, Prince Leopold and Bylot Island Migratory Bird Sanctuaries, and the Nirjutiqavvik National Wildlife Area, bringing the total protected area to 131,000 $km^2$, equivalent to 1.9% of Canada's oceans.

### *1.1.1 National Marine Conservation Areas*

National marine conservations areas (NMCAs) are markedly different from marine protected areas, and even national parks. The latter aim at protecting an ecosystem from the damage of human activity, often by closing off areas in an attempt to conserve a system in its current, and hopefully unaltered, state (Parks Canada, 2017). The purpose of an NMCA on the other hand, is to harmonize human activities with conservation practices, and therefore supports the ecologically sustainable use of the ecosystem (Government of Canada, 2015). The various human activities that are permitted within the boundaries of an NMCA include recreational and commercial fishing and shipping, as well as tourism and traditional cultural practices. Certain activities are still prohibited within an NMCA, such as ocean dumping, undersea mining, oil and gas exploration, and natural resource development.

Since only the boundaries were announced for the TINMCA, it is not yet an official protected area. Before its designation, the three governing bodies mentioned above need to develop an Inuit Impacts and Benefits Agreement (IIBA), which provides Inuit with the opportunities to secure benefits and identify detrimental impacts from the establishment, planning and management of conservation areas in the Nunavut Settlement Area (Government of Nunavut, 1993). Once the IIBA is created and agreed upon, which is expected to occur in early 2019, the TINMCA can officially be designated. This will ensure the protection of all waters and undersea areas, meaning from the seabed, its subsoil and the overlying water column; as well as any submerged lands or islands within the boundaries. An interim management plan will also be announced during the designation process, which will include initial zoning plans for the conservation area. In Canada, NMCAs are required to have at least one zone that encourages the sustainable use of the marine resource, such as recreational hunting and fishing, and at least one smaller zone that fully protects special features or sensitive elements of the ecosystem through a ‘no-take’ directive (Government of Canada, 2015). It is important to note that the TINMCA zones and management plans have yet to be developed and there are no limitations to zone sizes, resulting in the unique opportunity to ensure the sustainable use and protection of this highly productive and important ecosystem.

One of the major threats to the TINMCA is Arctic shipping; a relatively novel phenomenon since sea ice thickness and remoteness has previously deterred most vessels from transiting through the NWP. However, with the declining sea-ice extents the shipping season in the Canadian Arctic has extended. This has resulted in the doubling of Arctic shipping traffic through the NWP within the past decade, a phenomenon that is only expected to increase (Dawson, Pizzolato, Howell, Copland, & Johnston, 2018; Gascard et al., 2017). Additionally, since the TINMCA encourages sustainable shipping to occur within its boundaries, it is imperative that shipping impacts to the marine environment are mitigated, perhaps especially impacts on the three cetaceans. Recent literature has identified that more than half of the endemic Arctic marine mammals are vulnerable to vessel impacts, with the three Arctic cetacean populations in Tallurtiup Imanga being some of the most susceptible (Hauser, Laidre, Stern, & Franklin, 2018).

## 1.2 Management Problem and Research Objectives

Until recently the Arctic has been considered an acoustic refuge from shipping noises, but growing numbers of studies have speculated that the introduction of anthropogenic noise from increased shipping to the Arctic soundscape could be one of the greatest long-term threats to Arctic cetaceans living within this region (McWhinnie, Halliday, Insley, Hilliard, & Canessa, 2018; Reeves, Rosa, George, Sheffield, & Moore, 2012). All three endemic Arctic whales can be found within the TINMCA, where they have recognized annual calving and foraging grounds (Higdon, 2017). These species also rely on acoustics for communication, prey capture and survival, all of which could be seriously impacted by increasing vessel traffic (Lesage, Barrette, Kingsley, & Sjare, 1999). It is therefore important for marine conservation managers to recognize the concerns related to vessel noise, as well as the potential impacts, in order to better mitigate them through the upcoming interim management plan.

In order to understand these risks, a simulation was developed in an attempt to determine the intensities produced by vessels transiting through the TINMCA. Using a simplified sonar equation, and available data, intensities that reached the locations of the three cetaceans at two different frequencies were calculated and compared to physical damage thresholds to the mammals. By modelling the probability distribution of intensities heard by the three whales, managers can be informed of these potential impacts, and thus can develop realistic and applicable management recommendations to mitigate these effects. In other words, informed managers can create effective management regulations, which benefit both the stakeholders and charismatic cetaceans that inhabit the TINMCA.

# Chapter 2: Underwater Sound Propagation

## 2.1 The Physics of Sound

To understand why underwater noise poses such a significant threat to the Arctic environment, and specifically to the three whale species found in the TINMCA, it is necessary to start with the basics. Sound is defined as a mechanical or physical disturbance, otherwise known as energy, that travels through a medium and causes a rapid change in pressure over time (Bradley & Stern, 2008). This change in pressure is called the acoustic pressure, and the disturbance caused by the movement of sound can result in a force being exerted on a medium. The rapid pressure changes results in the sound disturbance moving as a longitudinal or compressional wave, resulting in the transfer of energy in a uniform direction (Nolet, 2017). It is important to mention that the individual particles of the medium do not travel with the sound wave, instead they vibrate back and forth, centered on a single point called the equilibrium position (DOSITS, 2017d). If a source of sound is present, the wave causes the individual particles to contract in areas of high pressure and expand in areas of low pressure; these alternating areas of compressions and rarefactions causes the sound wave to propagate forward through the medium (Figure 2).

The maximum change in acoustic pressure is called the amplitude, or peak pressure, and is often measured as the height of a sound wave. Alternatively, the energy stored in a sound wave is referred to as the acoustic intensity, and is a measure of energy per second over a unit area, or Watts/m$^2$. Due to the high degree of fluctuations in acoustic intensity, researchers often use a logarithmic scale to create reference values that are easier to manipulate and understand. For both acoustic pressure and intensity, the transformation involves dividing the absolute value by a reference value, and taking the logarithm of the result. Intensity level can therefore refer to sound pressure when squared (Bradley & Stern, 2008). This unit of measurement can be defined as one tenth (deci-) of one bel (B), or the decibel (dB), and is a logarithmic way of describing large power, or sound intensity, in numbers of modest size (Perry, 1998). In underwater environments, the reference intensity or sound pressure is measured as dB re 1 μPa. Thus, the amplitude is measured as the height of a wave at a given time, while the intensity is the amount of energy in a wave passing through a specific area during a given time. A sound is therefore perceived to be louder when the associated pressure wave has large amplitude, and thus more energy and intensity; and softer if the amplitude decreases, meaning there is less energy and intensity.

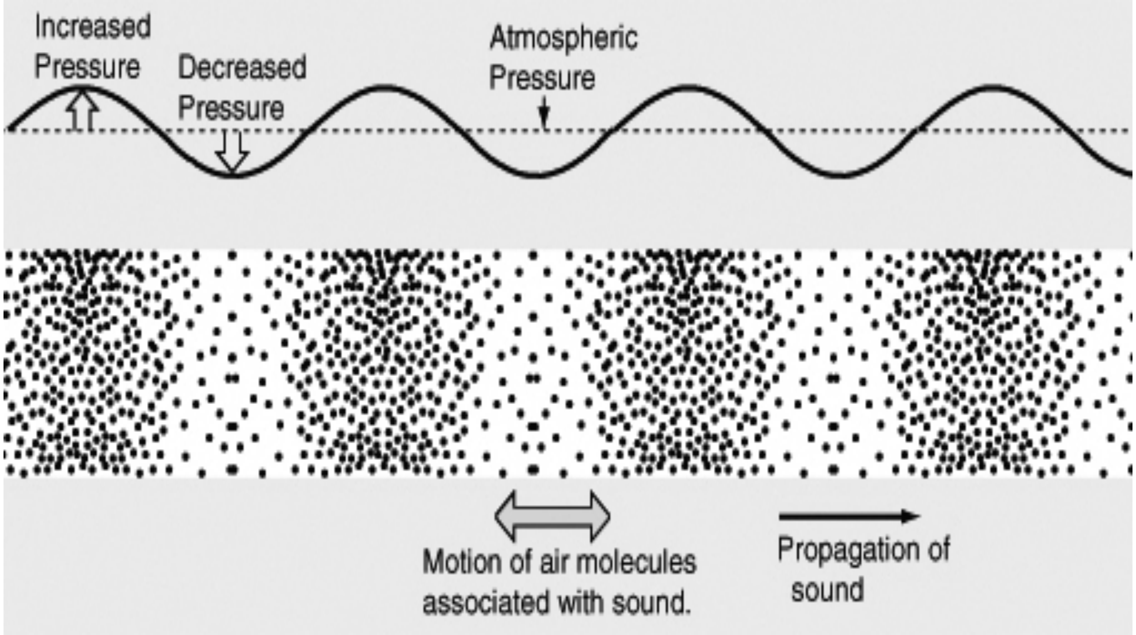

*Figure 2. Sound is often described as a wave, or acoustic wave, travelling through a medium in a uniform direction. In high pressure areas, caused by the disturbance of the wave, the individual particles of the medium contract, or compress; and in areas of low pressure the particles undergo rarefaction, or expansion. This contraction and expansion propels the wave forward, but not the particles in a medium (IRCAM, 2014).*

Since a wave has a repeating pattern, one complete repetition of the pattern is defined as a cycle, and the time needed to complete this cycle is the period (T). The distance that the sound wave travels in a single period is called the wavelength (λ) and is thus related to the speed at which sound travels (*c*) ($\lambda = c/f$ and $f = 1/T$ ; Nolet, 2017). A single wavelength can be measured as the distance (in meters, m) between two crests, or areas of high amplitude, or two troughs. The frequency (*f*) of a wavelength is described as the number of wave cycles per second and is measured in Hertz (Hz). A low frequency wave means that there is a larger wavelength and thus fewer cycles in a second, and is often described as a lower-pitched sound. Higher frequencies mean that there are more cycles in a second due to the fact that the wavelengths are small, and are described as having higher pitches.

### *2.1.1 Sound Spreading and Scattering*

In its simplest form, sound is described as a single wave travelling through a medium. In reality, it is a continuum of outward propagating waves spreading from a source, all the while distributing a fixed amount of energy over a larger and larger spherical area (Veirs, Veirs, & Wood, 2016). This geometric spreading results in the weakening of the sound due to the spread of energy over an increasing distance, but there is no net loss in energy. Spherical spreading can occur in deep water, but in shallow waters such as the littoral zone, more variability is added by the presence of boundaries. These boundaries constrain sound propagation into a waveguide, where losses are instead characterized by cylindrical spreading. These constraints result in lower spreading loss, as the energy stored in the sound waves have relatively less space, resulting in the energy being stored and maintained for longer distances (Bradley & Stern, 2008). However, since the seafloor and surface are rarely flat or barren, these rough surfaces can result in the sound wave being reflected away from the barrier. Additionally, because seawater itself is an imperfect medium, the suspended particles can also cause sound waves to depart from their intended straight path resulting in a fraction of energy being dissipated, a phenomenon termed scattering attenuation (Bradley & Stern, 2008).

Frequencies and wavelengths of a sound signal can also influence how much scattering will occur. In general, significant scattering will result when the object or barrier is bigger than the wavelength (Farcas et al., 2016). In the instance of low frequencies, generally between 1 to 4800 Hz, wavelengths range from 10 to 150 m, meaning that any obstacle smaller than these wavelengths will not impede the direction of the sound wave (National Marine Fisheries Service, 2018; Nolet, 2017). In instances of mid to high frequencies, generally 4.8 to 59 kHz, wavelengths vary from 10 to 0.01 m, and thus smaller natural obstacles can cause a sound wave to scatter much more readily in the ocean environment. This phenomenon is especially important to consider when looking at the distances various frequencies can travel in a medium. Due to the high degree of scattering in mid to high frequencies, the sound waves have more energy attenuation, severely limiting the distance of propagation. Lower frequencies on the other hand, can travel hundreds and even thousands of kilometers due to the limited number of large obstacles present in the ocean environment, thus minimizing the degree of energy loss during its propagation (Perry, 1998).

## 2.2 Wave Refraction and the Arctic Marine Environment

Although sound waves have the same underlying physics in water and air, the way sound travels through these mediums are very different. The density of water is much greater than the density of air, which causes the water particles to be closer together, thus allowing for a quick transmission, or movement, of sound energy (Farcas et al., 2016). The higher pressure results in sound waves being able to travel over four times faster in liquid mediums compared to gases, approximately 1,484 m/s in seawater compared to 343 m/s in air. Unfortunately, the speed of sound in marine environments is not a constant value, and rarely will sound travel in a straight line. Acoustic waves, and thus their speed, are influenced by the physical parameters of the ocean, with temperature being the most important factor, followed by water depth and salinity. The speed of sound at various depths in the ocean is called the sound velocity profile (SVP), and the variations in the sound velocity plays a major role in predicting the path that sound takes as it travels through this medium (Bradley & Stern, 2008).

When sound waves travel through the water column and encounter changes in the sound speed they become refracted, bending towards either the surface or the seafloor depending on the physical property that is prevailing at the depth of transmission (Farcas et al., 2016). It is important to note that the refraction of a sound wave will always be directed towards regions of slower speeds, as these are areas with slower moving water particles and thus become the limiting factor in the propagation of the wave. Since physical oceanographic properties are not in isolation from one another, each of the three parameters (temperature, depth and salinity) influence sound waves in the same moment of time, but with differing strengths. In deep open oceans at mid-latitudes these three parameters follow the SVP shown in Figure 3 quite closely, and when they all influence the refraction of sound it results in an area where there is a sound speed minimum. At roughly 1000 meters in depth, the temperature of the water column is at its lowest, and pressure and salinity begin to take over as the major factors for sound wave refraction (Figure 3). This means that sound waves travel much slower at this depth than in the surrounding water column due to the lower temperature, and also because this is the depth at which salinity and pressure are relatively minor factors compared to deeper areas. This results in a phenomenon called the sound channel, which allows low frequency sounds to travel exceptionally large distances throughout the ocean environment, with very little energy loss.

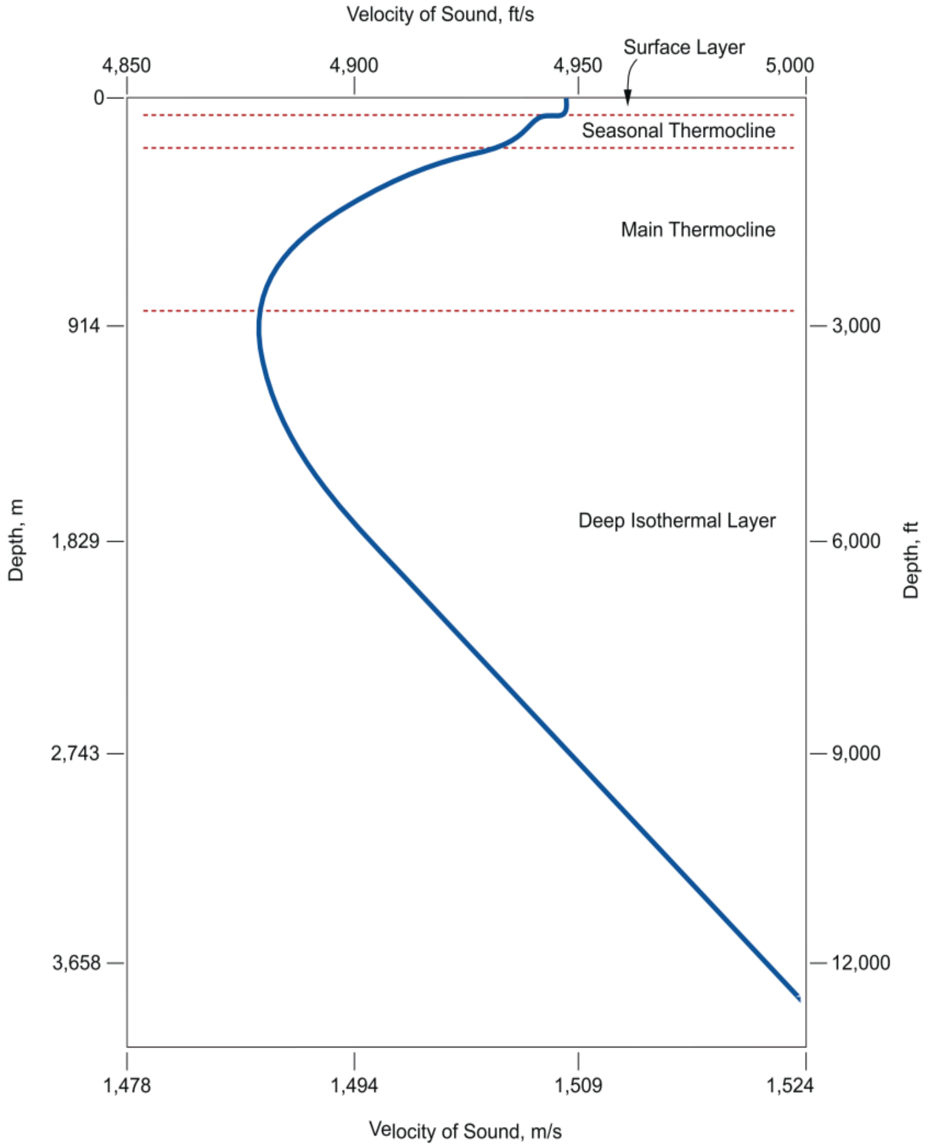

*Figure 3. The refraction, or bending, of a sound wave through a temperate water column. For the first few hundred meters, temperature plays a dominant role on the speed of sound, with faster velocities at warmer temperatures where particles have more energy. Beyond roughly 1000 meters, pressure and salinity begin to influence sound more, as the temperature undergoes a thermocline. The sound channel in these oceans occurs at depths averaging 1000 meters (DOSITS, 2017b).*

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. Focusing on the Arctic Ocean, the limited water exchange with surrounding ocean bodies results in the water column having a nearly uniform temperature and salinity, especially beyond the first few meters below the surface (Gavrilov & Mikhalevsky, 2017). Thus, the increase in pressure with increasing depths tends to be the dominant oceanographic variable affecting the sound speed in polar areas, which results in a somewhat uniform upward refraction of sound waves towards the surface. Additionally, the presence of ice in the Arctic increases the scattering and reflection effects on sound waves. This means that in polar regions, propagation of sound is characterized as upward refraction and surface reflection, and the rough ice surface accounts for both forward and back-scatter reflections (Mellen & Marsh, 1965).

The continued refraction towards the surface, and subsequent scattering results in a near-surface channel, which is comparatively similar to the deep-water sound channel described above in temperate oceans. Under ice, energy loss from spreading is increased dramatically when the sound pathway includes water-ice reflections, and the loss rapidly increases with higher frequencies and ice thicknesses (Roth et al., 2013). Thus, when the loss is combined with the SVP of the Arctic Ocean, sound waves are relatively constrained to the first 250 meters of the water column. This near-surface sound channel is specific to ice-covered waters, as the temperatures, pressures and salinities are lower near ice and thus the sound speed minimum occurs in these shallower depths. In regions where there is less ice coverage, the SVP begins to shift towards mid-latitude profiles, as the temperatures near the surface become warmer than the underlying water column. This shift results in a second sound channel located in deeper depths, though it is not nearly as strong as the near-surface sound channel above it (Gavrilov & Mikhalevsky, 2017). These two sound channels have major implications for how acoustic signals propagate through the Arctic Ocean, which also influences how marine organisms and researchers use these sound channels for communication and exploration.

### 2.3 Anthropogenic Noise Sources

In general, acoustic signals that are generated with a purpose and are therefore useful are defined as sounds, whereas acoustic waves generated with no purpose or that lack useful information are labeled noises (Tavolga, 2012). Anthropogenic noises are acoustic waves that are created from human activities, and often have dramatic effects on the surrounding acoustic environment. Sources of anthropogenic noise in the marine environment include but are not limited to: marine vessels; sonar activities; construction zones, which can come from building bridges, offshore windfarms, or oil and gas farm installations; pile driving, digging and dredging activities; and underwater explosions, including seismic testing (Nabi et al., 2018). Of these, the most prominent and widespread source of underwater anthropogenic noise comes from the transportation industry, which includes a range of vessels from cargo ships to yachts, and to cruise ships and icebreakers (Halliday, Insley, Hilliard, de Jong, & Pine, 2017; McDonald, Hildebrand, & Wiggins, 2006).

In general, the majority of sound waves produced by vessels originate from propeller cavitation, but hull and mechanical vibrations can also create noise (Nowacek, Thorne, Johnston, & Tyack, 2007). Cavitation refers to the generation of vapour bubbles, or cavities, within the water when the local water pressure is reduced below the vapour pressure limit (Spence & Fischer, 2017). These bubbles are often visible, especially when cavitation is fully developed, or when there is substantially more disturbance. When a propeller blade rotates through the water, one side creates suction while a positive pressure or force is created on the other side, which results in a pressure difference that propels a ship. Cavitation can form at different points or areas of propeller blades, based on its design or profile, and can even form on the propeller hub or hull appendages. These various forms of cavitation will have different noise impacts, since the cavitation bubbles form and collapse rapidly, generating noises with high intensities and broad frequency ranges (Spence & Fischer, 2017). Propellers that are cavitating heavily will often mask, or overpower, machinery-produced noise, which is created by a combination of the machinery's vibration, and the airborne noise within the machinery space.

There are three main paths of concern for underwater noise in ships produced by machinery: airborne, first structure-borne, and secondary structure-borne (Spence &

Fischer, 2017). The airborne path results in noise penetrating the ship's hull when a machinery item is located in a compartment adjacent to the surrounding water column. The airborne-to-underwater 'transmission loss' of the hull is used to quantify the amount of noise that radiates into the water for a particular airborne noise level. The first structureborne path relates to vibration that is imparted directly to the foundation by the machinery item. This vibration travels through all structures of the vessel, including the hull, which in turn creates underwater noise. The secondary structureborne path is a combination of the airborne and first structureborne paths, where airborne noise that is created by the machinery will enter all structural surfaces of the machinery space causing them to vibrate. This will then be transmitted to all structures of the vessel, including the hull, where it is radiated as underwater noise. Often, larger machinery items such as propulsion engines, turbines, diesel generator sets, and other large equipment items will tend to have the greatest influence on underwater noise.

The intensities and frequencies of the sound waves produced by ships and propeller cavitation also depend on the ship characteristics, such as its length, breadth, draught, speed and category (Aulanier, Simard, Roy, Gervaise, & Bandet, 2016). The intensities of sound waves produced from these sources are termed source levels (SL), and the geometric spreading and subsequent energy loss of the sound waves depend on the bathymetry, temperature and pressure of the surrounding water column (Aulanier, Simard, Roy, Gervaise, & Bandet, 2017) as described earlier. The lengths and builds of ships also help to determine the SLs and frequencies through calculations, which allow researchers to group different vessels into intensity classifications. For example, ships that are less than 100 meters in length on average have engines and propellers that emit 10 to 100 Hz frequencies depending on speed, and have SL intensities of about 150 dB re 1 μPa (Aulanier et al., 2016). When combining a model of the SL's frequency characteristics with oceanographic parameters and an underwater sound propagation model, researchers can then model the acoustic footprint of the vessel.

# Chapter 3: Arctic Cetaceans

## 3.1 Bowhead Whales

Bowhead whales are the gentle giants of the Arctic ocean and are the only mysticete, or baleen whale, endemic to the region (Darnis et al., 2012). The population of bowhead whales in the Baffin Bay and Davis Strait area numbered well over 12,000 individuals in the 1500's but was severely depleted by commercial whalers before the start of the 20th century (Heide-Jørgensen, Laidre, et al., 2003). Today the Eastern Canada-West Greenland (ECWG) population is estimated at around 6,000 individuals, but their longevity of 160 to almost 200 years, combined with low birthing rates, still puts this population in jeopardy (DFO, 2017). To compound their survivability further, bowheads are slow swimming large baleen whales, making them vulnerable to predation from killer whales and human activities such as shipping and subsistence hunting. Although the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the bowhead as special concern, the whale is currently not protected or listed under the *Species at Risk Act* (SARA), a designation that would initiate the development of a management plan for the conservation of the species (DFO, 2017; SARA, 2015). While lacking this form of extra protection, it is still critical for scientists, Inuit and managers to understand the bowhead whales' life history and identify any important areas for the continued survival and health of the species.

Like other large baleen whales, bowheads are a migratory species, although the scale and nature of bowhead movements in the four different Arctic subpopulations seem to vary locally or regionally (Reeves et al., 2013). For the ECWG population, individuals are believed to spend the winter in Hudson Strait and northern Hudson Bay, or along the pack-ice edge extending to coastal West Greenland (Heide-Jørgensen, Laidre, Jensen, Dueck, & Postma, 2006). In spring, bowhead whales have been tracked migrating to West Greenland, specifically Disko Bay, and continuing on to the TINMCA boundaries for the summer months of June to September (Heide-Jørgensen, Laidre, et al., 2003; Heide-Jørgensen et al., 2006; Reeves et al., 2013). Historically, bowhead whales have not been frequently observed in Tallurutiup Imanga, and only within the past few decades have they been seen in larger numbers by the Inuit communities there (NWMB, 2000).

Their migration patterns often follow the seasonal concentrations of benthic, epibenthic and pelagic species, such as zooplankton, copepods, amphipods and mysids, and the changing bloom locations could possibly explain why they have been frequenting the TINMCA boundaries more recently (Pomerleau, Ferguson, & Walkusz, 2011). Feeding behaviours also seem to vary seasonally and regionally, as summer dive depths recorded in the TINMCA region have shown that the number of shallower dives, generally less than 36 m, significantly increase after June; and deep dive depths of over 200 m increased when the whale was located in Baffin Bay (Heide-Jørgensen, Laidre, et al., 2003). In this study it was also noted that the whales spent approximately 81% of their time above the 20 m water depth line, and over 90% of its time above 50 m depths. This is significant especially since vessels very rarely exceed a 10 m draught, meaning that while bowheads are within the TINMCA boundaries there is a higher possibility that both bowheads and ships are within the same portion of the water column.

One possible reason why bowheads stay above the 50 m water depth in the TINMCA could be due to their social behaviours and vocalizations. Bowheads have three main sounds: moans, warbles and trumpets; that span lower broadband frequencies of 25 to 4000 Hz (Figure 4; Cummings & Holliday, 1987). Moans are relatively low frequency tonal sounds which last for about 2.5 seconds and range from 25-900 Hz with an average intensity of 159 dB. Warbles can extend up to 910 Hz with the most intensity around 400 Hz, and range from 152-169 dB; and trumpets or songs can extend above 4000 Hz (4 kHz), with the first phrase of each song being higher in frequency and more pulsive, with intensities averaging around 177 dB.

The functions of bowhead sounds and vocalizations are unfortunately poorly understood, but of the few studies that have researched bowhead behaviour and potential call relationships, some interesting observations have been found. For example, bowhead surface activity, which as mentioned previously constitutes over 80% of their swimming behaviours, usually includes socializing and sexual behaviours. These behaviours have been observed to be accompanied with long pulsed tonal calls that are focused on the lower frequency spectrum, specifically from 25 to 200 Hz (Richardson, Finley, Miller, Davis, & Koski, 1995). Additionally, this study observed that the time at the surface was higher for bowhead whales feeding in deep water, identified as depths over 50 m, with speculation that this is due to recovery periods after feeding. Associating this with the bathymetry in Tallurutiup Imanga, which has depths up to 1000 m, it can be inferred that bowheads in this area spend the vast majority of their time at the surface, socializing and recovering from feeding dives.

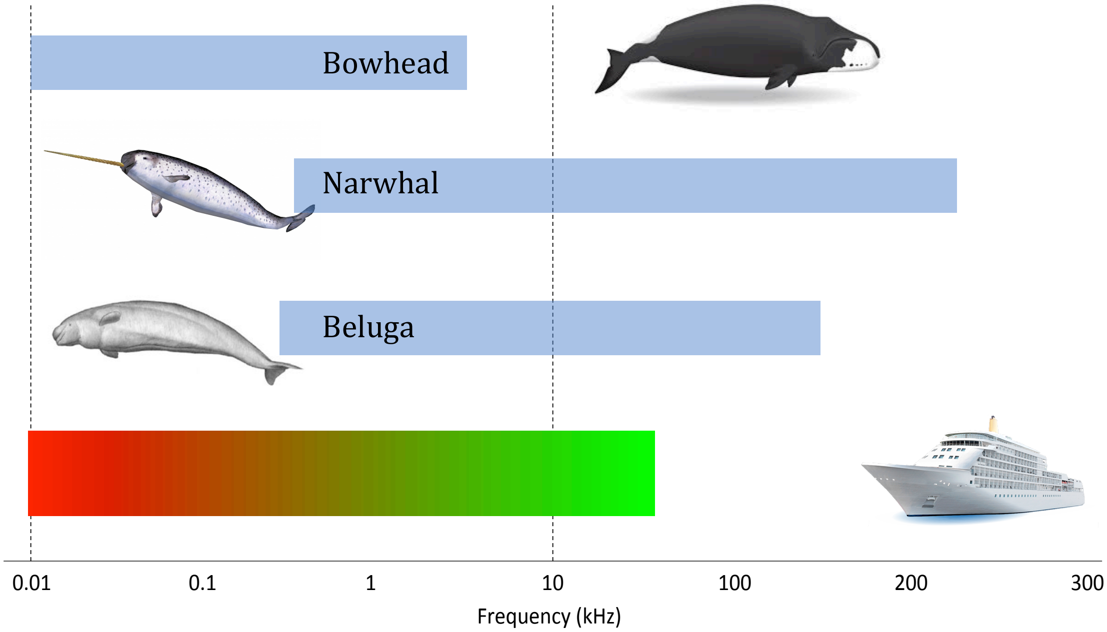

*Figure 4. Broadband communication and echolocation frequencies of the three endemic Arctic cetaceans, adapted from Cummings & Holliday, 1987; Panova et al., 2012; Watt, Orr & Ferguson, 2017. Shipping noise spans a large range of frequencies, but the highest intensities are measured at low frequencies, often below 200 Hz, and the intensity and frequency range of vessels can lead to behavioural changes in cetaceans, as well as the possibility of masking whale vocalizations and communication calls.*

Social activities at the surface may also be related to the presence of young, since bowhead calves are generally born between April and early June during the spring migration. Inuit have recorded seeing the bowheads that enter Pond Inlet during the summer months are usually mother and calf pairs, and large adults (NWMB, 2000). Bowhead whales seem to have a wide distribution within the TINMCA boundaries, seeming to prefer these inshore waters to the open Baffin Bay region, possibly for both feeding and predation avoidance. It is also believed that bowheads migrate through Tallurutiup Imanga, preferring to feed and concentrate in the Gulf of Boothia just south of the TINMCA boundaries during the summer months, though this movement is limited by the receding ice-extent (NWMB, 2000). For these reasons, there are no fully identified and agreed upon areas of bowhead concentrations within the TINMCA boundaries, even though bowheads have been observed in this area with increasing regularity. This leaves managers and scientists to accept that this water body is well within the bowhead range, though more research is needed to determine the possibility of important foraging and calf rearing areas within Tallurutiup Imanga (Figure 5).

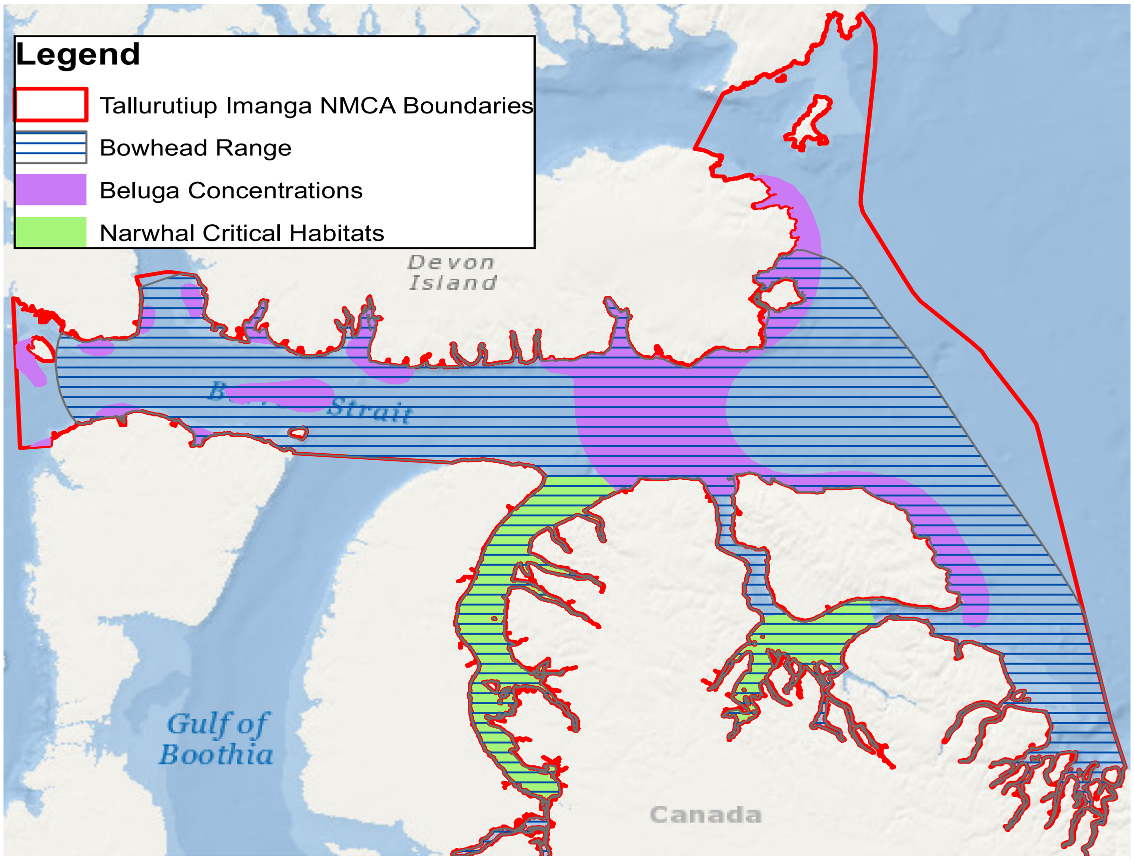

*Figure 5. The identified concentration areas of three cetaceans within the TINMCA boundaries provided by WWF-Canada and created by Higdon (2017). Due to a lack of scientific studies identifying bowhead areas of concentration, it was assumed that there was a uniform probability of where the whale would be located in the TINMCA boundaries.*

### 3.2 Narwhals

Historically nicknamed the unicorns of the sea, narwhals are one of the most unique cetaceans in the world. Easily identifiable by the male's large spiral ivory tusk, narwhals are fairly social whales, often seen in pods of approximately 5 to 500 individuals depending on the season (COSEWIC, 2005). There are two distinct Canadian populations, the Baffin Bay and Northern Hudson Bay populations, with a third thought to be endemic only to Eastern Greenland. Narwhals seen in the TINMCA boundaries during the summer months, generally between May to October, are believed to be a part of the Baffin Bay population, which winter in Baffin Bay and Davis Strait (Heide-Jørgensen, Dietz, et al., 2003). Important to traditional Inuit subsistence hunting as well as the economy for the eastern Canadian Arctic, the Baffin Bay population is considered to be relatively healthy in numbers, though there is still some uncertainty regarding life history parameters and the appropriate hunting levels to ensure the sustainable harvest of this species (COSEWIC, 2005). For this reason narwhals are considered as special concern under COSEWIC as managers are unsure of the potential impacts that continued harvests will have when compounded with additional threats, such as climate change, commercial fishing and shipping interactions. Although listed under COSEWIC, the narwhal has no status under SARA making a management plan on the federal level unavailable, and instead co-management of the species falls under the Nunavut Wildlife Management Board (NWMB) and the Department of Fisheries and Oceans.

The importance of the species to Inuit communities has led scientists to try and identify important areas, which will ensure better conservation and management of the population. Since narwhals are odontocetes, or toothed whales, the species is carnivorous with their summer diet primarily consisting of Arctic cod (*Boreogadus saida*; Matley, Fisk, & Dick, 2015). This essential prey species gathers in large schools near shore, often in depressions of bays at approximately 350 to 500 m depth where they feed on zooplankton and copepods (Majewski et al., 2016; Welch, Crawford, & Hop, 1993). Male narwhals have been observed to gain weight in these Arctic cod concentration areas, but females lose blubber over the course of the summer in these locations suggesting that the summer habitat selection in the TINMCA boundaries is related more towards calving requirements rather than feeding requirements (Higdon, 2017). The majority of narwhal calves are born in July and August in inlets, bays and fjords, which also correlate to Arctic cod concentrations (Hay, 1984). For these reasons, scientists and Inuit have identified that Eclipse Sound and the waters surrounding Bylot Island in TINMCA boundaries are key habitats for the narwhal, where they return annually for both foraging and calving activities in the ice-free summer months (Figure 5).

Narwhal diving and vocalization for the Baffin Bay population has also been studied, with a significant number of dives taking place between the surface and a quarter of total water depths, and fewer dives at greater depths reaching to the seafloor (Watt, Orr, & Ferguson, 2017; Watt, Orr, Heide-Jørgensen, Nielsen, & Ferguson, 2015). Furthermore, narwhals made more dives in the upper water column, or depths shallower than 100 m in the summer months than in any other season. Their location in the water column has been associated with three different vocalizations; pulsed sounds or calls, which are associated with intraspecies communication; as well as clicks and buzzes/whistles, which are linked with feeding, orientation and echolocation behaviours (Ford & Fisher, 1978; Watt et al., 2017).

Pulsed sounds comprise discrete, short duration and repetitive calls, with frequencies concentrated in two bands; from 0.5 to 5 kHz and from 12 to 24 kHz. Clicks range in frequencies of 12 to 69 kHz, and buzzes or whistles range from 300 Hz to 10 kHz (Figure 4). Due to their preference for deep-water prey where there is little light, narwhals have been recorded clicking and buzzing in deeper water depths, often between 170 m to 400 m (Watt et al., 2017). Narwhals spend the majority of their time, approximately 51-86%, at the surface or above 50 m depths, and of which 44-70% in the top 7 m producing calls and socializing at frequencies between 500 to 5000 Hz. From the information provided above, and taking into account the average draught and intensity levels emitted from vessels, it can be inferred that shipping noise will have impacts on narwhal socialization and behaviour, though the extent of this damage will be discussed further in this report.

### 3.3 Beluga Whales

The third cetacean endemic to the Arctic, and consistently seen in the TINMCA boundaries, is the white whale, also known as the beluga. These highly social odontocetes are identifiable by their ivory colour and are often seen in large pods containing 10 or more individuals (Cosens & Dueck, 1991). There are seven populations of beluga whales in Canadian waters, of which only one returns annually to Tallurutiup Imanga, namely the Eastern High Arctic-Baffin Bay (EHABB) population (COSEWIC, 2004). With an estimated size of 20,000 individuals, this population spends the winter months in West

Greenland and the summer months, generally between April and August, in the coastal and river estuaries on the west end of the TINMCA boundary (Figure 5). While in their wintering grounds there is a higher instance of mortality, often via subsistence hunts or ice entrapments, which resulted in COSEWIC designating this species as special concern, though it has no status under SARA (COSEWIC, 2004). Furthermore, the species is highly repetitive in its annual migration patterns and areas of concentration, returning year after year to the same spot in large numbers, further putting this species at risk from predation and shipping (Hauser et al., 2018).

Although the dominant prey of beluga is Arctic cod, the observations that belugas arrive in the TINMCA area with higher fat concentrations than when they leave suggest that they do not enter Tallurutiup Imanga for solely foraging reasons (Matley et al., 2015; D. Stewart, 2001). Belugas often have calves in tow by the time they enter the area, thus it is assumed that they use the waters for calf rearing and nursing activities, as well as for molting (COSEWIC, 2004). Diving behaviours of the EHABB populations have shown that during the summer months belugas tend to treat the majority of the water column as dead space, preferring to stay on the surface for socializing and travel or diving to the seafloor for foraging (Martin, Smith, & Cox, 1998). Belugas spend approximately 40-60% of their time socializing and interacting, which takes place at the surface waters between 15 and 40 m in depth (Lefebvre, Lesage, Michaud, & Humphries, 2018; Martin et al., 1998). During this period, they have been recorded producing various vocalizations ranging from 400 Hz to 22 kHz, with emphasis on bleating, vowels and pulsed tonal signals that range from 400 Hz to 2000 Hz (Figure 4; Panova, Belikov, Agafonov, & Bel'kovich, 2012). The other percentage of their time is spent foraging and travelling, with approximately 35% in depths over 40 m and 15% at the seafloor. Thus, vessel noise could potentially have impacts on beluga socialization and communication frequencies and behaviours, a possibility that will be assessed further on.

# Chapter 4: Acoustic Modelling

## 4.1 Modelling Methods

In order to understand and mitigate the potential impacts shipping noise could have on the cetaceans within the TINMCA boundaries, a probabilistic model was developed for each term in a simplified sonar equation ($RL = SL - TL$). The purpose of the model was to provide a probability of the received intensity level (RL), or what the whale would hear, using a probability distribution of SLs derived from four years of observed ship traffic data, including vessel type, speed, and draught in the region of interest. A probability distribution of transmission loss (TL) between the source and receiver in the region also needed to be calculated. This value, which is the loss of intensity and energy of a sound wave, takes into account the bathymetry (which is, suppositionally, known deterministically), a sound speed profile, the source depth or draught of the ship, the location of the receiver in the water column, and the probabilistic x-y positions of the source and receiver. To generate a probability of noise impact, the probabilities of the inputs (SL, source depth, source position, receiver location, and SVP) and deterministic inputs (seabed acoustic properties and bathymetry) were first determined from existing data. Then, a Monte-Carlo approach was used to compute the TL probability distribution and the RL probability distribution. For the results, 1000 samples were used for each whale species at the 800 Hz frequency, and 2000 samples for the bowhead whale at 50 Hz. Finally, since all three cetaceans congregate in the TINMCA in the summer months (see Chapter 3), shipping data in this area was constrained to the months of April to October, thus avoiding the need to simulate ice-covered waters in the TL modelling.

In developing the model, there was a need to determine where ships travelled in the TINMCA boundaries. Raw Automatic Information System (AIS) vessel tracking data from 2014-2017 were obtained from exactEarth Ltd., and refined by the Marine Environmental Observation Prediction and Response (MEOPAR) network programmers. The area of interest was expanded outwards of approximately 100 km from the TINMCA boundary to ensure that vessel travel near the edges of the region were fully captured. AIS point data were used to identify distinct vessels in the area, and matched to: vessel characteristics and attributes (as available) of vessel name; Maritime Mobile Service Identity (MMSI) and the International Maritime Organization (IMO) number; call sign; AIS class; length; breadth; speed over ground and estimated speed from distance and time between AIS data points, all measured in knots; draught; day and time of AIS data capture; and course type. AIS point data were then transformed to trajectory representations by linking pairs of vessel locations in sequence, which defines a linear interpolation between reported positions with a maximum separation time of 360 minutes in order to cover gaps in satellite reception of the AIS signals.

Due to the large amount of AIS unique vessel data, averages of speed and draught were used, and ship tracking data were merged based on the vessel and year. Vessel trajectory representations that were not within the TINMCA boundaries were then removed via the ArcMAP 10.5 clipping toolbox function. This resulted in the original raw trajectory data being reduced from 265 unique vessels to 172 within the study area and period. Additionally, any vessels that did not have recorded length or draught attributes were removed, which resulted in a final total of 160 unique vessels and their attributes to be analyzed and used for this study. Length ($ls$) and average speed ($v$) data for each unique vessel were used as variables for the source level ($SL$) equation, which was calculated at various frequencies ($f$ (Hz)= 1, 31.5, 50, 63, 100, 200, 400, 800, 1600, 3200, 6400, 12800, 25600, 51200), though only two were used in the Monte Carlo simulation due to computational and time constraints.

$$SL\ (f,v,ls) = SL_0 + 60 \log_{10}(v/12) + 20 \log_{10}(ls/300) + df * dl + 3.0$$

The frequency dependent term $SL_0$ was calculated as:

$$SL_0\ (f) = -10 \log_{10}(10^{-1.06 \log_{10}(f) - 14.34} + 10^{3.32 \log_{10}(f) - 21.425}) \text{ if } f \leq 500 \text{ Hz or}$$

$$SL_0\ (f) = -173.2 - 18 \log_{10}(f) \text{ if } f > 500 \text{ Hz.}$$

The variable $df$ was also dependent on frequency; $df = 8.1$ if $0 \leq f \leq 28.4$; $df = 22.3 - 9.77 \log_{10}(f)$ if $28.4 \leq f \leq 191.6$; and $df = 0$ if $f > 191.6$. The variable $dl$ depends on the length of the ship ($dl = ls^{1.15}/3643$). The equations were taken from Simard, Roy, Gervaise, & Girard, 2016, which was adapted from Ross, 1987.

The SL at each frequency was organized into a probability distribution function (PDF) histogram, and then cumulatively summed (Figure 6). It is important to note that the PDF for each frequency showed a bi-modal distribution, which is due to the variation in vessel length and type that entered the TINMCA boundaries. The smaller SLs are associated with the smaller vessels that entered the area of interest, and include fishing, sailing and pleasure craft vessels. The larger SLs are similarly proportional to the larger vessels that entered the TINMCA boundaries, which include tankers, general cargo, icebreakers and passenger cruise ships. The average draughts of the two groups identified in the PDF was also calculated. A random number (between 0 and 1) was then generated and matched to the bin value of the PDF. This number was then used as the synthetic source level (SSL), which changed depending on the random number generated during each run of the Monte Carlo simulation. Since the draught of a vessel is linearly associated with its length, as well as proportional to its SL at identified frequencies, if the SSL randomly chosen was equal to a SL associated with a smaller vessel, then the draught of the vessel was identified as 5 m. Alternatively, if the SSL was equal to a SL associated with a larger vessel, the draught value used was 8.8 m.

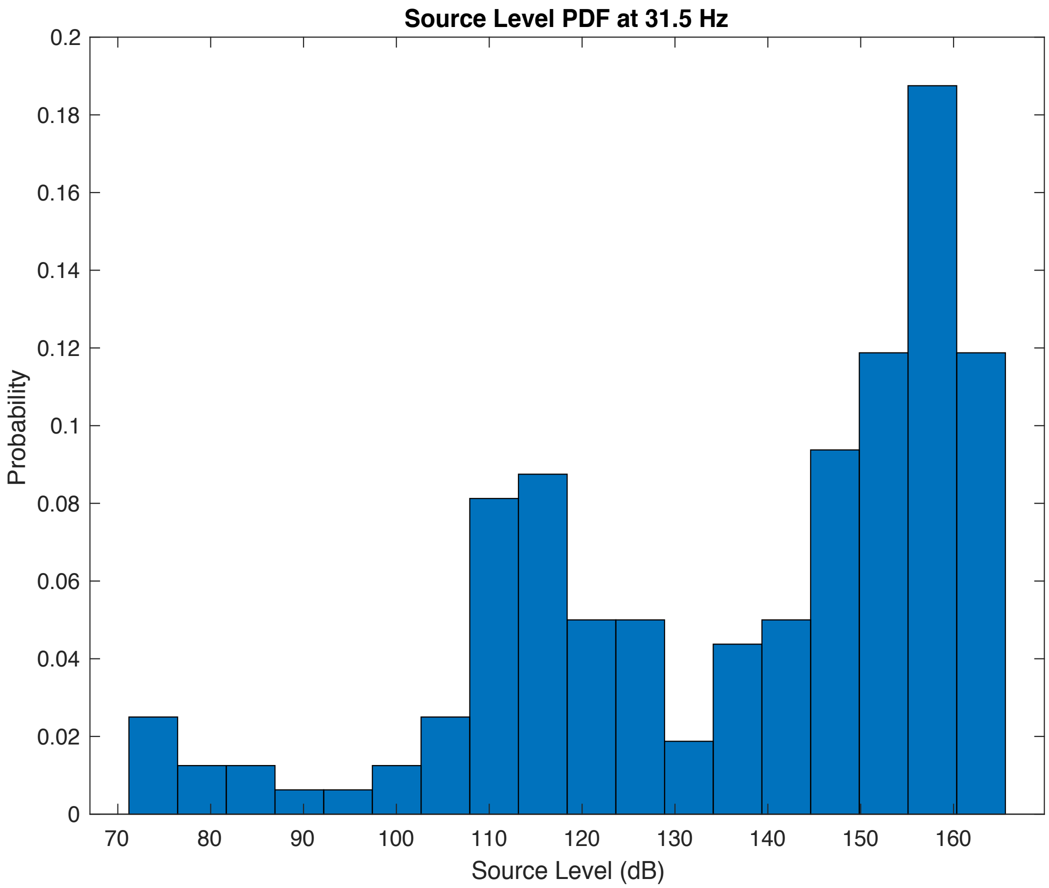

*Figure 6. The probability distribution function (PDF) of the source levels for various vessels that transited through the TINMCA boundaries during the 2014 and 2017 Arctic shipping season. The histogram shows a bimodal distribution, which is explained by the variability in the types of vessels that entered the area of interest. The smaller source levels are associated with pleasure crafts and sailing vessels, which are generally smaller in length and draught; and the larger source levels are associated with cargo, tanker and passenger cruise vessels, which are larger in both length and draught.*

### *4.1.1 Randomization of Vessel and Whale Locations*

In order to ensure that the location of a vessel was randomized, vessel tracking and trajectory data were also used to create a density map, using the ArcMAP line density tool. The output raster, in units of vessels/km$^2$/shipping season (April to October), was then converted to a gridded dataset and normalized in MATLAB_R2018a, to ensure the data was between 0 and 1 (MathWorks Inc., 2010). The rows within each column were also normalized to get a number between 0 and 1, and the cumulative sum of each column and row was calculated, giving the data derived probabilistic x-y position of vessels over the entire region. Again, for each run of the model, another random number was generated and matched to the appropriate location in the gridded dataset. This location was then identified in the bathymetry grid of the TINMCA area based on the cell's embedded latitude and longitude, a dataset gathered from the General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas, and specifically the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3 (Jakobsson et al., 2012).

The random location of the receiver within the TINMCA boundaries depended on the type of whale, since all three cetaceans had identified concentration and ranges within the study area (Figure 5). Thus individual gridded datasets of the location probabilities were created from shapefiles provided by WWF-Canada (Higdon, 2017). Due to the lack of information for bowhead concentrations, the known range of the whale was used, thus it was assumed that there was a uniform probability of a bowhead being in any given grid cell. For belugas and narwhals, there was an assumed three times higher likelihood of the whales being located in their identified concentration areas, relative to all other marine areas within the TINMCA. These gridded datasets were then normalized, and the columns and rows were cumulatively summed to achieve a numerical location, producing probabilistic maps of whale x-y locations. Another random number was generated and was matched to the column and row number of the whale concentration dataset. The associated latitude and longitude of the cell was used to find the whale location in the bathymetry grid. The distance between the source and the receiver was calculated using the haversine formula, which finds the shortest distance between two points on a sphere. If the path between the source and receiver was not interrupted by land, as identified through the bathymetry dataset, these locations were then chosen for the simulation. Otherwise, if there was intervening land the randomized ship and whale locations for that run were not used, and new locations were generated.

### *4.1.2 Transmission Loss Variables*

Other variables that were taken into account for each run of the model included the sound speed profile, the location of the whale in the water column, and the frequency of transmission. Due to the randomization of both the source and receiver locations in the TINMCA boundaries, it was considered appropriate to randomize the sound speed profile chosen for each calculation. Conductivity, temperature and depth data for various locations within Tallurutiup Imanga between the months of July to October, and the years

2014 to 2017, were gathered by the Canadian Coast Guard Amundsen and were obtained from the Polar Data Catalogue (Amundsen Science Data Collection, 2018). The SSP from this data was then calculated using the Gibbs Seawater Oceanographic toolbox available for MATLAB, which took into account the absolute salinity, conservative temperature and pressure data for each data set (McDougall & Barker, 2011). A total of 60 unique SSPs were calculated, which could be grouped into two distinct profiles for the area (Figure 7). To minimize partiality, a random SSP was chosen for each run of the model. In general, the two average SSPs are similar, except in the top 100 meters of the water column. In one profile the effects of solar sea surface heating can be seen, typical of an ice-free late summer Arctic Ocean. The other profile shows a cooler surface profile, where fresh water flux from ice melt and cooler temperatures produce a more homogenous upper ocean.

Another variable that needed to be considered in order to determine the TL between the source level and the receiver was the location of the whale in the water column. As mentioned above, the draught of the ship or depth of water needed to float the vessel was chosen based on the random selection of the SL for each run of the model. The location of the whale was also randomly chosen, by generating a random number between 0 and 1, and was then tailored to the probability of recorded whale depths.

A third variable that needed to be considered for the TL calculation was the frequency of the sound wave emitted at the SL. For comparability, the model was run at a frequency of 800 Hz for all whales, and a second frequency of 50 Hz was run for only the bowhead. The 800 Hz frequency was chosen because of the fact that all whales produce communication and social vocalizations at this frequency. The 50 Hz frequency was only used for the bowhead whale because of the audible thresholds assumed for the species, since it is believed that odontocetes cannot hear below 400 Hz, whereas bowhead hearing thresholds are primarily focused in these lower octaves. Furthermore, lower frequencies were chosen due to their propagation capabilities, since it has been observed that all three species tend to avoid vessels and stay at least 30 km away from ships, and sound propagates at different efficiencies depending on the frequency emitted (Erbe & Farmer, 2000). For this reason at 800 Hz, the maximum propagation range considered was 150 km, and at 50 Hz a maximum propagation distance was considered at 400 km. This was justified partly because of the calculation and computing limits used for the model, and also because at this relatively higher frequency, the TL beyond this distance would be drastic.

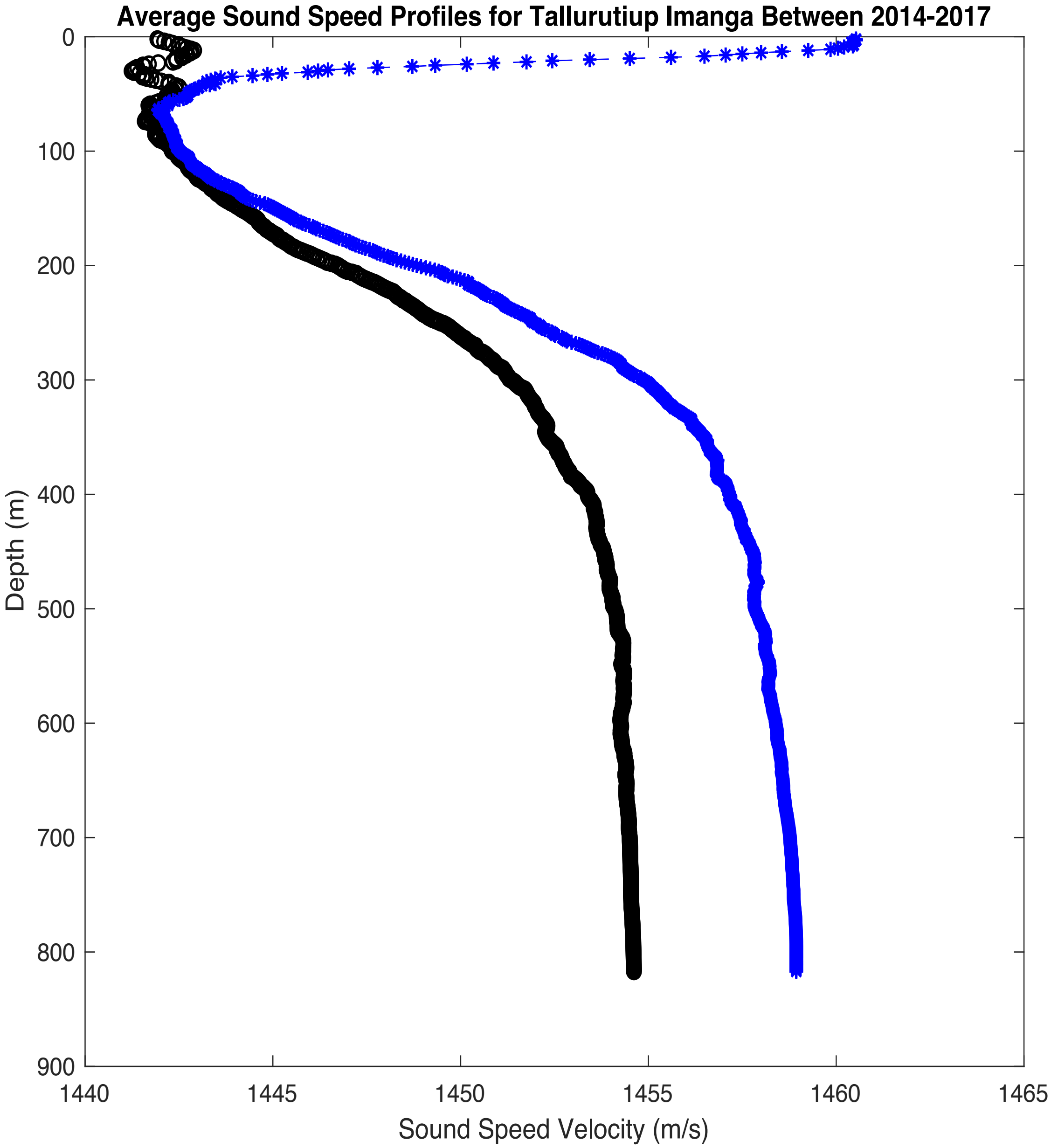

*Figure 7. The two main types of sound speed profiles seen in various locations within the Tallurutiup Imanga area, from data gathered between July and October of 2014 to 2017 (Amundsen Science Data Collection, 2018). There was a noticeably reduced sound speed velocity within the first 100 m of the water column, which can be explained by the lower pressure, cooler temperatures from the presence of ice, and the reduced salinity due to freshwater runoff and melting ice.*

The RL, once calculated, was then used to estimate the sound exposure level (SEL), which is the duration of time the receiver is exposed to the sound in a given area (Gervaise, Aulanier, Simard, & Roy, 2015). Due to limited data and in-situ measurements, SEL was calculated as an estimated constant for vessels transiting from the entrance of Eclipse Sound to the center of the bay. Average vessel speed through this 80 km or 46.1 nautical mile distance ($D$) was determined at 8.5 knots ($S$), resulting in a calculated average transit time ($T$) of 5.4 hours, or 19525 seconds ($T = D*60 / S$). The time dependent intensity level ($TdB$) was then determined using the calculated transit time $TdB = 10 \log_{10}(T/1)$, and a PDF was developed. For the purpose of this model, the RL PDF was interpreted as the average instantaneous RL for the entirety of the region ($T = 1$), while the SEL was estimated as the 'per ship' maximum ($SEL = RL + TdB$).

The final step in the model was to determine whether the RLs and SELs were above measured ambient noise levels. Ambient noise data recorded with various frequencies between August 2017 and August 2018 in Barrow Strait was used to determine average ambient levels associated with the study area. Ambient levels from months between August to October 2017, and April to August 2018 were taken and averaged at both 50 Hz and 800 Hz, and a PDF of the levels was created. This ambient noise PDF was then added to the RL and SEL histogram plot to see the probability of what the receiver would hear above the ambient noise levels. This was then compared to the National Oceanic and Atmospheric Administration (NOAA) guidance on assessing thresholds for whale noise damage, to determine what type of impact the RL and SEL would have once it is over the ambient noise level (National Marine Fisheries Service, 2018).

### 4.2 Modelling Results

AIS data identified a total of 172 unique vessels entering the TINMCA boundaries between the months of April to October of 2014 to 2017. Using an adaption of the Transport Canada classification system, there were 11 different industries that travelled through the region between the study periods (Figure 8). The majority of unique vessels were pleasure craft (30%) and bulk carriers (16%). There were a total of 283 transits through the TINMCA boundaries, with 21% of transits completed by pleasure craft, and 19% by bulk carriers. Excluding vessels that did not have length data associated with their AIS transceiver, the average length of the ships was 89 m, with 49% of vessels over 70 m in length and 51% of vessels smaller than 70 m. No pleasure craft vessels were found to have lengths over 70 m, and instead all research vessels, icebreakers, cruise ships, bulk carriers and tankers fell into this larger length category. Looking at transit numbers, 45% of total transits through the region were completed by vessels over 70 m in length.

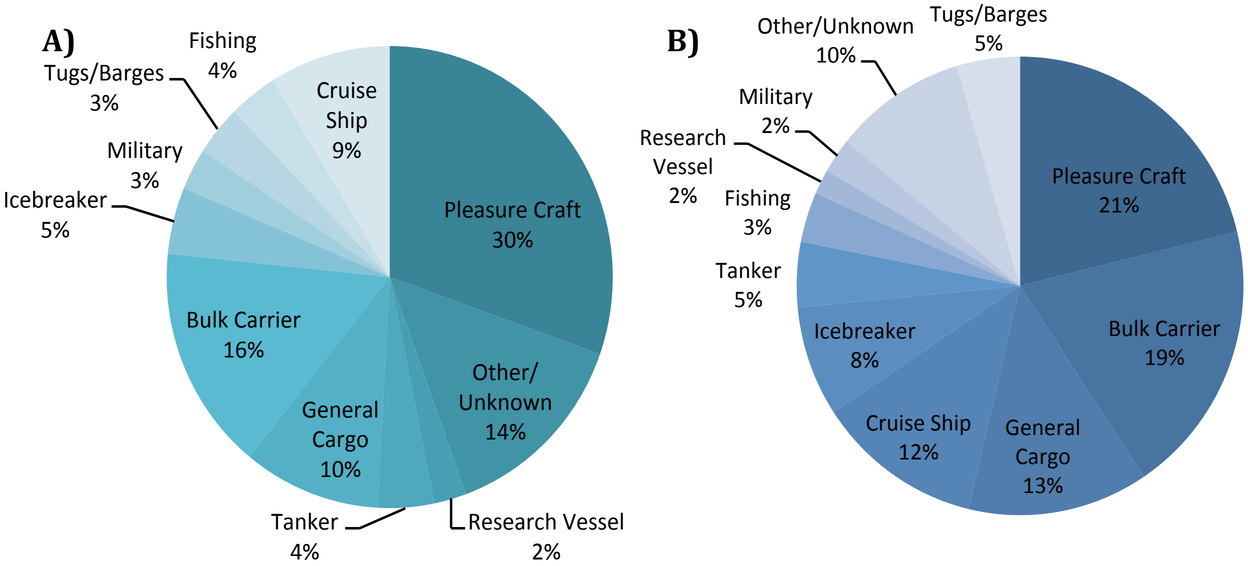

*Figure 8. Breakdown of vessel classes that entered the TINMCA boundaries between 2014 and 2017. A) The number of unique ships that entered the boundaries, identified by AIS number, as a total number, and not broken down by year. B) The number of transits each vessel class completed within the TINMCA boundaries. Transits were broken down by year, thus if a vessel entered in all four study periods the transit number was 4. Pleasure crafts (yachts and sailing) were most frequently seen in the area, with bulk carriers being the next most abundant. AIS data provided by exactEarth and refined by MEOPAR.*

A noticeable trend that arose when calculating the SL for each vessel was the proportional increase of intensity with increasing ship length and speed at all frequencies (Figure 9a). The largest intensities were observed to be in frequencies below 100 Hz, where 90% of SLs were above 100 dB re 1 μPa (Figure 9b). The largest intensities were calculated at 31.5 Hz with a maximum calculated SL of 169 dB re 1 μPa. Beyond 31.5 Hz, as frequencies increased the intensity levels decreased, while still having the same probability distribution function. Additionally, only 32% of the remaining SLs calculated at frequencies above 100 Hz exceeded the 100 dB re 1 μPa threshold.

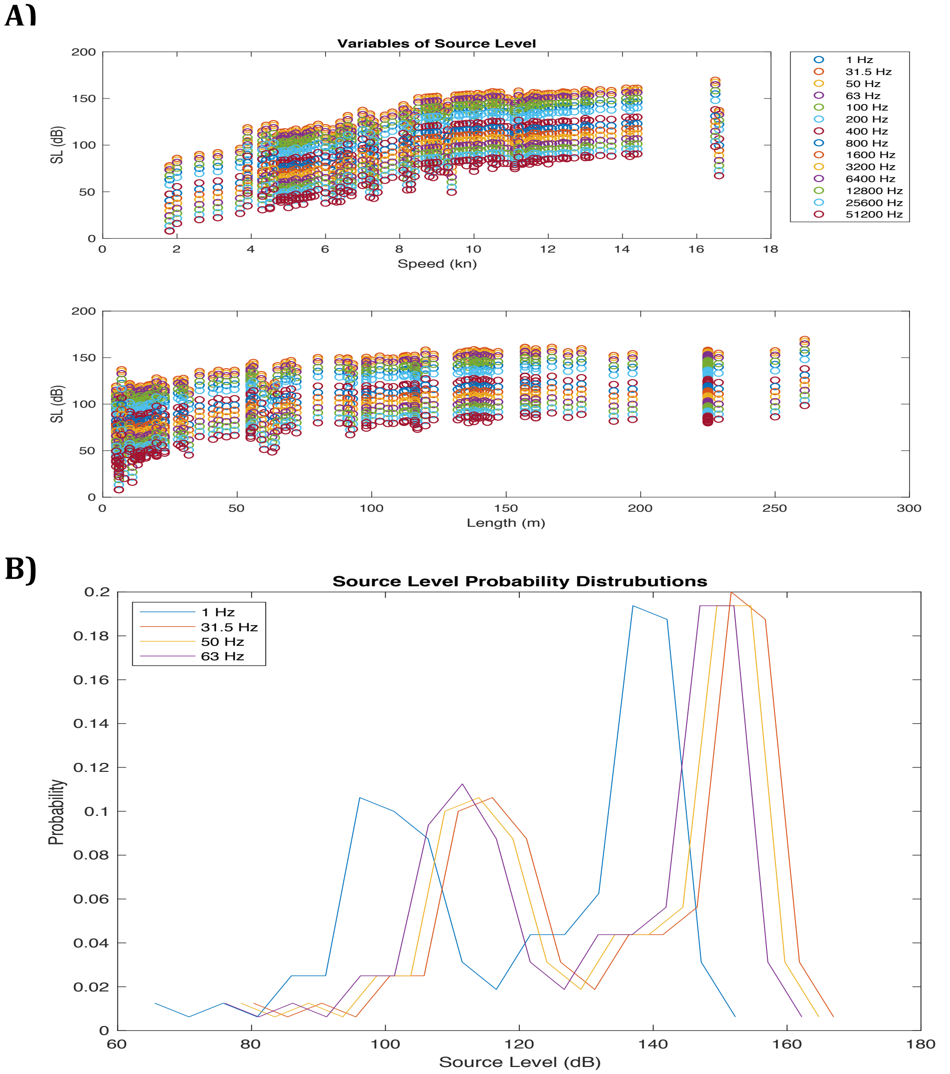

*Figure 9. A) Trends from the SL calculation show that with increased ship length and speed, the intensity of noise emitted from the vessel also increased at all frequencies. B) The loudest intensities were observed at lower frequencies, with peak intensity seen at 31.5 Hz at 166 dB re 1 μPa. After 31.5 Hz, the intensities gradually declined with increasing frequencies, but no change in the probability distributions of the SL.*

Calculated RLs showed that all cetaceans hear noise emitted from ships, at intensities greater than ambient noise levels (above 59 dB ambient mean) at 800 Hz, and bowheads also hear intensities from ships at 50 Hz (above 69 dB ambient mean; Figure 10). At 800 Hz, 26% of the time ship levels were audible to bowheads, 25% audible to narwhals, and 18% audible to belugas. At 50 Hz, vessel noise was audible to bowheads for 27% of the time. There was a significant difference between the mean RL above ambient noise for the three whales (one-way ANOVA, multi-comparison test; $p<0.001$), with narwhals and belugas having the most significant difference ($p<0.001$). The differences between mean RLs of bowhead and belugas, and narwhal and bowheads were also significant ($p=0.0159$ and $p=0.0045$, respectively). There was also a significant difference in the mean distance between each whale and a random ship location ($p<0.001$). Belugas had the smallest mean distance, with a value of 72.95 km, followed by narwhals (80.22 km) and bowheads (87.24 km). Interestingly, no instantaneous RL at either 50 Hz or 800 Hz reached intensities that could result in temporary threshold shifts (TTS) in the three whales, as identified by NOAA (National Marine Fisheries Service, 2018).

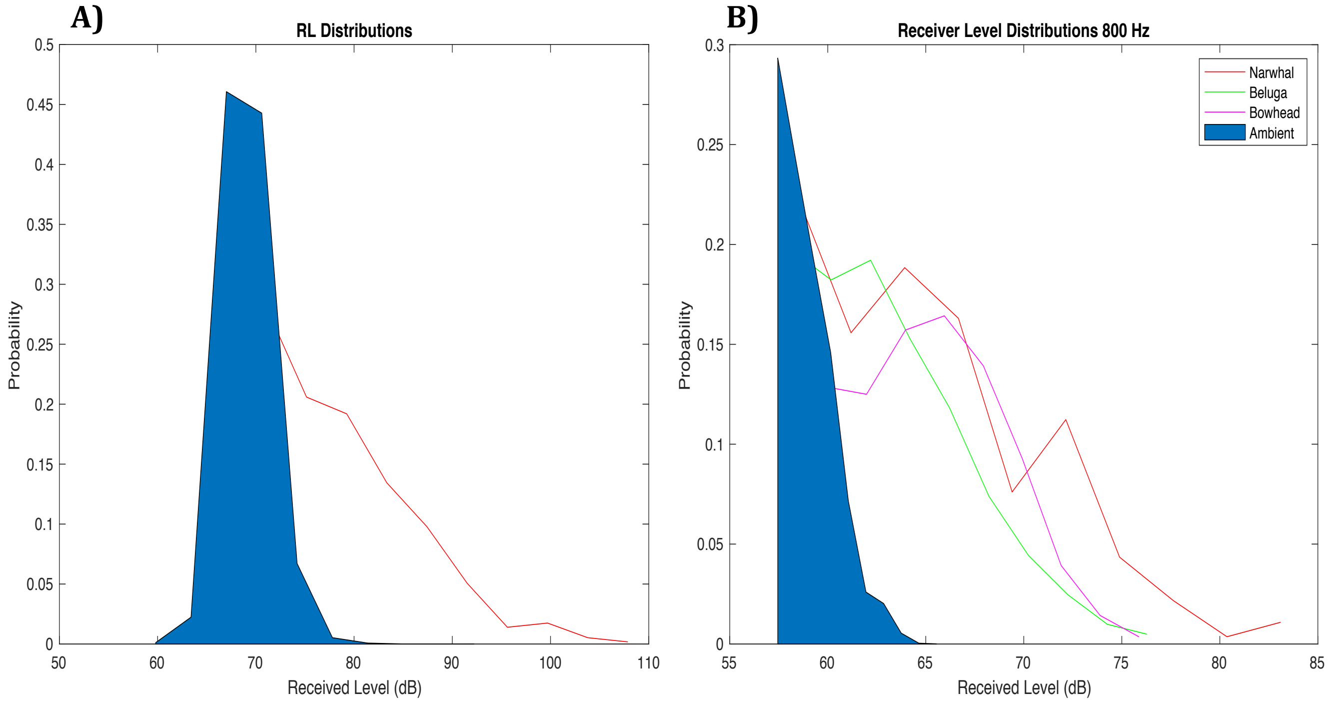

*Figure 10. The RLs for the three cetaceans within the TINMCA boundaries between April to October in 2014 to 2017. A) The probability of RLs above ambient noise levels for a bowhead whale at SLs emitted at 50 Hz. B) The probability of RLs above ambient noise levels for the three whales at SLs emitted at 800 Hz.*

The *TdB* for a vessel transiting through Eclipse Sound was measured at 42.9 dB, resulting in much louder cumulative SELs than instantaneous PDF averaged RLs. At 50 Hz, calculated SELs showed vessel noise being audible to bowheads 85% of the time, with an average intensity of 101 dB (Figure 11). At 800 Hz, the cumulative SEL resulted in vessel noise being audible to narwhals, belugas and bowheads for 85%, 81% and 88%, of the time, respectively. Even with this increased intensity, no cumulative SEL at the two frequencies reached the 179 and 178 dB TTS threshold, as set out by NOAA, although there was a substantial increase in the intensities at the receiver due to prolonged exposure.

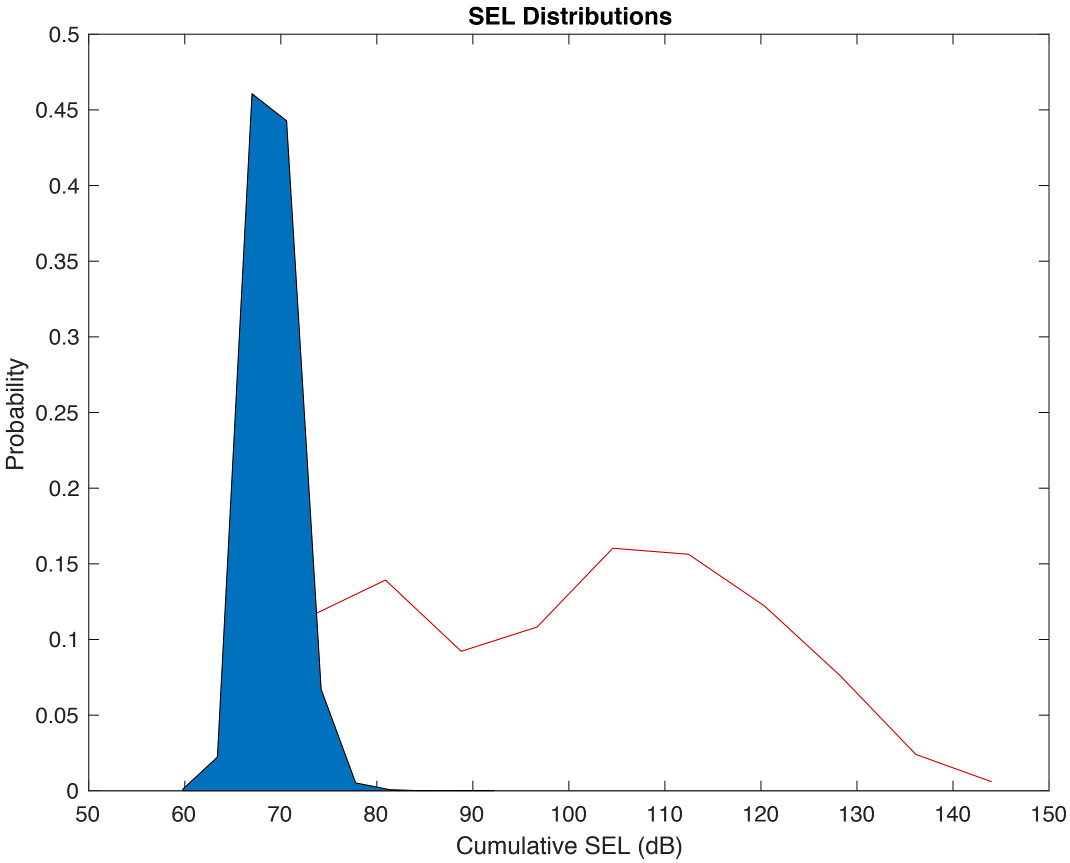

*Figure 11. The calculated cumulative SEL for bowhead whales at 50 Hz. The time dependent cumulative intensity resulted in a 42.9 dB increase from the instantaneous RL (T=1), increasing the probability of the whale hearing noise from vessels to 86%.*

# Chapter 5: Discussion

## 5.1 Effects on Calculated Received Levels

Over the past decade, vessel traffic through the Tallurutiup Imanga region has doubled, a phenomenon that is expected to continue within the coming years (Dawson et al., 2018). There has also been growing attention on how larger vessels, which produce lower frequency continuous noise, can potentially disturb various marine wildlife in this region (Scholik-Schlomer, 2015). Within the past four shipping seasons (2014-2017) almost half of the transits were made by vessels over 70 m in length, which included all commercial industry vessels and cruise ships. These larger vessels were calculated to produce SLs well above 100 dB re 1 μPa at numerous frequencies below 1000 Hz, though no SL, RL or SEL exceeded the 178 db re 1 μPa NOAA TTS boundary for low and mid-frequency cetaceans (National Marine Fisheries Service, 2018). It is therefore worth discussing why RLs and SELs did not reach these TTS thresholds, and explore how this simulation may not be entirely representative for the potential vessel noise impacts of this region. That being stated, all three cetaceans did have RLs and SELs above ambient noise thresholds at the calculated frequencies, and the potential risks this poses to the species are discussed in more detail below.

Although more attention is often given to the larger vessels that produced the loudest SLs in this region, focusing solely on one end of the vessel size spectrum does not accurately represent the vessel use of the area. In the TINMCA boundaries, smaller vessels less than 70 m in length generated the other half of transits, though their small size and slower speeds resulted in much quieter SLs (Figure 9). Furthermore, AIS data only provides information for vessels that have transceivers, thus the data used in this study was not able to look at the smaller pleasure craft often used by communities within the TINMCA (Canadian Coast Guard, 2018). This is important to consider as studies have shown that these smaller vessels can produce intensities that reach frequencies used by cetaceans, which is a concern since these vessels can be much closer to the receiver due to reduced navigation barriers (Jensen et al., 2009; Veirs et al., 2016). For this reason, it is important for managers to recognize that all vessels transiting through, and within, the TINMCA boundaries can pose a threat to cetacean disturbance, but due to data limitations, the full extent of this disturbance could not be studied extensively in this study.

Another factor to consider when analyzing why RLs were significantly lower than NOAA TTS levels, is the aspect that only individual SLs were calculated in this model. Although the Monte Carlo simulation showed that single vessel noise does reach the three cetaceans, it is important to note that this study, due to time constraints, could not measure the cumulative SLs of all vessels transiting through the area. Considering that both large and small vessels transit through the TINMCA in the same months of the year, there is a possibility that the number of sources in a given area could be more than one vessel at a time, resulting in higher intensities due to combined SLs (ECHO, 2018). Furthermore, noise radiated by a fleet that is composed of a mixture of ships of diverse sizes is expected to cover a wide range of frequencies and may potentially produce cumulative SLs well above the threshold set out by NOAA (Gervaise et al., 2012). Thus, even though shipping traffic through the NWP is relatively sparse in comparison to more southern transit routes, there are higher concentrations of transits specifically in the Eclipse Sound/Pond Inlet region, which could result in cumulative vessel noise that exceeds NOAA TTS levels. Additionally, another possible reason why SLs were relatively lower than expected is due to the presence of ice in this region. The safety of a vessel, its crew and its load is exceptionally important, and as a result, vessels transiting the TINMCA and the Arctic, are often travelling at slower speeds (McWhinnie et al., 2018). As the results showed, the speed of a vessel played a significant role in the SL calculation, which ultimately influenced the RLs and SELs.

Not surprisingly, the distance between the receiver and the source also played a significant role in the calculated RLs, SELs and TLs for all three cetaceans, especially at 800 Hz. Although belugas had the smallest mean distance, they also had the lowest mean RL, which can be explained by the fact that only 18% of calculated RLs were above ambient noise. This means that belugas within this area have a higher probability of being at distances over 150 km from traffic, reducing the overall mean RL since most of the vessel noise is masked, or overcome by ambient noise. Moreover, only a portion of important beluga foraging and calving areas fell within areas of high vessel density, reducing the probability of vessels being in the same area as the beluga. The narwhal and bowhead simulations on the other hand, had larger overlap between cetacean locations and regions of high vessel density, especially for the narwhal. This overlap increased the probability of the two cetaceans being within 150 km of a vessel, thus resulting in a proportional increase in calculated RLs, SELs and reduced TLs.

Measured ambient noise was also relatively high in this area compared to more temperate oceans, which did have an effect on the proportion of RLs that were above this natural threshold as the majority of vessel noise calculated at the RL was masked by ambient levels. A potential cause for these higher ambient levels could be due to the presence of ice during the period of hydrophone recording, as Barrow Strait, and other areas within the TINMCA, often contains icebergs and ice floes well into the month of June (Canadian Ice Service, 2016; Ozanich, Gerstoft, Worcester, Dzieciuch, & Thode, 2017). This area is highly influenced by thermal air temperatures and wind, which causes ice cracking, fracturing and collisions, resulting in ambient levels that can sometimes exceed 100 dB re 1 μPa at frequencies below 100 Hz, depending on the size of the ice block (Pritchard, 1990). Additionally, Barrow Strait is a relatively larger open-water area later in the summer, compared to other areas within the TINMCA, which also has an impact on the resulting ambient noise levels. Wind speed is generally faster over open water rather than enclosed areas due to the reduced protection land offers, and increased wind speeds have a proportional influence on water currents and wave development, further impacting ambient noise levels (Mellen & Marsh, 1965). For these reasons, ambient noise measured in the TINMCA is relatively higher than in temperate oceans, resulting in a higher audibility threshold for the three cetaceans within this region. In order to improve the results of this study, the ambient noise baseline should be determined from data collected throughout the TINMCA area, as the Barrow Strait data provide only a limited estimate.

SEL was calculated because NOAA considers the onset of TTS to occur when either RLs or cumulative SELs exceed the determined threshold (National Marine Fisheries Service, 2018). It was therefore necessary to model the theoretical minimum and maximum, since RL was interpreted as being the intensity heard at one second of exposure, or the average instantaneous PDF for the entire region. Since SEL is a logarithmic value, after 1 second of exposure there was a substantial increase in the intensities heard by the receiver (Figure 12). Within two hours of exposure, SEL values were already 35.7 dB louder than calculated RLs, which then tapered off after approximately 8 hours of exposure. Regardless of this increase in intensity, since RLs were already lower to begin with, the SELs were still quieter than TTS limits. It is important to recognize that in order to demonstrate the SEL as an extreme case, it was assumed that the cetacean would not exhibit any avoidance behaviours, and that the SL would be constant throughout this period. Although not entirely accurate, it can still be assumed that an exposure time of more than 1 second can still occur in this region, and RLs can thus be louder than what was modeled in this simulation. Although it is necessary to show how exposure time can potentially increase the intensities heard by the cetacean, in order to fully understand these impacts, and thus accurately simulate these impacts, there needs to be more understanding of how these cetaceans behave when in the vicinity of vessel noise.

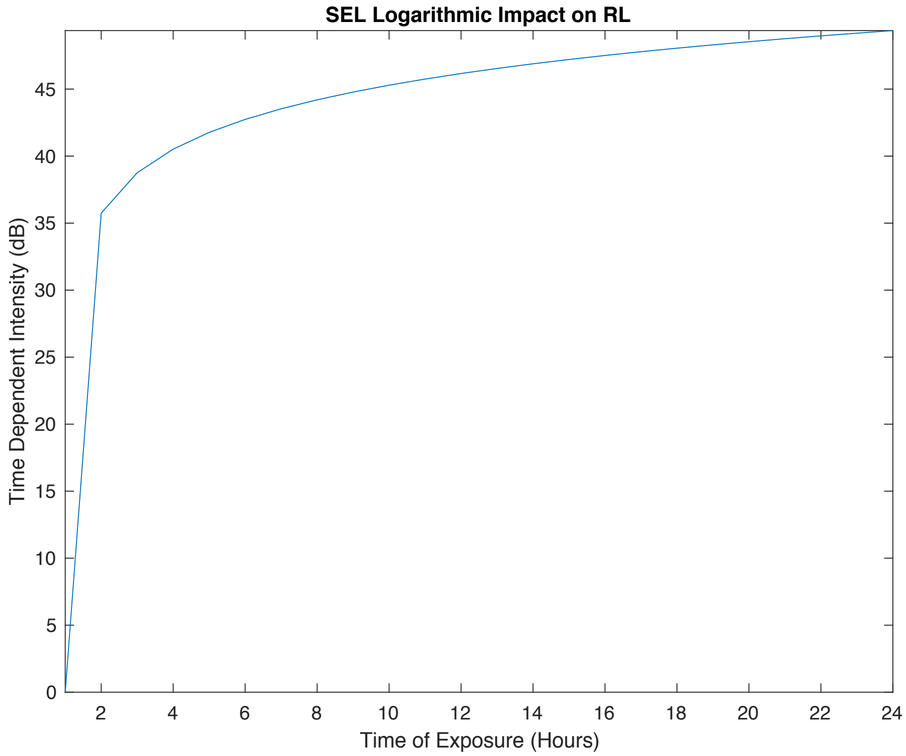

*Figure 12. There is a logarithmic growth in the intensities a receiver will hear within the first 24 hours of exposure to continuous vessel noise. In the case of the TINMCA cetaceans, the assumed maximum exposure level was 4 hours, which would result in an approximately 42 dB increase from the instantaneous RL.*

## 5.2 Zones of Impacts on Cetaceans

Although there has been an increase in the amount of studies attempting to determine the impacts vessel noise can have on cetaceans in more temperate areas, with respect to the three Arctic cetaceans found in the TINMCA boundaries research is relatively non-existent. Audiograms, which measures the hearing thresholds and sensitivities of a species, have only been studied in 20 marine mammals, none of which include bowheads or narwhals (Erbe, 2012). Audiograms have been developed from belugas in captivity and the Alaskan Bristol Bay beluga population, but there is concern that this may not be representative of all beluga populations in the wild, especially for those that have not been habituated to such a disturbance (Gervaise et al., 2012; Mooney et al., 2018). For this reason, researchers are trying to determine when man-made noises could cause permanent or temporary damage to cetaceans in order to provide management and policy guidelines to mitigate these impacts; though these regions of noise susceptibility do not perfectly mirror a species' region of best hearing (National Marine Fisheries Service, 2018). These guidelines divide cetaceans into five hearing groups based on hearing ranges to determine the generalized thresholds. Although the results of this study show that RLs and SELs do not reach the TTS and permanent injury thresholds as identified by NOAA, it does not mean that vessel noise in this region has no impact on these three cetaceans. On the contrary, vessel noise can pose significant risks to a cetaceans health without causing physical and direct damage as often seen with the threshold guidelines, and various zones of influence can be used to determine the potential impact noise can have relative to the distance from the source (Figure 11; Erbe, 2002, 2012).

The zone of audibility is much larger than other zones of influence due to the fact that audibility is limited by the sound disturbance dropping below either ambient noise levels, or a cetaceans hearing threshold (Erbe, 2002; Halliday et al., 2017). In instances where no audiograms are available for a population, such as the cetaceans within the TINMCA, it is assumed that when there is a reaction to a disturbance the sound is audible to the species, and for this reason any RL above ambient noise levels has the potential to cause temporary stress on the animal (Erbe, 2002). Additionally, audibility is thought to increase, or the species are believed to me more sensitive, to noise that is received at frequencies of their own calls (Erbe, 2012). Thus, in the case of the three TINMCA cetaceans, RLs were calculated at frequencies of 50 or 800 Hz, all of which are within the audibility range determined by their observed calling and communication broadband frequencies. Although this zone does not elicit behavioural changes or induce stress responses, the zone can act as a deterrent threshold to prevent the cetacean from moving closer to the disturbance (Goodson, 1997). It can therefore be expected that these cetaceans will hear RLs and SELs that are above the ambient noise levels calculated in this study, and as a result, may be deterred from entering important and established calving and foraging grounds.

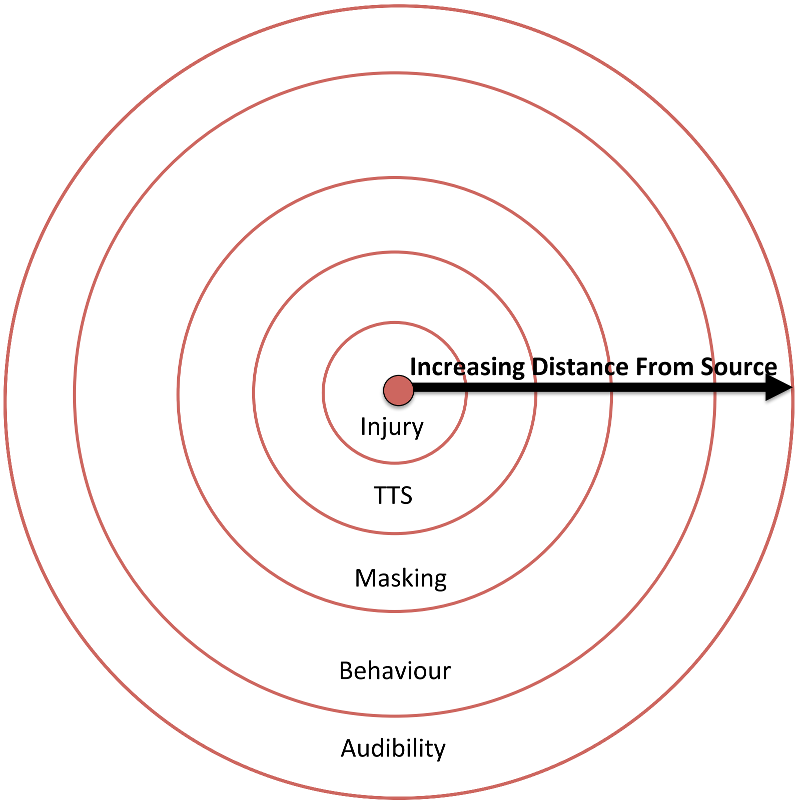

*Figure 13. The simplified diagram identifying the various zones of influence noise could have on cetaceans, depending on their distance from the source. Generally, severe and permanent damage could occur if the receiver was at the source, and severe physiological damage is minimized with increasing distances. The ambient noise levels or the individual cetaceans detection threshold, as determined by audiograms, limits the zone of audibility. Adapted from Erbe, 2010.*

### *5.2.1 Behavioural Impacts*

The zone of behavioural change or responsiveness is smaller than the zone of audibility because an animal is not likely to alter activities or become stressed to sounds that are barely audible, requiring the receiver to be closer to the source to induce such responses (Erbe, 2012). Indications of behavioural disturbance include changes in swim direction and speed, dive duration, surfacing duration, blow rate, movement towards or away from a source, or changes in acoustic communication or behaviour (Erbe, 2010). Behavioural changes caused by the onset of stress or disturbance from vessels can have effects on the energy budget of animals, which can have additional deleterious consequences on populations' productivity and health. In the case of high intensity and low frequency continuous noise produced by vessels, the disturbance could cause an animal to cease foraging, which can either reduce or even stop energy acquisition (Nabi et al., 2018).

All three Arctic cetaceans have been observed to show disturbance indicators when in the vicinity of ships, with belugas and narwhals responding to vessels more than 80 km away (Cosens & Dueck, 1993; Finley, L.G.L. Limited, Environmental Research Associates, & Program, 1986). Bowheads exhibit avoidance behaviours when in the same vicinity as anthropogenic noise, with some reports claiming that they actively detour around persistent industrial noises, such as ships (Nabi et al., 2018). This can lead to prolonged periods without feeding and increased energy demands to swim away from the disturbance, impacting their energy budget and potentially influencing their reproductive success (Nabi et al., 2018). This is especially worrying since these large cetaceans are long-lived with low reproductive rates, and with prolonged disturbance this could potentially have larger effects on the species population.

Belugas have been observed to exhibit strong avoidance behaviours in the presence of vessels within the TINMCA area, and have been seen fleeing rapidly from an area towards coastal inlets while also emitting high frequency and repetitive alarm calls (Finley et al., 1986; Gervaise et al., 2012; Lesage et al., 1999). Since the TINMCA contains important foraging and nursing areas for this species, the energy cost of fleeing due to a vessel disturbance can compromise lactation (Nabi et al., 2018). If a decrease in lactation occurs, this could impact the fetus, prolonging the developmental phase and thus lactation, potentially influencing the demography of the population.

Narwhals seemingly have the most severe reaction to vessel disturbance, where they become silent and move slowly away from a vessel or even become entirely motionless, seeking open water for refuge (Finley et al., 1986; Lesage et al., 1999). In the Eastern Greenland population, narwhals have been observed to remain silent and stop hunting for an average of 23 hours after being disturbed, a response thought to be similar to the whales' response to their predator, the killer whale (Blackwell et al., 2018). These severe reactions can have major implications on narwhal survival, as reduced mobility increases the risk of the animal being exposed to louder SLs as vessels move closer, and the hiatus in hunting can have implications on calving success, which occurs in the TINMCA areas. The responses observed for the two odontocetes in the TINMCA are believed to be unique in the marine mammal literature, strongly suggesting that these cetaceans are naive to this disturbance and have therefore not had the time to adapt or habituate to shipping, compared to other populations (Finley et al., 1986).

Masking cetacean communication can also occur, generally at mid-distances from the source and zone of audibility. This can cause a reduced communication space that may result in a loss of information between senders and receivers, as well as others eavesdropping on the message (Cholewiak et al., 2018). There have been no studies regarding the potential effects that masking from vessels could have on the three cetaceans found within the TINMCA, but a recent study looking at North Atlantic Right Whales found that in almost all cases AIS size vessels had the largest effect on masking, drastically reducing communication space especially in areas of high traffic (Cholewiak et al., 2018). Generally, baleen whales are assumed to be more sensitive to low-frequency sounds, especially due to their dependence on this frequency range for communication and navigation. For this reason, these larger whales are impacted more than the other marine mammals from vessel noise due to the overlap in frequencies. In the case of the beluga and narwhal, they do have communication frequencies at lower levels identical to vessel frequencies, but no studies to date have looked at the possibility of masking effects on these cetaceans.

# Chapter 6: Management Recommendations

## 6.1 Spatial Management Tools

The purpose of the simulation was to provide a better understanding of the perceived risks that vessel noise in the TINMCA could have on the three cetacean species, which could then be used to inform managers of the possible tools available in order to reduce these impacts. Although Tallurutiup Imanga is an exceptionally large area, all three cetaceans congregate in this region beginning in the warming spring months, and often remain well until the late fall, which unfortunately corresponds exactly with the shipping season in the eastern Arctic (Mckenna et al., 2017). This spatial overlap was also notable in the simulation results, which demonstrated that if a vessel was located in an important cetacean area, there was a higher probability that the instantaneous RL would be audible to the animal. Additionally, the spatial distance between a whale and a ship played a major role in the RLs and SELs, with closer distances resulting in higher intensities, which is especially worrying in areas of important cetacean habitat. For this reason, recognizing that the vessels and cetaceans share the same area, it is important to identify management tools that can mitigate the spatial conflict in the NMCA.

That stated, it is unrealistic to propose that the entire area be closed to shipping, as it is the eastern entrance of the NWP, and communities in the North rely on shipping for the goods and services the industry provides (Kelley & Ljubicic, 2012). It is also important to recognize that NMCAs encourage the sustainable use of a marine space, and prohibiting vessel traffic requires an agreement between Transport Canada and Environment and Climate Change Canada (Government of Canada, 2015). Thus, one of the key issues that managers have to acknowledge, and thus mitigate, is the conflict between the cetaceans and vessel noise in the same time and space, without markedly limiting or disrupting vessel use and safety (Erbe, 2012). There are a number of options that reduce spatial conflict between vessels and cetaceans, but often these methods are fraught with stakeholder opposition or are generally not applicable to Arctic environments (McWhinnie et al., 2018). For this reason, managers must look towards options that are already being implemented and do not pose safety hazards to vessels transiting in such a dynamic area.

### *6.1.1. Low Impact Shipping Corridors*

One such opportunity that has the potential to severely minimize spatial conflicts, and thus noise impacts, is the low impact shipping corridor initiative. Created and supported by the Oceans Protection Plan, the project is co-led by Transport Canada, the Canadian Coast Guard, and the Canadian Hydrographic Service, with further consultations and input from various Arctic communities. The intent of the initiative is to create shipping corridors throughout the Arctic that reduces marine incidents by incentivizing vessels to stay in designated areas and routes, which provide predictable services such as search and rescue operations or reliable satellite surveillance (Carter, Dawson, Joyce, Ogilvie, & Weber, 2018). The corridors do not force vessels to follow these transit routes, as safety of a vessel and its crew is priority in such a remote and dynamic area, and as a result it allows vessels to choose alternative routes if safety is a concern. Consultations are still ongoing between the Government of Canada, Non-Governmental Organizations and Arctic communities, to ensure that the corridors do not negatively affect cultural and traditional activities.

Although not originally intended to incorporate conservation objectives, the corridors could still provide managers with a possibility of reducing vessel noise impacts on cetaceans. Understandably, it is not likely feasible to reroute the corridors to avoid cetacean habitat when they are directly in the path of transit, but narrowing the corridors is a possibility. The corridors provide incentives to minimize vessel routing variability, which simultaneously has the potential to reduce the acoustic footprints of the vessels. Since the RLs and SELs calculated in the simulation were from random vessel locations, by reducing this variability there is a higher probability of whale locations being beyond the 150 km limit, which in turn reduces the probability of the noise being audible. In areas such as important beluga nursing areas, which are located directly in the middle of the TINMCA, a narrowing of the corridors to limit the potential noise footprint from vessels could simultaneously ensure that the distance between the two users is maximized. This reduces the probability of the RL being audible, and also reduces the probability of the SEL to be at physiologically damaging levels. Thus, managers have the opportunity to safeguard the three cetaceans populations by limiting vessel location variability, without impacting vessel routes and procedures.

### *6.1.2. Areas to be Avoided*

While the low impact shipping corridors advise vessels where to go, areas to be avoided (ATBAs) tell mariners where not to go (Huntington et al., 2015). ATBAs are set out by the IMO and recommend that vessels avoid designated areas, either due to danger or because it is culturally or ecologically significant (McWhinnie et al., 2018). ATBAs also provide managers with a tool that results in relatively quick compliance rates. Although voluntary, the Roseway Basin ATBA, located in the Scotian Shelf on the East Coast of Canada, demonstrated that such measures have the potential to reduce vessel traffic through the area by 71% within the first five months (Vanderlaan & Taggart, 2009). In areas of the TINMCA where cetaceans have a higher risk of being disturbed by vessel noise, such as recognized nursing areas, ATBAs can be used to minimize vessel traffic through these areas during the more sensitive months, while simultaneously ensuring that vessel safety is not put at risk.

This management tool reduces spatial conflict between cetaceans and vessels, but only if implemented properly. An ATBA that is relatively small in size may not sufficiently separate the two marine users, potentially resulting in distances that are less than 150 km. This distance was shown to result in a high probability of vessel noise being audible to cetaceans through SELs, but the distance also resulted in RLs being audible as well. Therefore, establishing smaller ATBAs may not properly mitigate vessel noise impacts on the cetaceans in this area. On the other hand, if the ATBA is too big, ships may be asked to transit through unsafe areas, which may reduce compliance rates. Furthermore, since the TINMCA is a relatively small area compared to the rest of the Arctic, and its bathymetry is not sufficiently mapped, a larger ATBA may result in vessels being forced to transit closer to the shore, or near more hazardous areas in an attempt to follow the IMO guidelines. If this is the case, this could result in vessel and crew safety being put at risk, which may result in captains ignoring the ATBA altogether. Thus an ATBA should be a sufficient size to ensure spatial separation from marine mammal clusters, while small enough to guarantee that vessel and crew safety is not put in jeopardy. It is necessary to note that IMO-established ATBAs would not have an impact on mitigating small pleasure craft transits and their noise impacts because IMO only regulates international shipping procedures. For this reason, other spatial options may be necessary, specific to tourism within the TINMCA.

## 6.2 TINMCA Tools

The purpose of an NMCA is to encourage the sustainable use of a marine space by providing opportunities for the people of Canada, and the world, to enjoy the country's natural and cultural marine heritage (Parks Canada, 2017). Seemingly opposite from a marine protected area due to their more accessible nature, NMCAs are still required to protect, or conserve, a portion of the marine space. Each NMCA requires managers to identify zones of use within the area, with at least one zone focusing on encouraging the sustainable use of the marine resources and, at minimum, a single, smaller zone that fully protects the sensitive elements of an ecosystem (Government of Canada, 2015). There is no requirement on the size of the zones, as this depends on the size of each individual NMCA and the ecosystem it surrounds, and there is no specified definition as what constitutes an ecosystem element. In the case of the TINMCA, this leaves managers, communities and scientists to interpret and develop a management plan appropriate for this area. The ambiguity surrounding what defines a sensitive ecosystem element allows for some interpretation that this can include any biologically significant feature, from an apex predator to a complex habitat. Due to their size, all three cetaceans play an important role in the TINMCA food chain and ecosystem, and can potentially be grouped into this loosely defined ecosystem element feature (Mckenna et al., 2017). For this reason, managers should be identifying and delimiting areas that are important for these three species. Such areas could be the beluga and narwhal nursing areas, or important narwhal foraging areas (Figure 5).

Limited by their ability to control vessel movement through the TINMCA, managers could look into using incentives to limit vessel noise impacts on the three cetaceans, especially in important and known concentration areas. One such incentive could be the implementation of fees, which fines vessels that are not up to efficiency standards at the time of entering these sensitive zones or areas. In other words, mangers could implement a fee if any vessel, including cruise ships, pleasure craft, and even commercial industry vessels, have not had a hull or propeller cleaning in the recent past.

The main source of vessel noise is propeller cavitation and machinery vibration, which is also an attractant for biofouling organisms (Stanley, Wilkens, & Jeffs, 2014). Generally, more biofouling on the hull means that the engine has to work harder and is therefore less efficient, causing additional cavitation and engine vibration, as well as increasing fuel consumption (Spence & Fischer, 2017). For this reason, by encouraging vessels to become more fuel-efficient, this simultaneously reduces the potential for cavitation, and ultimately minimizes noise impacts on the three cetaceans within the TINMCA. Furthermore, this incentive does not put vessel safety at risk by altering their transit routes, and may also provide opportunities for a source of income.

It is important to recognize that one of the main difficulties for managers of the TINMCA is enforcement, especially due to its large size and relatively remote location. For this reason, incentives and zoning plans may not be successful if they cannot be monitored. It is therefore vital for managers to recognize that they cannot ensure the protection of the three cetaceans by relying on their own resources, and they must instead give trust to the surrounding communities and stakeholders. During consultations on the low impact shipping corridors, noise impacts on whales was identified as a key concern for communities surrounding, and within, the TINMCA (Carter et al., 2018). This community recognition can be interpreted as a potential willingness for members to help managers ensure that the species is minimally impacted by vessel noise, but only if they are given sufficient resources to do so. Thus, managers should accept and inspire community participation to enforce any management plans that are developed within the TINMCA, with the goal of safeguarding the acoustic soundscape of the region.

### *6.2.1 Vessel Tools*

Although it is necessary for managers to try and restrict vessel variability through spatial constraints and fees, working directly with the vessels is another approach managers can try to ensure compliance and mitigate noise risk within the NMCA. One such method would be developing a code of conduct for vessels for when they transit through the TINMCA boundaries. This code of conduct could include a minimum setback distance specific to the three cetaceans, The general 100 m limit for non-listed SARA species currently set out by Fisheries and Oceans Canada may not be sufficient enough to minimize noise impacts on these animals, and managers could consider increasing this to 400 m (Fisheries and Oceans Canada, 2018). The code of conduct could also include a request for vessels to try and ensure that they follow a straight course while transiting through important cetacean areas, avoiding erratic behaviour to reduce their acoustic footprint in the NMCA. And finally, a code of conduct could encourage vessels to participate in scientific studies occurring in the region, by providing appropriate contact information for when a vessel sees a cetacean. This not only allows scientists to gather data on the species, but it also encourages vessels to have a vested interest in the animals they share a marine space with.

A final management tool specific to vessels, which could potentially result in the greatest control on vessel noise impacts on the three cetaceans, is to implement speed restrictions throughout the NMCA. When calculating SLs for the simulation, there was a clear relationship between intensity and speed, particularly with respect to larger vessels (Figure 9). For this reason, managers should seriously consider implementing a TINMCA speed restriction, potentially at 13 knots. Even though SLs were louder at this speed than at slower knots, anything less would potentially put the vessel at risk from strong currents and ice presence. Although loud, the model showed that even at this speed RLs and SEL probabilities do not reach TTS levels, which means that physical damage may not occur to these species. This stated, in especially important habitats for the three cetaceans a speed restriction at 10 knots may be necessary to further minimize SL intensities, but this should be a voluntary measure and specific to smaller pleasure crafts and tourism vessels, as they have more maneuverability compared to larger commercial vessels.

### 6.4 Further Research

Although developing recommendations and identifying spatial management tools is necessary for ensuring that vessel noise impacts on the three cetaceans are minimized, these management solutions can only be successful if they are adaptable. Arguably, research on the potential risks that anthropogenic noise poses to the various species found within the TINMCA is sorely understudied compared to more temperate areas, and more information is needed to develop holistic management plans. Regardless, a shortage of knowledge should not be grounds for inactivity, as stated by the precautionary principle;

but managers should recognize that as research grows in this area there may be more effective tools available that improve the quality of life for cetaceans in this region (Billé, 2008). For this reason, any management plan developed for this NMCA should request and accept further scientific information and community participation, as this ensures that the management plan has capacity to improve in the coming years.

One such area of research where managers could use more information is the apparent use and emitted SLs associated with small community pleasure craft. Currently, noise studies concentrate on larger vessels that are equipped with AIS transceivers, but this focus does not fully capture the vessel use in the area. There are three coastal communities located directly within the TINMCA boundaries, and two more included in consultations, which all depend on the marine system for navigation and nourishment (Mckenna et al., 2017). By identifying community vessel use within the TINMCA, models can be developed to calculate the various SLs they produce and the potential impact they have on the acoustic environment. This is necessary, since at this point in time management recommendations focus more on mitigating larger vessel noise impacts, without fully understanding how these smaller vessels fit into the picture. Once this information is gathered, management plans can be adjusted to mitigate disturbance from these vessels, while simultaneously ensuring that such plans do not impact community activities.

Further research should also be conducted on the acoustic environment in the TINMCA itself. Placing more hydrophones throughout Tallurutiup Imanga, especially in regions of high ice flow and shallow fjords, can provide scientists and managers with a more holistic understanding of the region's soundscape. The ambient noise data used in this study was measured through hydrophones in Barrow Strait, which is not fully representative of the entire NMCA. Thus, managers should recommend that more ambient noise studies be conducted throughout the year in Eclipse Sound, Admiralty Inlet, Jones Sound and the entrance into Prince Regent Inlet. Since the Arctic is undergoing tremendous changes due to climate variability, it is important to measure the resulting change in the acoustic soundscape, as there is a possibility of higher ambient noise levels due to the increased rate of ice cavitation (Cholewiak et al., 2018).

Regardless of the intended purpose, managers still need this data to appreciate what is audible to the cetaceans when human presence is low, and to understand how anthropogenic noise compares to the natural system. This understanding can, and should, be done through the measurement of cumulative SLs and in-situ SELs. The simulation conducted in this study demonstrated that the three cetaceans do receive potentially damaging intensities from vessels, especially when exposed for long periods of time, but a computer-based model can only go so far. The next step in understanding and mitigating vessel noise impacts on the three whales of the Arctic is to actually measure what the intensities vessels produce, and the amount of time they stay in an area.

Finally, studies need to be conducted on these whale populations. In order for managers to understand the potential novelty of vessel noise disturbance on these species, they need to know how these animals react, as well as the potential for physiological and physical damage. Although the simulation resulted in no RLs or SELs reaching TTS thresholds, it does not mean that the whales are not impacted or disturbed. Physical hearing damage is a concern, but so is physiological and behavioural disturbance, areas of study that have been relatively non-existent for these northern populations. Even though there is a growing body of research focusing on cetacean and vessel interactions, it cannot be assumed that all populations react the same. In the case of the narwhals, the Eastern Greenland population stops feeding for an average of 24 hours after being disturbed, but since vessel noise is such a novel activity in the eastern Canadian Arctic, scientists cannot assume that the population in the TINMCA reacts as predicted (Blackwell et al., 2018; Cosens & Dueck, 1991). Thus, it is important to know the initial reaction to vessel presence for these populations, but it is equally important to study the prolonged impact on the animal. Managers can only do so much with the information they have, and in the case of the three cetaceans found in the TINMCA, the lack of available information may result in ineffective conservation management plans.

# Chapter 7: Conclusion

Until recently, the Arctic has been considered an acoustic refuge from vessel noise, but more studies have predicted an increase in conflict between the shipping industry and three endemic cetaceans found in this region. For this reason, vessel noise in the recently announced TINMCA boundaries, and its possible impacts on cetaceans, is an important issue that will require a great deal of attention, research and collaboration amongst scientists, managers and communities. Although calculated SLs, RLs and SELs did not surpass the TTS threshold, this does not mean that belugas, narwhals or bowheads are not impacted by vessel noise. In order to accurately predict vessel noise risks to these three species more research is needed, especially in order to understand the behavioural changes the cetaceans exhibit when disturbed by this industry. A lack of information is not grounds for inactivity though, and managers do have tools available to them and can begin implementing precautionary management approaches. In order to ensure management that plans are successful in the future, the tools must be adaptable and open to suggestions provided from further research and community consultations. The purpose of an NMCA is to harmonize human activities with conservation practices, and by understanding the impacts these activities can have on the cetacean populations, plans can be developed to ensure this happens.

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