Effects of Noise from Ore Carrier Shipping on Narwhal (*Monodon monoceros*) during the Open Water Season in the East Canadian Arctic.

by

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Abstract

Shipping is increasing in Arctic regions, exposing previously naïve marine mammal populations to underwater shipping-related noise. I assessed the impact of shipping on the acoustic habitat of narwhal (*Monodon monoceros)* and other local marine fauna. Broadband sound pressure levels (SPL; 10 Hz-25 kHz) under auditory weighing functions were compared between times of ship presence and absence using noise levels from passive acoustic recorders. Effects of ship presence and noise on narwhal behaviour were also analyzed. Broadband SPL were significantly reduced under narwhal hearing scenarios relative to unweighted levels. Narwhal perceived shipping noise at low levels and did not perceive increases until ships were within 5 km. No significant changes in narwhal behaviour were observed when only ships were present. Behavioural changes caused by other stressors were observed. Ship presence frequently occurred along with other stressors, limiting observations of behavior in the presence of ships. Continued monitoring is recommended.

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Table of Contents

List of Tables

List of Figures

List of Symbols, Nomenclature or Abbreviations

AIS: Automated Identification System

AMAR: Autonomous Multichannel Acoustic Recorder

ASAR: Autonomous Seafloor Acoustic Recorder

BSA: Behavioural Study Area

HFC: High Frequency Cetacean

PCW: Phocids in water

LFC: Low Frequency Cetacean

PTS: Permanent Threshold Shift

RAD: Relative Abundance and Distribution

SSA: Stratified Survey Area

SEL: Sound Exposure Level

SPL: Sound Pressure Level

TTS: Temporary Threshold Shift

VHFC: Very High Frequency Cetacean

Introduction

Narwhal

The Arctic (north of Latitude 66.3ºN) is a region with some of the harshest conditions for life on Earth. Due to being in a polar region, the area alternates between summers with 24-hour sunlight and freezing winters with no sunlight for months. The Arctic undergoes dramatic changes between seasons, the most dramatic and influential being the expansion and retreat of sea ice. Many animals in the Arctic have evolved specialized adaptations to survive in this environment (Scholander 1955, Welch et al. 2014).

Narwhal (*Monodon monoceros*) is one such animal that has evolved to live exclusively in the Arctic. They are one of two extant members of the Monodontidae family alongside its relative, the beluga whale (*Delphinapterus leucas*). Males grow up to 5.4 m and females grow up to 4.95 m (COSEWIC 2004). Narwhals are typically white when born and become dark grey in adolescence before reaching their more familiar speckled white and black colouration in adulthood (COSEWIC 2004). Narwhals are renowned for their long, spiraled tusks that extend forward up to three meters from their upper jaw. This very long left incisor is mostly seen in males, but is occasionally present in females (COSEWIC 2004, Reeves & Tracey 1980). On rare occasions narwhals have been found with two tusks (Reeves & Tracey 1980).

Narwhals can be found in waters off Russia, Canada, Greenland, United States, and Norway, specializing in areas that experience dense sea ice cover (COSEWIC 2004, Laidre and Heide-Jørgensen, 2011). They spend winters offshore in deep water among dense pack ice and can dive up to 800 m where they forage for prey, usually Arctic cod (*Boredogadus saida*) or Greenland halibut (*Reinhardtius hippoglossoides*; Finley & Gibb 1982, Koski and Davis 1994, Kenyon et al. 2018).

Narwhal show high site fidelity for their summering grounds (Heide-Jorgenson et al. 2015). As the sea ice retreats in spring, narwhal follow leads in the ice as it breaks up and make their way towards summering grounds (Watt et al. 2017). In the Eastern Canadian Arctic, narwhal tend to aggregate in deep reaching fjords such as Milne Inlet and Admiralty Inlet in the Eastern coast of Baffin Island from July to September when the region is ice free (Richard et al. 1994, Dietz et al. 1995).

During their time in the coastal regions, narwhal face risk of predation from several sources. Killer whales *(Orcinus orca*) have multiple ecotypes that have different hunting techniques for a wide diversity of prey species, including marine mammals. In the Eastern Canadian Arctic, marine mammal eating killer whales are seen seasonally preying on Arctic dwelling marine mammals including belugas, ringed seals (*Phoca hispida*), bowhead whales (*Balaena mysticetus*), and narwhal (Higdon et al. 2012). Killer whales have been regular visitors to the Arctic since records began in 1850 (Higdon et al. 2012). Their presence in the Arctic has been increasing over the last few decades due to longer ice-free seasons related to climate change (Higdon et al. 2012, Lefort et al. 2020).

Narwhal in these inlets are also consumed by local Inuit communities via quota-based subsistence hunting (DFO 2013). In the Eastern Canadian Arctic, local Inuit prize narwhal for their lucrative tusks and for their skin, which is eaten raw or frozen with a thin layer of blubber. The narwhal is an animal of great cultural importance to the local

Inuit, who traditionally hunt narwhal with harpoons and air-filled seal bladders from shore and from kayaks. In the modern day, the use of firearms and motorboats is more common but traditional forms of hunting still occur. Narwhal are key sources of nutrition and sustenance for the local Inuit communities that depend on them. A healthy narwhal population is tied to the food security and well-being of these remote communities (Hovelstrud et al. 2008).

Due to the remoteness of their habitat, narwhals are challenging to study. Population studies estimate between 23,397 and 87,932 narwhal in the Baffin Bay population (COSEWIC, 2004). In addition, very little is known about their lives when wintering offshore, and our understanding of their social structure is limited. In recent years, a variety of tagging and monitoring projects have revealed more about narwhal migratory behaviour, physiology, and population dynamics (Dietz et al. 2001, Heide-Jorgenson et al. 2015, Breed et al. 2017, Watt and Ferguson 2017, Williams et al. 2017, Kenyon et al. 2018). There has also been an increased urgency to better understand the biology of narwhal. The Arctic has been undergoing dramatic changes over the last 50 years due to the onset of anthropogenic climate change. The region is warming at double the rate of the global average increase in temperature, seasonal sea ice extent has been decreasing, and the underwater environment has become noisier (Laidre and Heide-Jørgensen 2005, Southall et al. 2020). Due to their heavy dependence on the increasingly unpredictable seasonal sea ice, narwhal have been highlighted as one of the most vulnerable Arctic species to climate change (Laidre et al. 2008).

Anthropogenic Noise

One of the indirect effects of climate change will be increased human commercial and industrial activity in the Arctic. The Canadian Arctic has long been considered a prospective route for shipping between the Atlantic and Pacific Oceans. This famed “Northwest Passage” was considered impassable by early explorers, but as the climate has warmed over the last century, navigating Arctic waterways has become more feasible. It is expected that Arctic shipping traffic will increase substantially in coming decades (Aulanier et al. 2017).

Expansion of human populations, infrastructure, and resource extraction globally as well as the advent of acoustic technology has led to developments into the research of underwater noise over the last few decades (Shannon et al. 2016). As this field has developed, it has also become apparent that human activity has a substantial effect on the noise levels of the world’s oceans. Explosions from seismic exploration, naval sonar, pile-driving from construction of offshore wind turbines, and commercial shipping have all been identified as major sources of anthropogenic noise that contribute significantly to increases in underwater noise levels (Weilgart, 2007). Shipping in particular has been estimated to have increased low-frequency background sound levels has doubled every decade over the past few decades (Weilgart 2007). This increase has raised concerns that anthropogenic noise may be having harmful effects on marine life, especially marine mammals, which are highly dependent on their acoustic environment for survival (Nowacek et al. 2007).

Marine Mammals and Noise

There are several considerations to be made when assessing whether an animal is impacted by anthropogenic noise. One of the first concerns is the nature of the noise source itself. Bioacousticians have divided anthropogenic noises into two types: impulsive and non-impulsive (Southall et al. 2019). Impulsive sounds are generally discrete, high amplitude signals with very short durations such as seismic explosions, pile driving, and naval sonar (Southall et al. 2019). While short in duration, the high amplitude of these signals has been known to cause significant damage to marine mammal hearing and has been known to lead to mass stranding of marine mammals (Nowacek et al. 2007). Non-impulsive sounds, or continuous noise, are sounds that tend to have longer durations than impulsive sounds and are generally lower in peak amplitude (Southall et al. 2019). The noise generated by shipping is an example of a non-impulsive noise. Both of these types of sounds can lead to short-term and long-term hearing damage to marine mammals if the animal has been sufficiently exposed (Gomez et al. 2016).

Another consideration is the subject of the exposure. Animals are not equally sensitive to acoustic magnitude at all frequencies. The same physical noise exposure may not be equally perceived by animals with different hearing abilities. The hearing range of a marine mammal can vary from infrasonic (<10 Hz) in baleen whales to ultrasonic (>100 kHz) in porpoises. Marine mammals have been divided into several functional hearing groups by Southall et al. (2019) to help researchers estimate the amount of noise exposure occurring in the acoustic habitats that would be likely perceived by animals within that functional hearing group.

While anthropogenic noise can cause hearing damage and mortality, the effects of noise can also be more subtle, including behavioural responses such as avoidance, or increased physiological stress (Southall et al. 2019). These effects can occur even if the increased noise levels are low, and such effects can be highly variable between individuals in a population and are context-specific (Southall et al. 2007, Gomez et al. 2016). These subtle effects are much harder to detect within a population, but the consequences can be substantial if the effects interfere with critical life history functions such as feeding, raising young, or detecting predators. When assessing the impact of noise on a population, the ecological, social, and individual contexts of the animals need to be considered (Gomez et al. 2016, Southall et al. 2019). We must consider how the noise from the source of interest affects the acoustic habitat (the noise environment as perceived by the subject) where these animals reside. Acoustic habitat will vary among different marine mammal groups due to the highly dissimilar hearing ranges of the functional hearing groups.

Noise in the Arctic

Until recently, the Arctic soundscape has been relatively free of many sources of anthropogenic noises that have led to increases in underwater noise levels elsewhere. As the presence of anthropogenic noise increases in coming decades, it is important to understand the potential impact that introduction of new sources of noise may have on the local wildlife. In 2015, an iron mine based in the Qikqtaaluk region of Northern Baffin Island began exporting iron ore from its port in Milne Inlet during the ice-free season. This industrial activity has introduced ore carriers, cargo vessels, oil tankers, and icebreakers into Milne Inlet and operations have been ongoing during the ice-free season each year since. The shipping route to and from the port overlaps with narwhal summer habitat, including the body of water between Upper Milne Inlet and Koluktoo Bay. Narwhal frequently travel in and out of Koluktoo Bay past Bruce Head as part of their ancient migratory route and it serves as an important refuge for narwhal during the summer months (Adrian Ootova, Pond Inlet, Nunavut, personal communication).

Since the mine has been in operation, there has been an environmental monitoring program in place to monitor the narwhal and the ore carriers, and to determine if the ore carriers influence narwhal behaviour in the inlet (Frouin-Muoy et al. 2020, Golder Associates Ltd. 2020a, 2020b, 2020c). This study is a small part of the program that is conducting an environmental assessment of the mine's activities as required by regulators. Shipping traffic includes bulk carriers exporting ore from the mine, general cargo ships, and oil tankers. The icebreaker "MSV Botnica" services this shipping route during the shipping season. Shipping operations occur in the open water season, usually lasting from July to October depending on ice conditions.

Research Questions/Objectives

This study investigates the effect of the recent introduction of large vessel traffic, in particular ore carriers, on the acoustic habitat and behavior of narwhal that use Milne Inlet during the ice-free season. The area of interest is the section of the shipping route in Milne Inlet that overlaps with narwhal habitat near Koluktoo Bay. I address two separate research questions in this thesis:

1) What noise levels are narwhals and other marine mammals exposed to during a single ore carrier transit? This chapter uses sound levels from passive acoustic monitoring devices and Automatic Identification System (AIS) to track shipping in the area to investigate how the presence of a vessel can contribute to noise levels in the study area. Hearing weighting functions from Southall et al. (2019) are applied to noise levels to simulate the underwater acoustic habitats of three cetacean hearing groups as well as phocid pinnipeds. The effects of shipping noise are assessed through these weighted noise levels to determine how each group may experience the sound pressure levels (SPL) of a passing ore carrier.
2) How do narwhals respond to the presence of shipping and its associated noise? This chapter uses land-based visual survey data to assess if the presence of ore carriers, as well as their associated noise, cause narwhal to change their surface behaviour when they are in the area around the shipping route. Narwhal abundances and group behaviours are examined in the presence and absence of shipping, and the results are compared with narwhal behaviour when other stressors were present, such as killer whales and Inuit hunting activity.

Chapter 1 : Exposure of ore carrier noise to marine mammals in Milne Inlet and Koluktoo Bay

Introduction

Anthropogenic Noise Pollution

Over the last two decades, the use of acoustic technology has become an increasingly popular tool to monitor marine mammals. Autonomous acoustic recorders collect data for extended periods of time regardless of weather, and at a lower cost compared to traditional survey methods. Acoustic monitoring has been used to better study marine mammal underwater communication, seasonal migrations, and their acoustic environments (Weilgart 2007, Shannon et al. 2016, Marcoux et al. 2017, Southall et al. 2020).

In recent decades, there have also been rising concerns about noise pollution. Pollution is defined as the release of a potentially harmful chemical, physical, or biological agent to the environment due to human activity (Weilgart 2007). This definition also extends to noise pollution, which is the release of unwanted acoustic energy from human activities. Anthropogenic noise can be released by design, which is the case for air gun based seismic surveys, and naval sonar operations (Weilgart 2007, Shannon et al. 2016). Acoustic pollution can also be released unintentionally as a by-product of human activity, most notably by shipping (Weilgart 2007). In some areas of the world, low-frequency background ocean noise has increased by 3 dB every decade for the last few decades. This has been attributed to an increase in worldwide commercial shipping (Weilgart 2007, Tyack 2016).

One of the major concerns is the effect of growing levels of anthropogenic noise on the lives of marine mammals, especially cetaceans. Cetaceans use sound for important biological functions including navigation and communication. Anthropogenic noise pollution can mask communication calls, shift long term trends in animal acoustic and physical behavior, and expose marine mammals to increased risk of temporary or permanent hearing loss, also known as temporary or permanent threshold shifts (TTS/PTS; Erbe et al. 2016, Gabriele et al. 2018, Blair et al. 2016, Bejder et al. 2006, Nowacek et al. 2007).

Underwater noise levels can vary considerably among different locations. While shipping contributes much to the modern soundscape of the world's oceans, sound levels are also affected by wind, bathymetry, seismic activity, biological activity, as well as the presence of ice (Southall et al. 2020, Urick 1983).

Marine Mammal Hearing

Marine mammals have evolved a variety of ways to hear underwater. In odontocetes, sound travels in through their lower jaw into the inner ear (Mooney et al. 2008), in pinnipeds the hearing pathway is more like other terrestrial mammals (Møhl and Ronald 1975), and while baleen whales have earbones, their hearing pathway is poorly understood (Southall et al. 2019). Because of the anatomical diversity of hearing pathways, marine mammals have a wide diversity of hearing ranges from infrasonic (<10 Hz) hearing in baleen whales to >100 kHz in small porpoises (Kastelein 2002, National Marine Fisheries Service 2018, Southall et al. 2019). These differing hearing sensitivities across frequencies lead to varying perceived levels of exposure to the same source of noise. Auditory weighting functions have been developed for many different animals to transform sound levels to estimate the noise levels perceived by the subject. The most widely known weighting functions include the A-weighting developed to simulate human hearing, and there have also been several weighting functions developed for marine mammal hearing (Houser et al. 2017, Southall et al. 2019). The weighting function adjusts the received levels from the hydrophone to have the same frequency response as the audiogram of the species concerned. The use of weighted broadband SPL and weighted sound exposure levels (SEL) have been used in both human and animal studies as common metrics for noise exposure (Pawłaczyk-Luszczyńska 2003, Vos 2004, Martin et al. 2019, Tougaard and Beedholm, 2019).

Narwhals are dependent on using sound as a means of navigation and communication. They produce whistles, clicks, and knocks for communication, and use echolocation clicks to navigate and hunt (Marcoux et al. 2012). Until recently, narwhal that summer in Milne Inlet lived in a pristine acoustic environment with very low shipping traffic, so the introduction of ore carrier shipping in their summer habitat is a relatively new phenomenon. While effects of modern anthropogenic activity on the narwhal have not been explored in depth, narwhal have been observed displaying avoidance behavior during icebreaking in the shoulder season (Cosens and Duck, 1993). However, it is not yet clear if this same behavior will occur in the presence of ore carriers during the open water season.

Looking Ahead

As climate change advances, the Arctic is becoming rapidly warmer, and sea ice coverage has been steadily decreasing over recent decades (Stroeve and Notz 2018). This opening of the Arctic will lead to opportunities for resource exploration in some areas that were previously inaccessible. Shipping traffic associated with industrial and commercial activity in the area is expected to increase in coming decades (Aulanier et al. 2017, Halliday et al. 2017). With the forecast of increased shipping traffic in the Arctic, developing a comprehensive understanding of the potential impacts of shipping on local marine fauna is of paramount importance. This is particularly the case for narwhal since local Inuit depend on the narwhal for subsistence and culture. The shipping route in Milne Inlet overlaps with important narwhal summer habitat (Marcoux et al. 2009), and so it is a key location to assess the impact that ore carriers may have on the species.

Research Questions/Objectives

The goal of this chapter is to understand the acoustic impact that shipping has on the soundscape of Milne Inlet and Koluktoo Bay, and how local marine mammals perceive the noise from shipping. This was done by using recordings from passive acoustic monitoring devices from up to five locations across four years. The perception of noise by marine mammals was estimated by using four hearing weighting functions by Southall et al. (2019). These weighting functions were used to estimate the noise levels perceived by narwhal and other local marine mammals. Noise levels were examined at multiple locations in the study area and across up to four years. Acoustic metrics including broadband SPL and SEL were calculated and compared to determine how ore carriers contribute to acoustic habitats of local marine fauna when transiting through Southern Milne Inlet. Noise levels were measured along the shipping route and in the important narwhal habitat of Koluktoo Bay. Characteristics of ship passages were also examined to determine if certain factors contributed to higher noise levels.

Materials and Methods

Study Area

This study took place in Milne Inlet; a large inlet in Northern Baffin Island in the Qikqtaaluk region of Nunavut, Canada (72.066ºN, 80.476ºW). Milne Inlet is a large inlet that is a part of the Eclipse Sound system, which also includes Tremblay Sound. Milne inlet ranges from Eclipse Sound South, around Bruce Head, and terminates at a fork, with Assomption harbor and the mine port to the South and Koluktoo Bay to the West (Figure 1.1). This study took place at the southern end of Milne Inlet, ranging from the base of Stephen's Island to the fork of Koluktoo Bay and Assomption Harbour, covering an area of ~133 squared kilometers (Figure 1.1). Koluktoo Bay is a historically significant summering ground for narwhal, who return every year, aggregating in the hundreds and possibly thousands (Marcoux et al. 2009, Adrian Ootova, Pond Inlet, Nunavut, personal communication). Narwhals regularly move in and out of the bay throughout the summer, entering and exiting past Bruce Head. The area is a traditional hunting ground for local Inuit, who frequent the area during summer in small outboard engine boats. There are several hunting camps in the area, the majority of which are located on the west side of Milne Inlet and serve as places from which local Inuit hunt narwhal and seal (Adrian Ootova, Pond Inlet, Nunavut personal communication).

Figure 1.1: Map of Milne Inlet/Koluktoo Bay including the locations of Bruce Head, Koluktoo Bay, the Mine Port, and the nominal shipping route (in red). Maps sourced from Google (2020).

A port belonging to Baffinland Iron Mines Corporation is located at the terminus of Assomption Harbour. This port exports iron ore extracted from the interior of Baffin Island, and offloads cargo and fuel from general cargo and oil tankers that service the mine. While ore extraction occurs year-round, exportation only occurs during the ice-free shipping season from July to late October. The shipping route passes Koluktoo Bay and continues out into Milne Inlet (Figure 1.1). Anchorage sites were located beyond the study area near Ragged Island (72.473194 ºN, 80.018069 ºW) where ships wait for space at the port. It takes ~23 hours for a typical bulk carrier to be filled up, and so the study area would typically experience two ships in a day: one leaving (Northbound), and one entering (Southbound). The southern part of Milne Inlet area was the best location for documenting the interactions between ships and narwhals due to the reliable presence of both narwhals and shipping (Marcoux et al. 2009). Bruce Head, the headland that separates the upper and lower sections of Milne Inlet also provided an excellent vantage point over most the study area for land-based observational surveys to be conducted.

Data Collection:

Recorder Deployments

Since the mine has been in operation, monitoring programs have been implemented to assess the impact of shipping on the local marine wildlife (Frouin-Muoy 2020, Golder 2020a, 2020b, 2020c). In 2014, 2015, 2018, and 2019, environmental monitoring of the shipping route included passive acoustic monitoring. The same recording locations were used among years allowing for noise levels to be compared across years (Figure 1.2).

Figure 1.2: Map of Milne Inlet/Koluktoo Bay indicating the locations of the five Autonomous Multichannel Acoustic Recorders (AMARs) and nominal shipping route (in red). Maps sourced from Google (2020).

Recorder deployments were conducted by two different subcontractors with different naming methods, so recorder locations were standardized across all years into a lettered system. Recording locations A and D along the shipping route were used across all years of recording, all locations were used in 2018, and locations A, C, and D were used in 2019 (Figure 1.2). The recorder depths ranged from 190 m to 300 m depth (Table 1.1).

Greeneridge Sciences deployed two Autonomous Seafloor Acoustic Recorders (ASARs) along the shipping route in 2014, designated as ASAR North and ASAR South (Table 1.1), and were later assigned in this study as locations AMAR D and AMAR A respectively. The ASARs recorded at a sampling rate of 44.1 kHz, and minute by minute third octave bands from 10 Hz to 20 kHz were later extracted by Jasco Applied Sciences. They were deployed on 30 July 2014 and were retrieved on 26 September 2014, providing 50 days of recordings. The 2015 deployments followed the same strategy as the 2014 deployments, with ASAR North and South in similar locations and with the same sampling rate (Table 1.1). They were deployed on 2 August 2015 and were retrieved on 3 October 2015, providing 62 days of recordings.

In 2018, Jasco Applied Sciences deployed five Autonomous Multichannel Acoustic Recorders (AMARs) in the study area. AMAR 1 and AMAR 4 were deployed in locations A and D (Table 1.1). In addition, three AMARs were put in new locations (Figure 1.2). AMAR 2 (Location B) was located near AMAR 1 (Location A) but located off the shipping route towards the mouth of Koluktoo Bay. AMAR 3 (Location C) was placed in Koluktoo Bay itself and AMAR 5 (Location E) was deployed along the shipping route near Stephen’s island (Figure 1.2).

Table 1.1. List of autonomous recorder deployments in 2014, 2015, 2018, and 2019 with year, name, location (general and latitude/longitude), duty cycle and sampling rates, and total minutes of LF/HF recordings.

Year	Recorder Name	Location	Deployment Latitude/Longitude	Deployment Depth (m)	Duty Cycle & Sampling Rate	Minutes of LF/HF Recordings
2014	ASAR N	D	72.066/-80.5121	291	44.1kHz	82069/
2014	ASAR S	A	72.0344/-80.6127	281	44.1kHz	82097/
2015	ASAR N	D	72.0645/-80.4877	300	44.1kHz	64636/
2015	ASAR S	A	72.035/-80.6651	200	44.1kHz	88884/
2018	AMAR 1	A	72.0277/-80.6459	209	14 min 64kHz/ 1 min 200kHz	73682/5263
2018	AMAR 2	B	72.0355/-80.6656	205	14 min 64kHz/ 1 min 200kHz	73730/5267
2018	AMAR 3	C	72.0716/ -80.7604	201	14 min 64kHz/ 1 min 200kHz	73954/5287
2018	AMAR 4	D	72.0677/-80.5157	225	14 min 64kHz/ 1 min 200kHz	73708/5265
2018	AMAR 5	E	72.1121/-80.4904	245	14 min 64kHz/ 1 min 200kHz	74097/5292
2019	AMAR 1	A	72.0276/-80.6477	190	14 min 64kHz/ 1 min 628kHz	72590/5185
2019	AMAR 2	C	72.07/-80.7597	202.5	14 min 64kHz/ 1 min 628kHz	72604/5186
2019	AMAR 3	D	72.0672/-80.2086	223.5	14 min 64kHz/ 1 min 628kHz	72575/ 5183

In 2019, three AMARs were deployed in locations of A, C, and D. In both years, AMARs were set to have a duty cycle rotation with 14 minutes at a 64 kHz sampling rate, from which 10 Hz -25 kHz third octave bands were provided, and one minute at a higher frequency sampling rate (200 kHz in 2018, 628 kHz in 2019; Table 1.1), from which third octave bands were provided for 10 Hz -100 kHz in 2018 and 10 Hz -315 kHz in 2019. The minute by minute third octave bands datasets from ASARs and AMAR recordings were provided by Jasco Applied Sciences.

AIS Ship Tracking Data

Automatic Identification System (AIS) is a tracking system that uses dedicated VHF transponders onboard a ship that can be tracked by orbiting GPS satellites. AIS data provides the ship's identification, length, location in latitude and longitude, and speed. It is typically used to monitor vessel traffic and avoid collisions, but AIS data has also been used in research into shipping and noise (Hermannsen et al. 2019, Mikkelson et al. 2019, Frouin-Muoy et al. 2020). AIS shore-based receivers were deployed during all field seasons in Milne Inlet. Located at a high vantage point on Bruce Head, the AIS receiver had a virtually uninterrupted view of the shipping route in Milne Inlet. AIS data collected by shore-based receivers were periodically collected either by researchers via helicopter or a hike from Bruce Head camp, escorted by a polar bear monitor. The data collected from shore was collected in tandem with exactEarth (2020). GPS satellite tracking data was available in the study area during all study years, however there were no transits of ore carriers in 2014, and a very small number in 2015. The magnitude of AIS entries was significantly lower with ~3000 entries for 2014 and ~6000 entries for

2015 compared to ~40,000 entries for 2018 and 2019 each. Analysis involving AIS was limited to 2018 and 2019 due to the lower quantity of AIS entries in 2014/2015 compared to 2018 and 2019.

Acoustic Analysis

Hearing Weighting Functions

Four marine mammal hearing functional groups from Southhall et al. (2019) were used to represent the hearing of the various local marine mammal species in the study area. Audiograms have not been created for narwhal, however beluga whale audiograms were one of the cetaceans used to create the high frequency cetacean functional weighting group (HFC; Southall et al. 2019). Given that narwhal are in the same family as beluga (Monodontidae), are roughly similar in size, and in some cases have been observed interacting with one another, I assume here that they exhibit similar hearing abilities. Several audiograms have been conducted for beluga in captivity and in the wild (Awbrey et al. 1988, Klishin et al. 2000, Castellote et al. 2014), and was one of the species used to formulate the high frequency cetacean weighting function in Southall et al. (2019). For this study, the high frequency cetacean weighting function will be used to simulate the hearing of narwhal. The weighting functions were taken from the exposure functions in Southall et al. (2019).

Bowhead whales, like other baleen whales, have not had audiogram measurements performed. The modelled low frequency cetacean weighting function (LFC) was applied to simulate their hearing. Audiograms are available for ringed seals (Sills et al. 2015), however a generic phocid in water (PCW) weighting was used to simulate hearing for ringed (*Pusa hispida*), bearded (*Erignathus barbatus*), harp (*Pagophilus groenlandicus*), and hooded seals (*Cystophora cristata*). An additional hearing weighting function was also applied; the very high frequency cetacean (VHFC) to represent the hearing of harbour porpoises (*Phocoena phocoena*). Although not known to visit the study area, harbor porpoises are found in other Arctic regions (Lehnert et al. 2013).

Broadband Measurements

Broadband SPLs (in dB re 1 μPa) were calculated using the 1/3 octave band levels from 10 Hz to 25 kHz for both LF and HF recording minutes to provide a continuous and standardized measurement of Broadband SPL across the measured frequencies. Since shipping noise is continuous and dominates in frequencies below 1 kHz (Arveson and Vendittis 2000), this 10 Hz – 25 kHz Broadband SPL was considered to be an appropriate sound metric to used in this analysis. Broadband SPL was calculated for every minute of recording for the unweighted noise levels and with the HFC, LFC, PCW, and VHFC weightings applied. This provided five different Broadband SPL measurements for every minute of recording, one representing raw measured noise, and four which represented the hearing of the different marine mammal hearing groups.

AIS Analysis

Characteristics of ship transits were defined in the AIS data depending on its general direction and its location relative to recorders. An ore carrier was considered ore-laden if it was departing outbound (90° > course >270°) from port and unladen if it was inbound port from the north (southbound, 90° < course < 270°). For AMAR locations A, D, and E (along the shipping route), the deployment latitude was used to determine if the ship was north or south of the AMAR. From this and the previously determined direction, it could be determined if the ship was moving towards the recorder, or away from it. For AMARs B and C, since they were located perpendicular to the ore carrier transit direction from AMAR A, their ship locations were categorized as either north or south of AMAR A. AIS data was sporadic in the timing of received entries, and as a result did not bear the same resolution in time as the acoustic recorder. To remediate this, the AIS data was reorganized to have one AIS entry per minute. In the case that there were multiple ship entries in a minute, the entry with the closest distance to the recorder was used. Once in the same resolution, the AIS data was aligned to the minute-by-minute noise levels from the recorders.

Interpolation of Ship Presence

Output of AIS entries over time were not always consistent. During a ship transit, there were gaps in the AIS data coverage that resulted in a false negative for ship presence. These gaps generally did not last longer than a few minutes. An interpolated presence /absence of ships was used to fill in the gaps and to facilitate measurements when it was important to know that no ore carriers or other large ships were in the area. Ship presence was interpolated as present if an AIS entry for a ship was (1) transiting within 15 km of the AMAR and was present within 60 minutes (either side) of a given recording minute or (2) transiting within 15 km of the AMAR and was present within 15 minutes (either side) of a given recording minute. This large 60-minute bracket was applied to prevent ship noise from appearing in times where ships were considered absent. The 15-minute bracket was used to limit the times to when a ship was in or close to the study area. The time between the 1-hour and 15-minute bracket is considered an area with mixed confidence in ship presence or absence and was excluded from Broadband SPL comparisons of times when ships were present versus times when ships were absent.

Statistical Analysis

Statistical analysis of the data was conducted in Microsoft Excel (Microsoft Corporation 2018) and RStudio (RStudio Team 2019).

Weighting Functions

A percentile is a score below which exists the given percentage of the data (eg. 5% of the values in the data will be found below the 5th percentile). The 0, 5th, 25th, 50th, 75th, 95th, and 100th percentiles of each third octave band from AMAR A in 2018 were used to examine the effect that each hearing weighting function had on the third octave band SPL from 10 Hz to 25 kHz of the unweighted noise levels. The effect was examined in AMAR A in 2018. The unweighted, HFC, LFC, PCW, and VHFC weighted third octave band percentiles were plotted to compare differences across the frequency spectrum of the noise data.

Broadband SPL Comparisons

Broadband SPLs were compared between times when ships were present within a 15 km radius +/- 15 minutes versus times when ships were absent within a 15 km radius +/- 60 minutes to assess if the presence of ships in the area significantly contributed to noise levels across locations in 2018 and 2019. The 45-minute bracket between the two categories was excluded from analysis. The comparison was done for unweighted, HFC, LFC, PCW, and VHFC weightings. The effect of presence versus absence of shipping on the broadband SPL was tested with a student's t-test for each location, weighting, and year, with each being compared independently. A significant difference in mean Broadband SPL was considered significant if the effect size exceeded 3 dB. The t-tests applied for broadband comparisons between times when ships were present versus absent require the assumption of normality and independence of the data (Sawilowsky and Blair 1992). Linear, LFC, and PCW Broadband SPLs showed relatively normal distributions, however HFC and VHFC Broadband SPLs had a left-skewed distribution. T-tests can be robust to deviations in normality with large sample sizes. Due to the large sample sizes of the recording broadband levels, the results inferred from these t-tests can still be interpreted as valid differences/ non-differences.

Broadband SPLs were also examined between the study years. The noise levels from 2014 and 2015 had a lower sampling rate than 2018 and 2019, so for this comparison, Broadband SPLs were recalculated using third octave bands between 10 Hz – 20 kHz so that the sampling rates were equivalent and comparable between all years. Broadband SPL differences between years were examined under all weighting scenarios, and were visually interpreted using boxplots.

Spatial Mapping with Generalized Additive Models

AIS data points were mapped over the study area with estimated Broadband SPL predicted using a generalized additive model (GAM) from the R package “mgcv”. GAMs are flexible models that create smoothed fitted models by splicing the data into *k* chunks (Wood 2017). The Broadband SPL was estimated using latitude and longitude of AIS points with corresponding broadband values from AMARs A-E in 2018 and A, C, and D in 2019. The estimated Broadband SPL was mapped onto the AIS data points to observe general trends in ship noise contribution and the effect of local geography as an ore carrier travels northbound or southbound. GAMs were performed for unweighted and HFC weighted Broadband SPL, at all recorder locations in 2018 and 2019. The number of knots was assigned for each model so that the p-value for the k-1 index was less than 0.05. The maps were then visually analyzed to compare the noise profile of Broadband SPL in the study area between different recorders, different transit directions, and the use of the HFC weighting function. This analysis was only performed for unweighted and HFC weighted Broadband SPL to focus on the effect on narwhal.

Per-Transit Measurements

To quantify the effect of a single ship transit, an analysis was performed that looked at the noise exposure caused by individual ship transits. A transit was defined as when a ship transited either from the Upper area of Milne Inlet to just north of the anchorage at the port (Southbound/empty), or from the port to upper Milne Inlet (Northbound/ore-laden). The date and times of these transits were defined by the date and time of ship presence within 15 km of AMAR A ± 60 minutes. Each transit was manually identified and given a unique identification number, with numbers increasing incrementally throughout the listening period of each year. When more than one ship (of any type) was categorized as present (within an hour of first/last AIS location), the transits were classified as overlapping. The travel direction, average speed when <15 km from AMAR A were taken for each transit from AIS data.

Ambient Level

To assess the impact of a single transit, it was important to have ambient noise level measurements for that given transit. Ambient noise varies across time, and so the local ambient level needed to be quantified to accurately assess how much noise is being contributed by shipping. A series of measurements were taken for each transit to quantify the acoustic impact of the passage on the soundscape. This ambient level was measured as the average Broadband SPL (Unweighted, HFC, LFC, PCW, VHFC) up to 60 minutes prior to the beginning of a transit. In the cases when an ambient measurement could not be made due to the presence of another transit in those 60 minutes, the ambient level from the most recent prior passage was used.

Duration Measurement

Each transit had a measurement made to estimate the amount of time that the ship was considered audible above ambient level during its transit. This was measured as the total number of minutes within a transit that the Broadband SPL (Unweighted, HFC, LFC, PCW, VHFC) was 3 dB above the ambient level. This assumes that all noise levels 3 dB above ambient during a transit are due to ship noise, although it is possible for noise levels to increase from other sources.

Sound Exposure Level

SEL is a measurement of sound (in dB re 1 μPa^2·s) that can be used to estimate the exposure level of noise over time (Martin et al. 2019). This is particularly useful for measuring sources of chronic noise, like shipping. SEL can be used to test if an anthropogenic noise source reaches or exceeds a threshold for inducing TTS or PTS for a given species, as outlined in Southall et al. (2019). The formula for SEL is the following:

$$SEL_{cum} = SPL + 10\log_{10}(t_s)$$

where Broadband SPL is equal to the mean sound level over the duration, and t_s is the noise exposure duration in seconds. Here, exposure duration is measured as the total time a transit exceeded 3 dB above the ambient level. SEL was calculated for unweighted and the four functional hearing groups using their respective mean Broadband SPL, exposure duration, and ambient level for each transit. The SEL of each weighting was compared to the TTS and PTS threshold levels (NMFS 2018; Southall et al. 2019), to determine if TTS or PTS levels are reached or exceeded by any transits.

To explain variation in SEL, a stepwise regression model selection was created to determine if the year of recording (2018/2019), direction of transit (Northbound/Southbound), mean ambient level prior to transit (dB re 1μPa), or mean transit speed (knots) had a significant effect on the estimated SEL. The model with the lowest AIC was used to select the most parsimonious model. A linear model was run for unweighted, HFC, LFC, PCW, and VHFC SELs separately.

Results

The Weighting Functions

For HFC and VHFC weightings, frequencies 10 kHz and lower experience a dramatic linear decline with decreasing frequency compared to the unweighted values (Figure 1.3). One-third octave SPL percentiles below 100 Hz in HFC and VHFC are weighted so heavily that the estimated SPL is below 0 dB re 1 µPa (Figure 1.3). LFC weighting had the most similar sound profile to the unweighted noise levels, with the SPLs per third octave band being slightly lower than the unweighted SPL. The PCW frequencies below 1 kHz show a similar decline as seen in HFC and VHFC, however the decline is less extreme and the amplitudes of frequencies above 1 kHz are more similar to those of the LFC weightings (Figure 1.3).

Broadband Comparisons on Times with Ships Present & Absent

Alongside the effects of the hearing weighting functions, mean noise levels differed depending on the year of recording, the recorder location, and the presence of shipping. In 2018, Unweighted Broadband SPLs increased considerably during times when ships were present at all AMAR locations, with 7-10 dB increases for times when ships were present at AMAR locations A, B, D, and E, and a 4 dB increase at AMAR C (Figure 1.4, Table 1.2). In 2019, increases were still present but were lower compared to 2018, with AMAR D noise levels not increasing when ships were present (Figure 1.5, Table 1.2). HFC and VHFC weightings showed no significant increases in noise level between times when ships were present versus when ships were absent for 2018 or 2019 at any AMAR location (Figure 1.4, Table 1.2). In these weightings, the calculated

Broadband SPLs are considerably lower than the unweighted, LFC and PCW broadband, SPL.

LFC followed a similar pattern of increased Broadband SPL as Unweighted, with significant increases of 3-7 dB for times when ships were present at all AMAR locations in 2018 and AMAR A in 2019, (Figure 1.5, Table 1.2). The PCW weighting had lower increases in SPL than LFC and unweighted but did show some significantly increases in broadband SPL when ships were present at AMAR D and E in 2018 and AMAR D in 2019 (Figure 1.5, Table 1.2). The HFC and VHFC adjusted received levels consistently saw no increases in ship presence. The unweighted, LFC, and PCW Broadband SPLs also had no significant increases during ship presence at some locations in 2019 even though they were significant in 2018. Across locations, AMAR C/Koluktoo Bay consistently had the lowest increases in noise level during times when ships were present. Only Unweighted and LFC showed significantly higher noise levels when ships were present, and for both weightings the increase was only significant in 2018 (Figures 1.4, 1.5, Table 1.2).

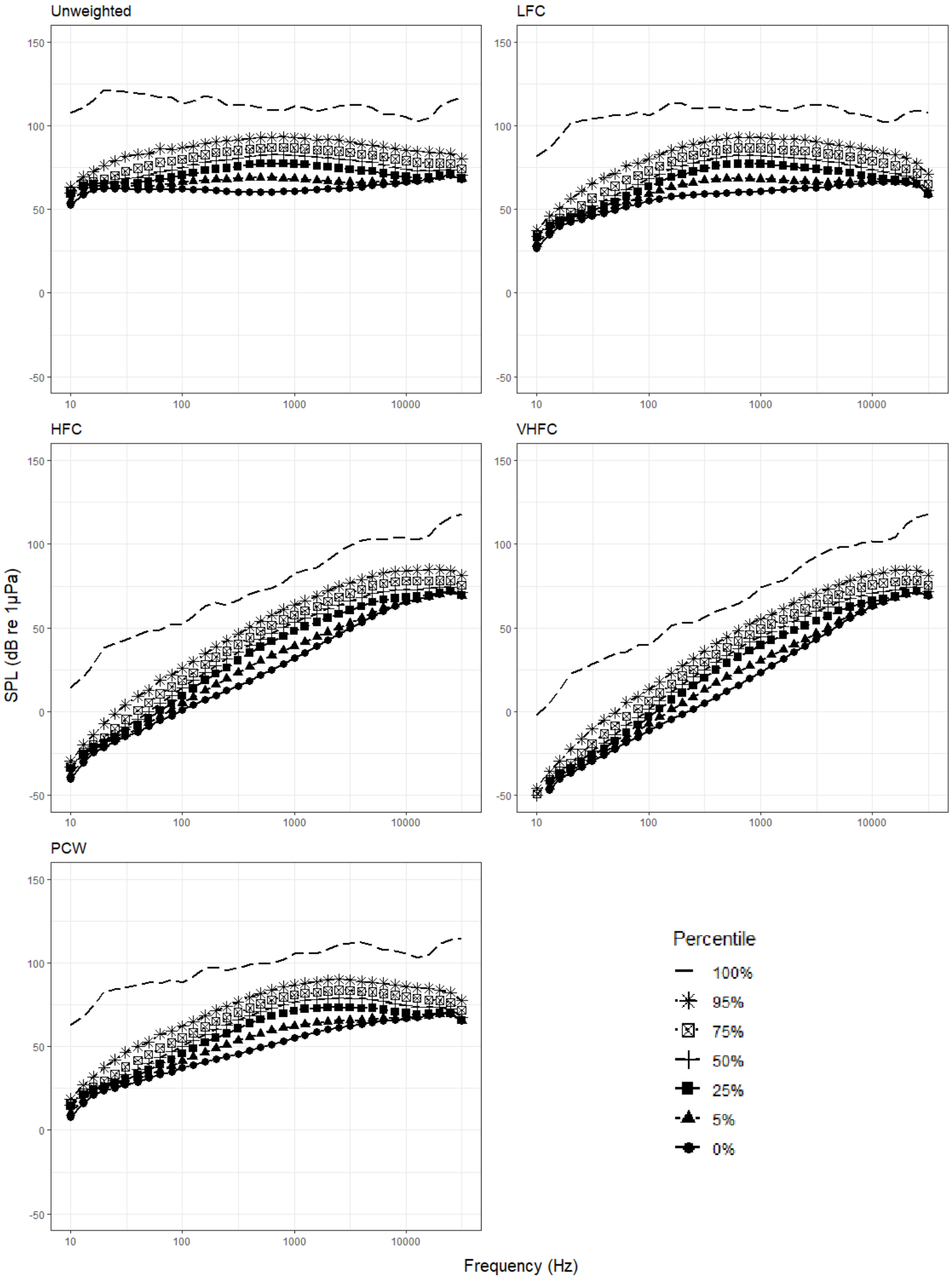

Figure 1.3: Panel graphs showing 0, 5th,25th, 50th, 75th, 95th and 100th percentiles of the full recording period for Unweighted, HFC, LFC, PCW, and VHFC Broadband SPL for third octave bands from 10 Hz to 25 kHz at AMAR A in 2018.

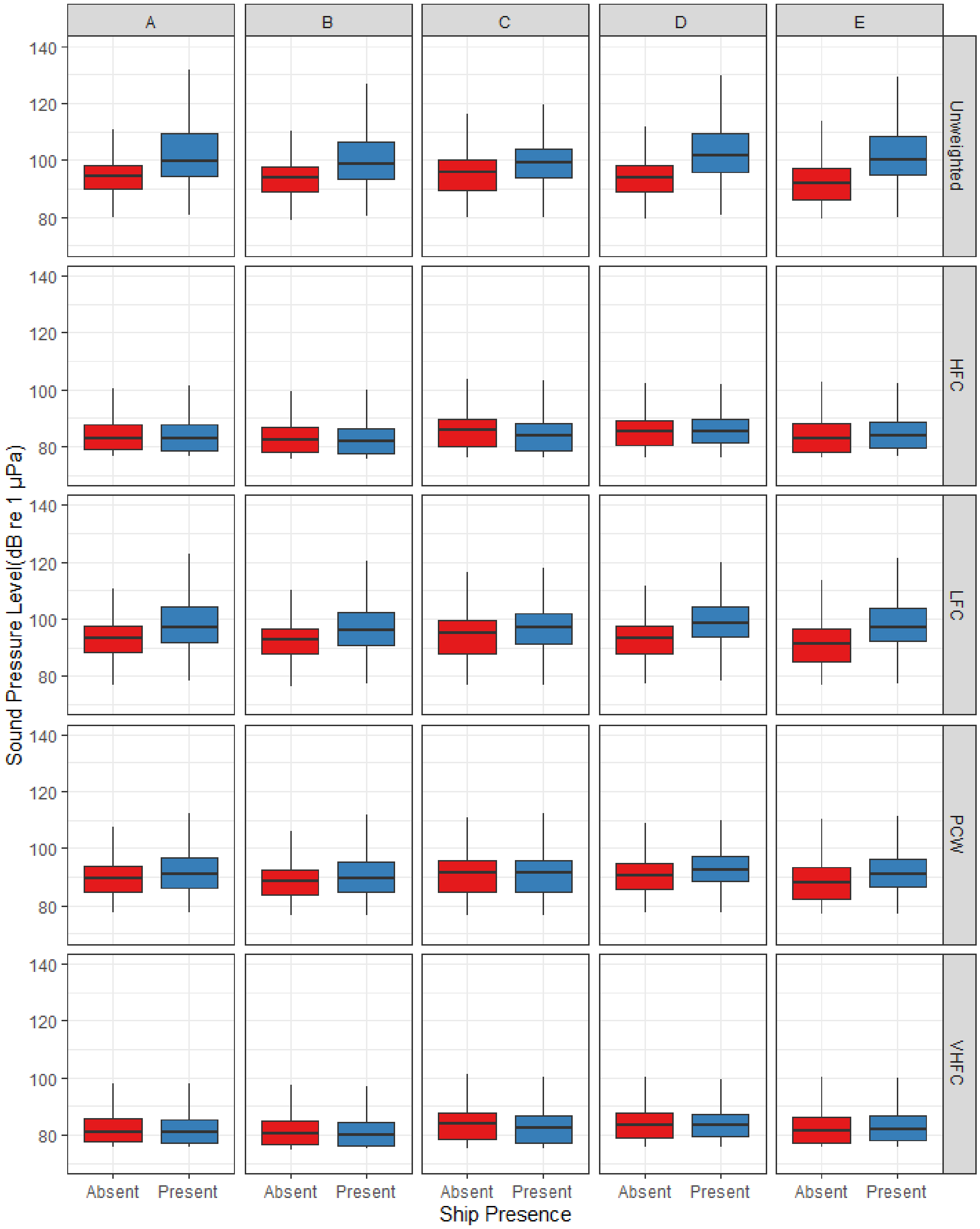

Figure 1.4: Boxplots displaying the 5th, 25th, 50th, 75th, and 95th percentiles of Broadband SPLs of underwater noise between times when ships were present (blue) within 15 km ± 15 minutes, and times when ships were absent (red) within 15 km ± 60 minutes, for Unweighted, HFC, LFC, PCW, and VHFC weightings across AMARs A-E from 2018 recordings.

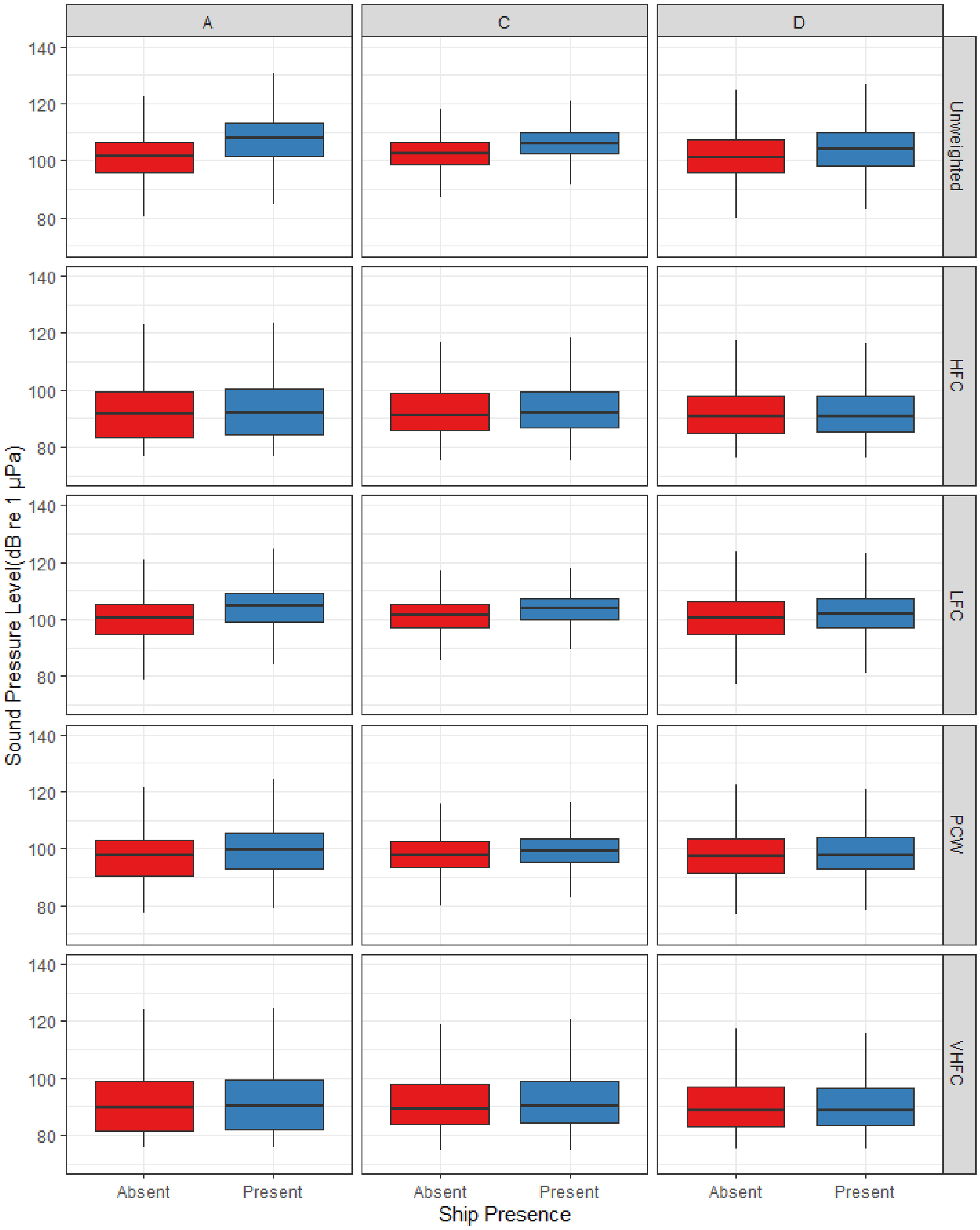

Figure 1.5: Boxplots displaying the 5th, 25th, 50th, 75th, and 95th percentiles of Broadband SPLs of underwater noise between times when ships were present (blue) within 15km ± 15 minutes, and times when ships were absent (in red) within 15 km ± 60 minutes, for Unweighted, HFC, LFC, PCW, and VHFC weightings across AMARs A, C and D from 2019 recordings.

Table 1.2: T-test results for comparisons of times when ships were present or absent in 2018 and 2019 for all locations and weightings. Tests with increases greater than 3 dB highlighted in bold with an *.

Weighting	Year	Location	t	df	p-value	Absent Mean (dB re 1 µPa)	Present Mean (dB re 1 µPa)	Difference in Means (dB re 1 µPa)
Unweighted	**2018**	**A**	**-107.4**	**30368**	**<0.0001**	**94.2**	**102.5**	**8.3***
Unweighted	**2018**	**B**	**-100.4**	**30974**	**<0.0001**	**93.5**	**100.9**	**7.4***
Unweighted	**2018**	**C**	**-70.7**	**38917**	**<0.0001**	**95.0**	**99.6**	**4.6***
Unweighted	**2018**	**D**	**-119.5**	**29858**	**<0.0001**	**93.8**	**102.8**	**9.0***
Unweighted	**2018**	**E**	**-126.8**	**29670**	**<0.0001**	**92.0**	**102.1**	**10.1***
HFC	2018	A	-6.8	39651	<0.0001	84.2	84.6	0.3
HFC	2018	B	1.2	41552	0.227	83.3	83.3	-0.0
HFC	2018	C	22.3	46502	<0.0001	85.4	84.4	-1.0
HFC	2018	D	-12.6	38278	<0.0001	85.6	86.3	0.7
HFC	2018	E	-19.6	36749	<0.0001	84.0	85.0	1.0
LFC	**2018**	**A**	**-83.0**	**33214**	**<0.0001**	**92.9**	**98.8**	**5.9***
LFC	**2018**	**B**	**-77.0**	**33224**	**<0.0001**	**92.2**	**97.6**	**5.4***
LFC	**2018**	**C**	**-46.2**	**41137**	**<0.0001**	**93.8**	**96.8**	**3.0***
LFC	**2018**	**D**	**-96.7**	**32157**	**<0.0001**	**92.7**	**99.5**	**6.8***
LFC	**2018**	**E**	**-101.5**	**32630**	**<0.0001**	**90.7**	**98.4**	**7.7***
PCW	2018	A	-39.0	35876	<0.0001	89.5	91.9	2.4
PCW	2018	B	-36.2	35512	<0.0001	88.4	90.7	2.3
PCW	2018	C	-6.4	43399	<0.0001	90.4	90.7	0.3
PCW	**2018**	**D**	**-49.7**	**35697**	**<0.0001**	**90.2**	**93.2**	**3.0***
PCW	**2018**	**E**	**-57.6**	**35229**	**<0.0001**	**88.1**	**91.7**	**3.6***
VHFC	2018	A	-3.4	40424	0.0005	82.8	83.0	0.2
VHFC	2018	B	6.4	43128	<0.0001	82.1	81.8	-0.3
VHFC	2018	C	24.7	46888	<0.0001	84.0	82.9	-1.1
VHFC	2018	D	-8.1	38656	<0.0001	84.3	84.6	0.4
VHFC	2018	E	-15.6	36574	<0.0001	82.7	83.5	0.7

Table 1.3 contintued: T-test results for comparisons of times when ships were present or absent in 2018 and 2019 for all locations and weightings. Tests with increases greater than 3 dB highlighted in bold with an *.

Unweighted	**2019**	**A**	**-95.0**	**32892**	**<0.0001**	**101.4**	**108.2**	**6.8***
Unweighted	2019	C	-70.6	37151	<0.0001	102.6	106.3	**3.7***
Unweighted	2019	D	-37.7	41345	<0.0001	101.9	104.5	2.6
HFC	2019	A	-9.52	41031	<0.0001	92.6	93.7	1.1
HFC	2019	C	-10.2	41849	<0.0001	92.7	93.5	0.8
HFC	2019	D	-2.36	42110	0.01823	92.2	92.4	0.2
LFC	**2019**	**A**	**-76.7**	**35942**	**<0.0001**	**99.9**	**105.1**	**5.2***
LFC	2019	C	-53.9	38768	<0.0001	101.0	103.8	2.8
LFC	2019	D	-30.2	43692	<0.0001	100.3	102.3	2.0
PCW	2019	A	-39.6	40715	<0.0001	97.1	99.8	2.7
PCW	2019	C	-25.9	42695	<0.0001	97.9	99.3	1.4
PCW	**2019**	**D**	**-47.5**	**40626**	**<0.0001**	**96.9**	**100.1**	**3.2***
VHFC	2019	A	-5.5	40972	<0.0001	91.5	92.0	0.5
VHFC	2019	C	-9.0	41458	<0.0001	91.5	92.2	0.7
VHFC	2019	D	-0.1	41974	0.9284	90.8	90.8	0.0

Broadband SPL across years

When the overall Broadband SPL of 2019 are compared to the noise level recordings of 2014, 2015, and 2018, 2019 had unusually high noise levels (Figure 1.7). Further, SPL increases at AMAR A are observed in 2019 at all frequencies, with more dramatic increases at <100 Hz and <10 kHz in 2019. Increases are seen in percentiles as low as the 5th percentile, indicating this increase is occurring for the majority of the listening period (Figure 1.7). The increase in broadband SPL is observed at AMARs A and D, and is seen in both unweighted broadband and HFC broadband SPLs (Figure 1.6). These increases may be a product of higher levels of ambient noise due to wind, etc.

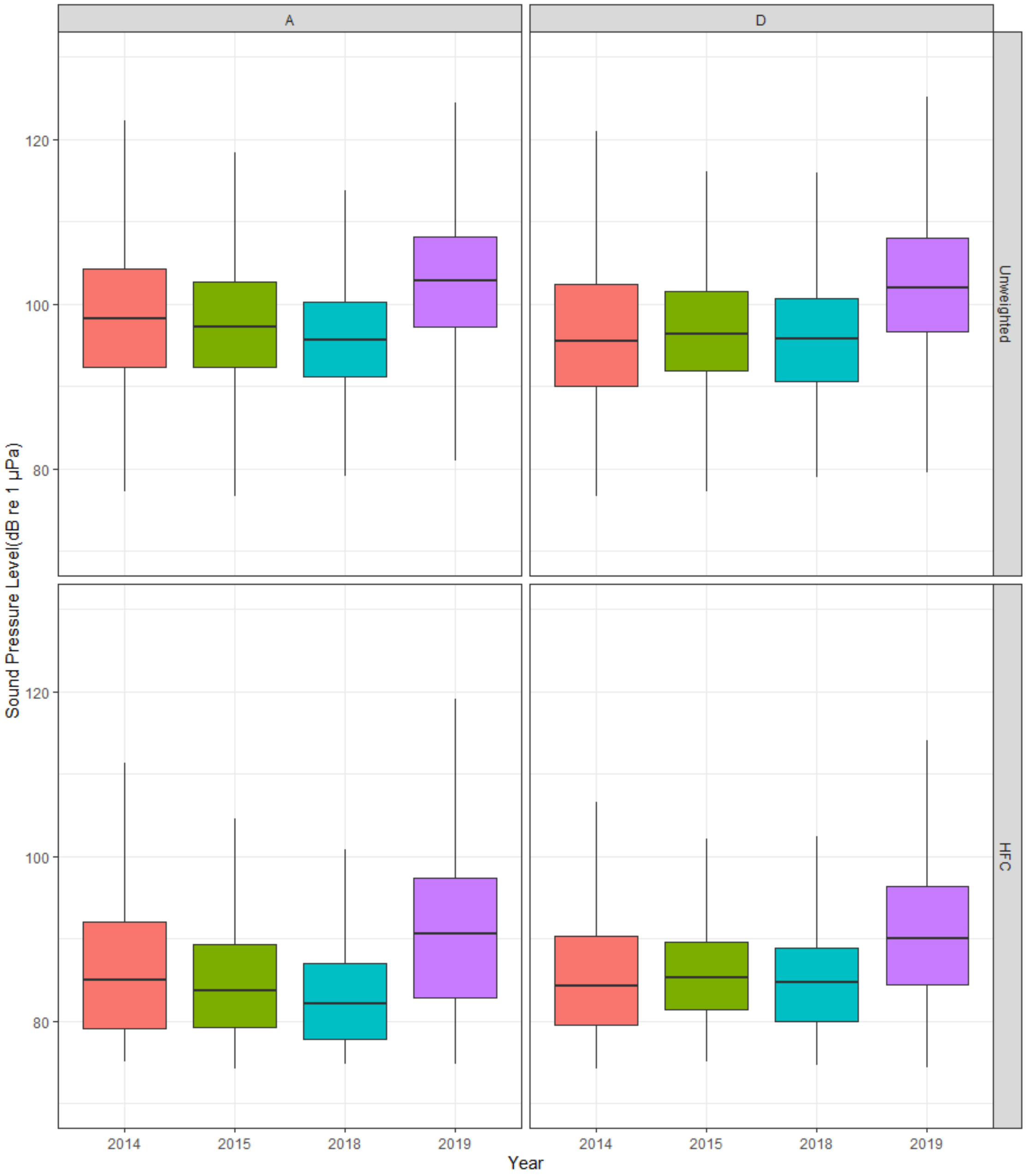

Figure 1.6: Boxplots displaying the 5th, 25th, 50th, 75th, and 95th percentiles of Unweighted Broadband SPL and HFC Broadband SPL for the full recording periods (excluding outliers) from recorders at locations A and D from years 2018 and 2019, as well as 2014 and 2015 where available. Broadband SPLs were calculated using 10 Hz-20 kHz third octave bands for all years.

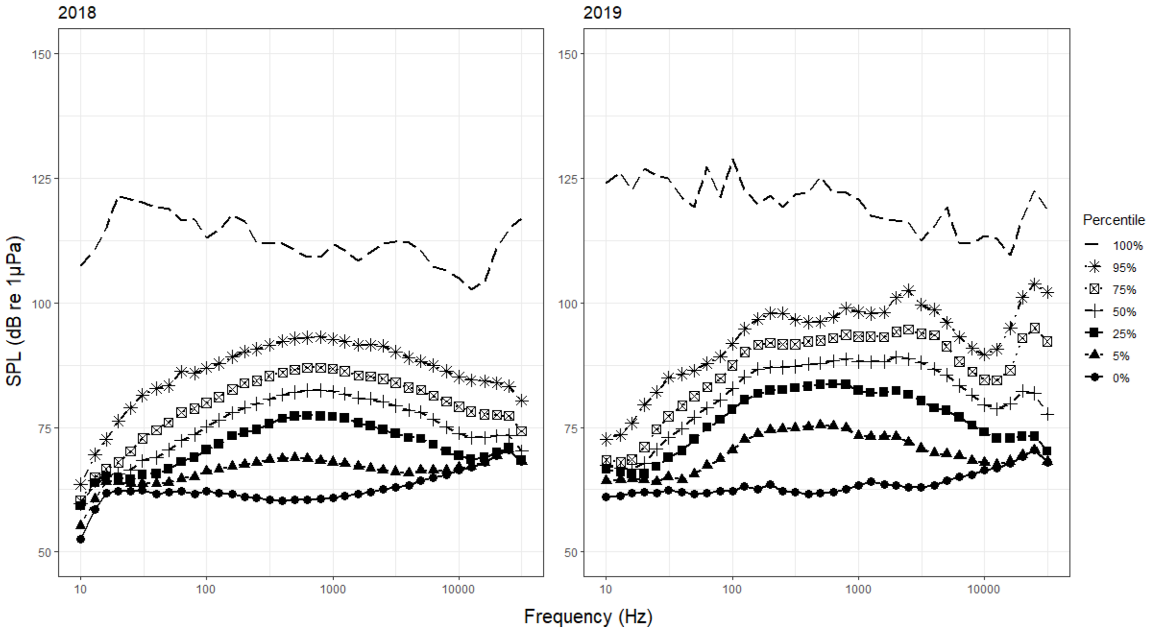

Figure 1.7: Unweighted Third Octave Bands from AMAR location A from recorders in 2018 and 2019 during times when ships were absent from the study area in Milne Inlet.

Spatial Extent of Ship Noise

The spatial maps of the AIS data points show a large difference in spatial patterns between the unweighted and HFC Broadband SPL during ore carrier passages. The fit of the models also varied considerably between recorder locations, year of recording, and whether the HFC weighting function was applied (Table 1.3). As with broadband comparisons, increases in unweighted Broadband SPL are associated with ship presence at all locations in 2018, including AMAR C in Koluktoo Bay, but the magnitude of perceived noise varies depending on the location of the recorder, the location of the vessel, and is affected by local geography (Figure 1.8). At AMAR A, ships begin to increase the unweighted Broadband SPL once they enter a direct line of sight to the recorder,, and when they exit beyond direct line of sight, the Broadband SPL decreases back to ambient (Figure 1.8). A similar pattern is observed for AMAR B and D, which are situated close to but slightly off the shipping route. Unweighted Broadband SPL increases when a has a direct acoustic path to the recorders, but the magnitude of increase is less than at AMAR A (Figure 1.8). AMAR C is 6 km from the shipping route and is the most sheltered location by land. Here the Broadband SPL increase only occurs when the AMAR has direct line of sight of a passing ship and shows the lowest increase in unweighted Broadband SPL of all the recorder locations (Figure 1.8). AMAR E shows increased unweighted Broadband SPL up to a greater distance North of it than South, possibly due to having exposure to the more open sections of Milne Inlet where noise can be heard further away (Figure 1.8). Slightly increased noise levels are also observed when the vessel is in upper Milne Inlet and when the vessel is travelling

Table 1.4: Generalized additive model parameters *k, k*-1 index and its corresponding p-value, R^2, and *n* for GAM models used in Northbound and Southbound large vessel data in the study area predicting unweighted and HFC Broadband levels as seen in Figures 1.8-1.11.

Weighting	**Year**	**Location**	**Direction**	**k**	**k-1 index**	**k-1 index p-value**	**$R_{adj.}^2$**	**n**
Unweighted	2018	A	Northbound	140	1.01	0.79	0.842	7395
			Southbound	210	0.99	0.14	0.747	8364
Unweighted	2018	B	Northbound	140	1.02	0.95	0.829	7395
			Southbound	200	0.99	0.34	0.704	8364
Unweighted	2018	C	Northbound	140	1.03	0.95	0.659	7395
			Southbound	200	1	0.56	0.388	8372
Unweighted	2018	D	Northbound	140	1.02	0.89	0.791	7395
			Southbound	220	1	0.39	0.685	8386
Unweighted	2018	E	Northbound	140	1.03	0.98	0.796	7395
			Southbound	180	1.01	0.78	0.632	8487
Unweighted	2019	A	Northbound	140	1.02	0.96	0.615	7395
			Southbound	160	0.98	0.085	0.127	9606
Unweighted	2019	C	Northbound	140	1.03	0.98	0.306	8800
			Southbound	200	0.98	0.07	0.0478	9606
Unweighted	2019	D	Northbound	140	1.02	0.98	0.0691	8800
			Southbound	140	0.99	0.26	0.139	9606
HFC	2018	A	Northbound	140	0.98	0.07	0.358	7395
			Southbound	140	1.01	0.91	0.2	8364
HFC	2018	B	Northbound	150	1.01	0.71	0.341	7395
			Southbound	140	1.02	0.94	0.141	8364
HFC	2018	C	Northbound	140	0.99	0.17	0.0641	7395
			Southbound	140	0.99	0.1	0.0439	8372
HFC	2018	D	Northbound	140	0.99	0.18	0.367	7395
			Southbound	140	0.99	0.14	0.133	8386
HFC	2018	E	Northbound	140	0.99	0.11	0.359	7395
			Southbound	140	0.99	0.22	0.147	8487
HFC	2019	A	Northbound	140	1.04	1	0.0997	8800
			Southbound	170	0.99	0.16	0.0469	9606
HFC	2019	C	Northbound	140	1.04	1	0.0707	8800
			Southbound	200	0.99	0.26	0.0478	9606
HFC	2019	D	Northbound	140	1.04	1	0.0591	8800
			Southbound	140	1.02	0.95	0.04	9606

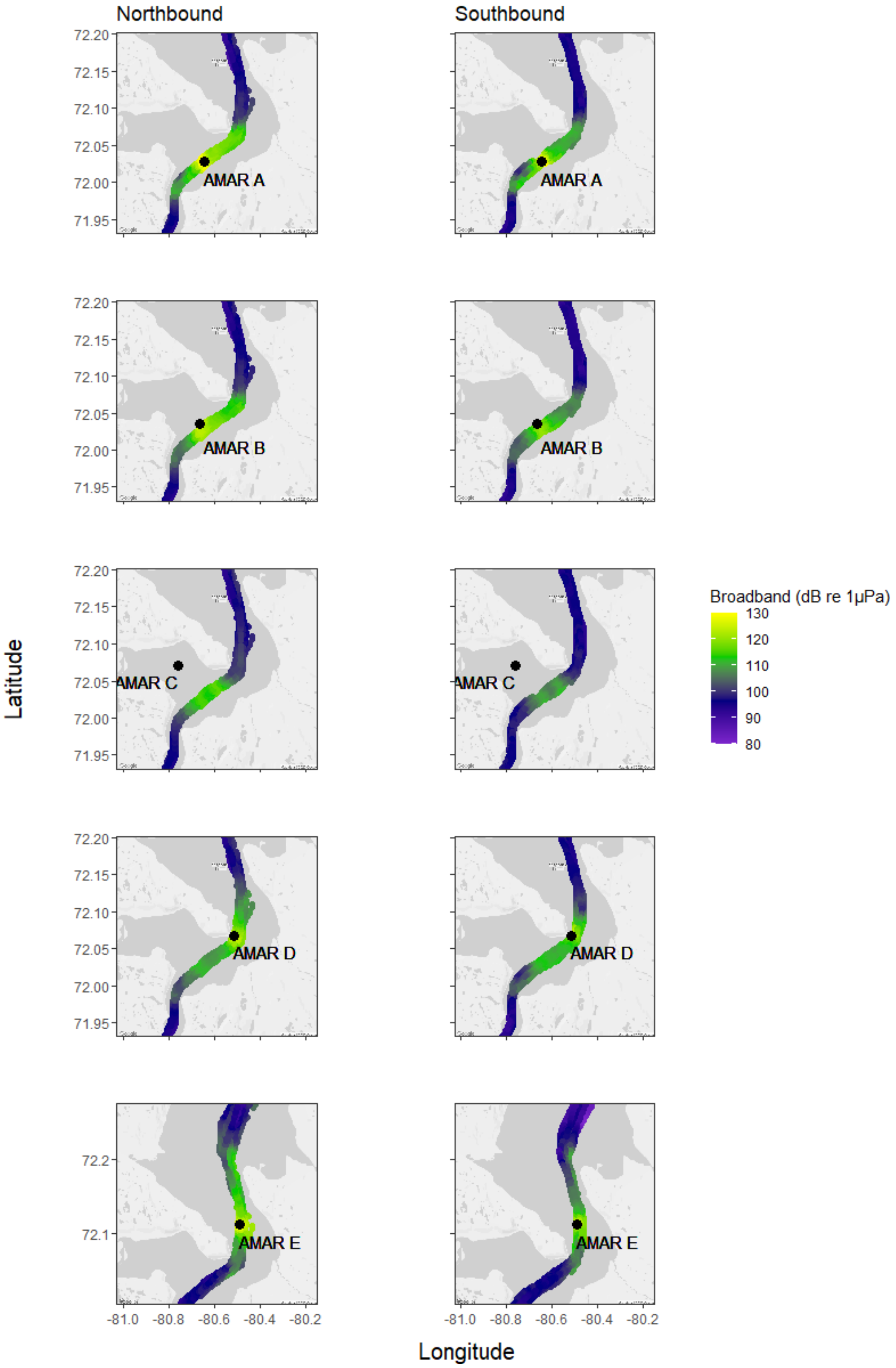

Figure 1.8: Latitude and longitude of 2018 bulk carrier AIS positions within Milne Inlet, with estimated broadband SPL (unweighted) from generalized additive models for AMAR locations A-E from 2018. Maps sourced from Google (2020).

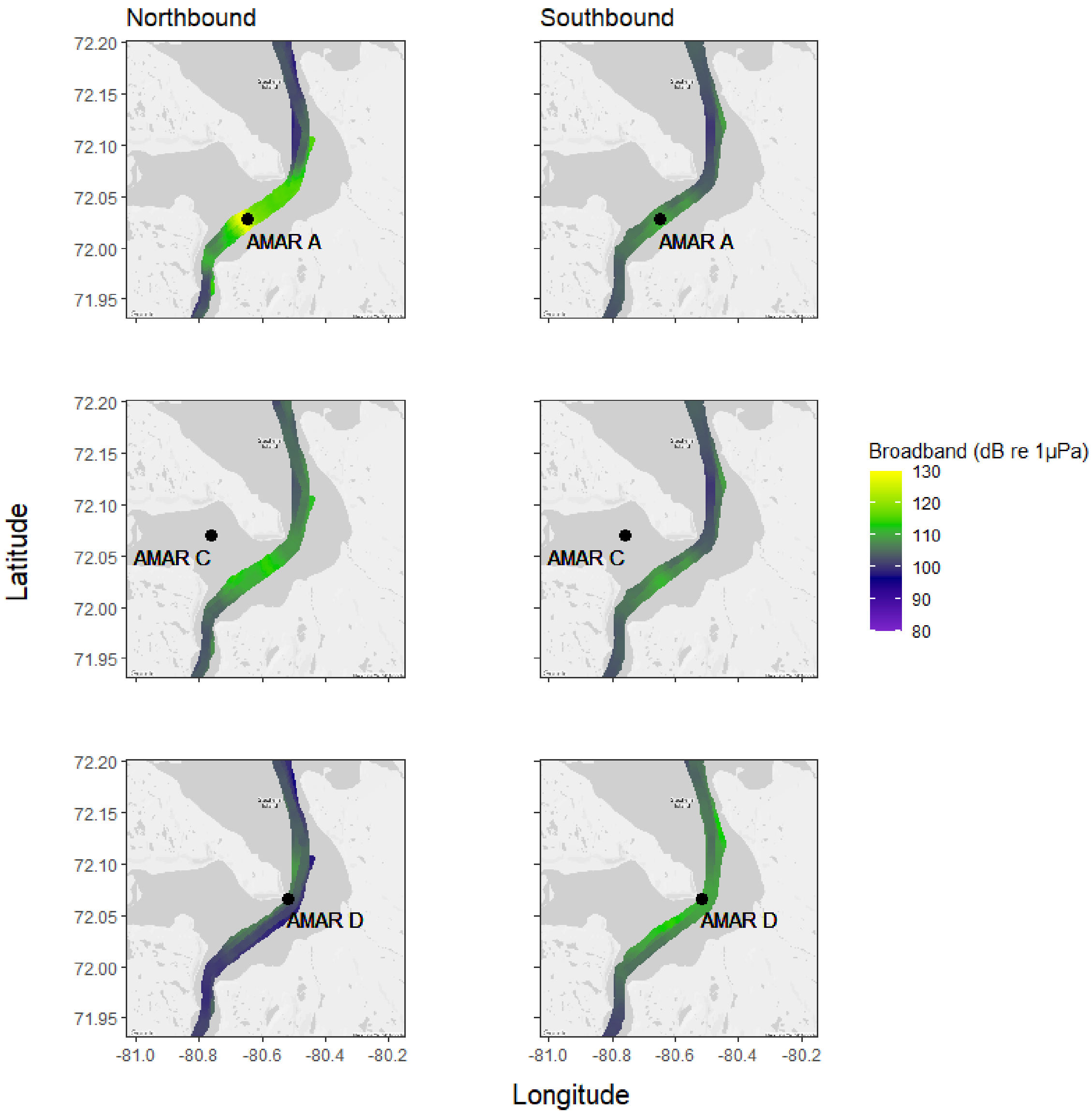

Figure 1.9: Latitude and longitude of 2019 bulk carrier AIS positions within Milne Inlet, with estimated broadband SPL (unweighted) from generalized additive models or AMAR locations A, C, and D from 2019. Maps sourced from Google (2020).

northbound as opposed to southbound (Figure 1.8). 2019 showed a similar spatial distribution of noise at location A when northbound, but otherwise the patterns are less clear compared to 2018. Broadband SPLs were estimated to be higher beyond the direct acoustic path in 2019 compared to 2018, and so a less noticeable increase was observed (Figure 1.8 and 1.9). The increases in noise level beyond line-of-sight in 2019 is likely due to the higher ambient noise levels in 2019 (Figure 1.6).

There is also a notable increase in the noise profile of Northbound transits when vessels are ore-laden compared to Southbound transits when the carriers are empty. Northbound passages appear to reach higher maximum Broadband SPLs and increases more suddenly when the vessel comes within of the recorder, indicating the vessels are producing more noise when ore-laden (Figure 1.8 and 1.9).

The spatial noise profiles of Broadband SPLs during ship passages show less change relative to a ship's location when the HFC weighting is applied. Not only is the increase in magnitude lower, but the increase does not occur until the ship is very close to the recorder (Figure 1.10). This is the case for AMARs A and E, and to a lesser magnitude AMARs B and D in 2018 (Figure 1.10). AMAR C observed no change in HFC Broadband SPL with passing ships (Figure 1.10). 2019 showed virtually no change in Broadband SPL when ships were close to any of the recorder locations, and like the unweighted Broadband SPL, overall noise levels increased in 2019 compared to 2018 (Figure 1.11). In 2019, at all locations, ore carriers travelling further east as they turned around Bruce Head were estimated to increase the Broadband SPL (Figure 1.11). Given that this appears in both HFC and unweighted broadband SPL and at all three locations, it is likely this increase is an artifact of one or two vessel passages that occurred during a time with high ambient levels and is unlikely to be related to vessel noise given the trend is seen at recorder locations with no direct line of sight to the vessel position (Figure 1.11).

The R^2 adjusted value for the GAMs differed considerably between different locations, the year of recording, and between the unweighted and HFC weighted Broadband SPLs (Table 1.3). GAMs predicted unweighted Broadband SPL in 2018 had better fits with higher R^2 adjusted values than in 2019 and had highest R^2 adjusted values when the recorder location was on or near the shipping route (Table 1.3). HFC Broadband SPL had much poorer fits and showed very little correlation between ship location and broadband SPL in the study area across all locations (Table 1.3). AMAR C was consistently the location with the poorest fits and lowest R^2 adjusted values across both years and weightings (Table 1.3). The GAMs estimating HFC Broadband SPLs had consistently lower R^2 adjusted values compared to unweighted Broadband SPLs (Table 1.3).

The lower R^2 adjusted values indicate that the ship's location along the shipping route is not a strong predictor for HFC broadband SPL at these locations, weightings, and years, and that the noise levels may be more affected by ambient sources of noise such as wind speed. This is further supported by the lack of significant increases in broadband SPL in the presence of ships from the broadband comparisons (Table 1.2).

Noise Levels Per Transit

There were 114 and 130 ship transits identified in 2018 and 2019 respectively. Of the total 244 transits, 202 were bulk carriers, 29 were general cargo, three were icebreakers, 10 were oil and chemical tankers, two were service vessels, and there was one transit from both a fishing vessel and a Canadian warship. Ninety-four transits showed overlap in presence with other ships and were excluded from further analysis. This left 44 bulk carrier transits in 2018 (24 Northbound, 20 Southbound) and 71 transits in 2019 (36 Northbound/35 Southbound) remaining

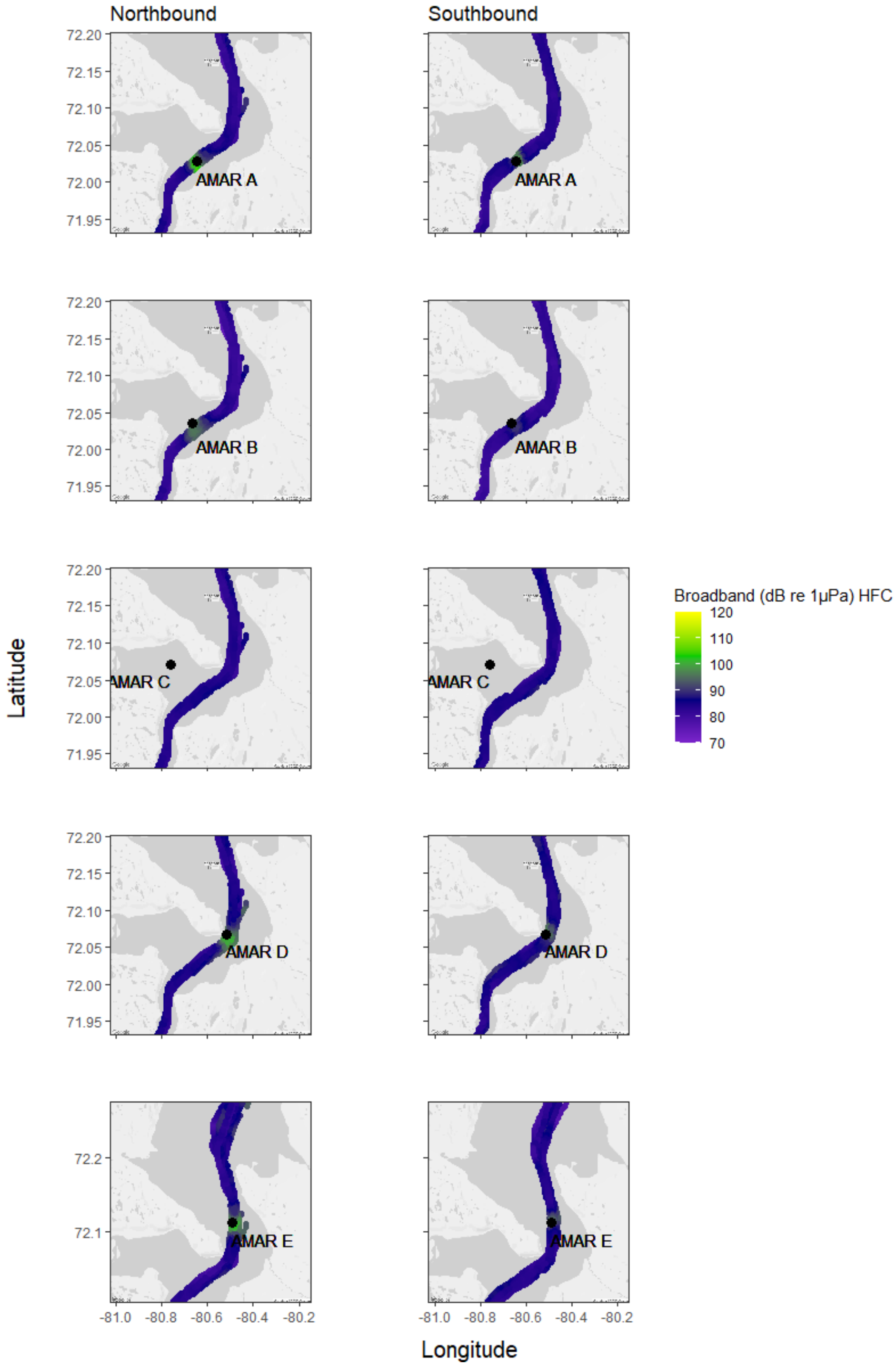

Figure 1.10: Latitude and longitude of 2018 bulk carrier AIS positions (Northbound and Southbound separately) with estimated broadband SPL (HFC) from generalized additive models for AMAR locations A-E from 2018. Maps sourced from Google (2020).

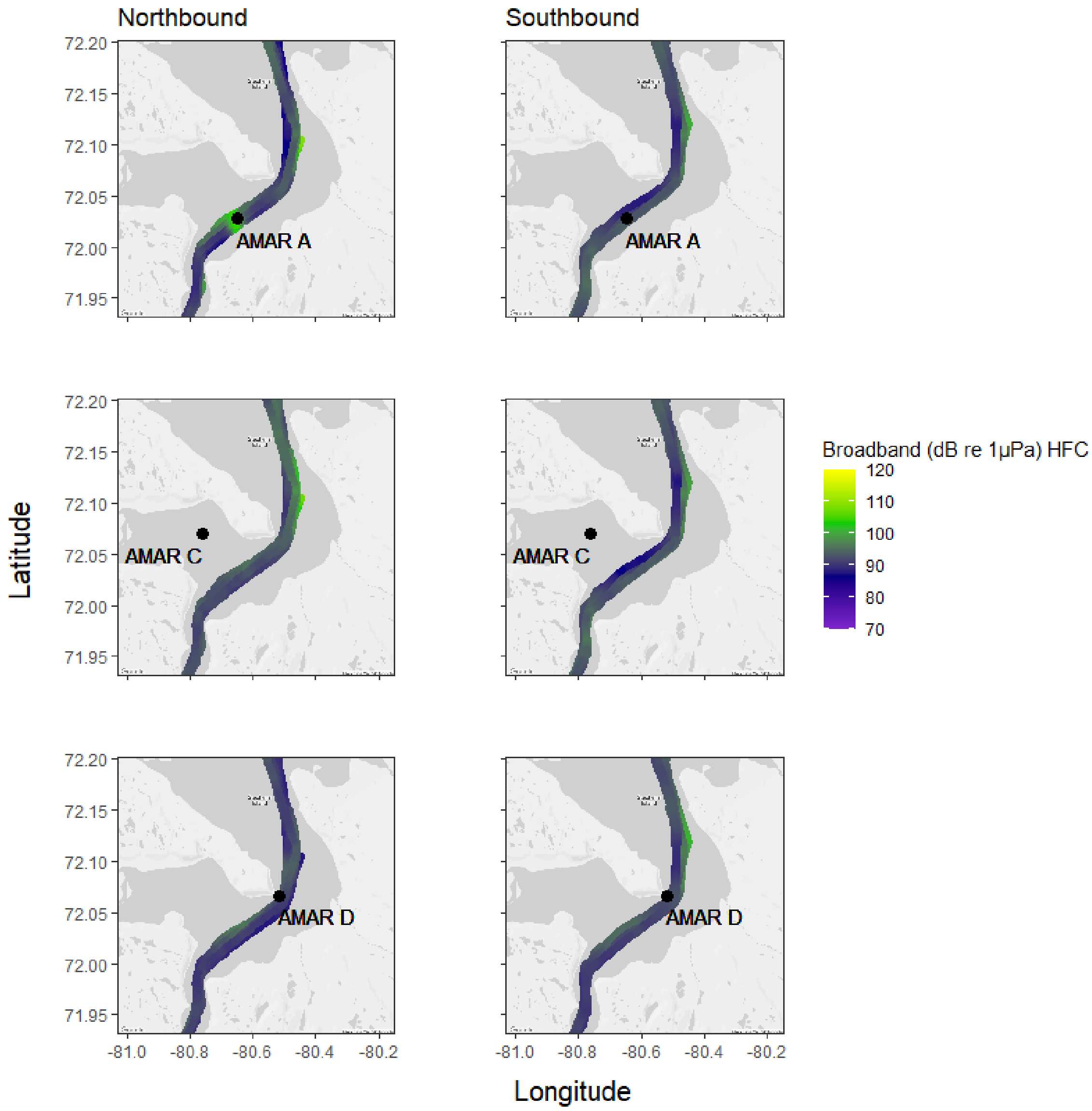

Figure 1.11: Latitude and longitude of 2019 bulk carrier AIS positions with estimated broadband SPL (HFC) from generalized additive models for AMAR locations A, C, and D from 2019. Maps sourced from Google (2020).

for analysis. Of these 115 transits, 29 used ambient levels calculated from the previous transit due to the presence of other ships in the ambient measurement.

As with previous analyses, ambient broadband SPL, transit durations, and transit SEL followed similar patterns to previous analysis. Ambient levels, durations and SEL appeared to be higher and more variable in 2019 than 2018 (Figures 1.12, 1.13, and 1.14), differences between weighting functions followed similar patterns to previous analyses; with HFC and VHFC weighting functions having lower noise level values relative to LFC and PCW (Figures 1.12, 1.13, and 1.14). Locations seemed to have similar ambient levels across all weightings (Figure 1.12).

The estimated duration of the noise level of each transit varied depending on weighting, location, and year (Figure 1.13). In 2018, AMAR C had the highest variability of transit duration compared to AMAR A and D. In 2018 the difference between the different weighting functions was similar to the differences observed in the Broadband SPL comparisons, but in 2019 all locations had similar magnitudes of variability in duration (Figure 1.13). Despite high variability in transit duration length, the calculated transit SELs show lower variability and more distinct differences between locations and weightings (Figure 1.14). HFC and VHFC weighing functions have much lower SEL values than unweighted, LFC, or PCW weighing functions in both recording years (Figure 1.14). In 2018, SEL at AMAR C was lower than at AMAR A or D for all weightings, but in 2019 AMAR C was only slightly lower for unweighted, LFC, and PCW weightings. HFC and VHFC weighing functions showed very little difference in mean SEL between locations A, C, or D in 2019. For all locations and both years, the calculated SEL values did not exceed the weighted thresholds for TTS or PTS for any of the functional hearing groups outlined in Southall et al. (2019). It is also worth noting that HFC and VHFC weighting functions had abnormally high numbers of transits at AMAR C that had durations with no minutes 3 dB above ambient, and thus did not have SEL measured and were removed from analysis. This was the case for 57 transits for HFC and 56 transits for VHFC.

For the stepwise regression of the linear models, year and the estimated ambient Broadband SPLs prior to the transit were selected as significant variables for unweighted and all four hearing groups (Table 1.4). Unweighted, LFC, and PCW weighing functions also included recorder location as a variable, unweighted included the interaction between year and location, and the LFC weighing function was the only variable to include vessel direction as an important variable. Mean transit speed was not considered an important variable by the stepwise process for any of the linear models (Table 1.4).

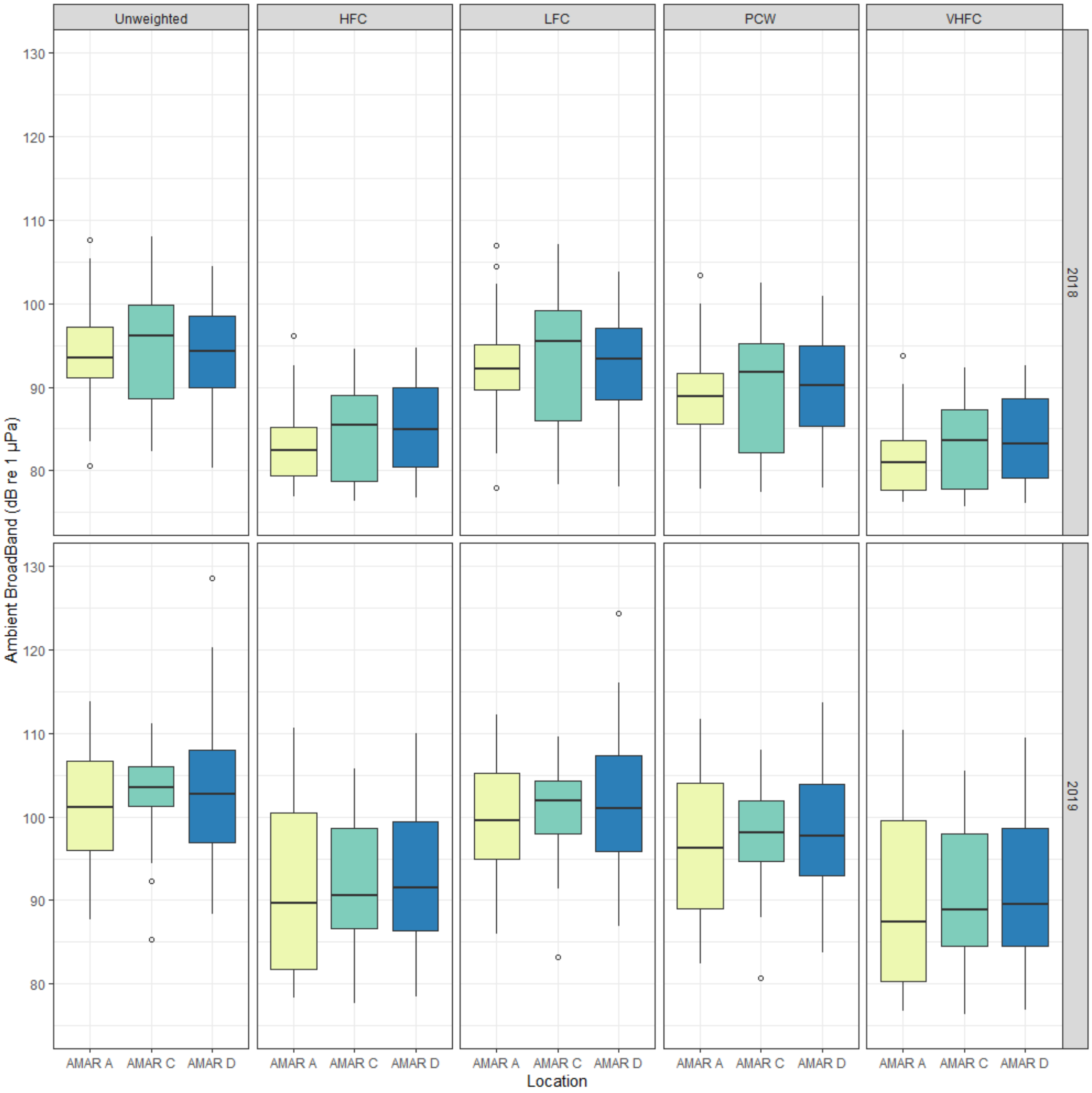

Figure 1.12: Boxplots displaying the 5th, 25th, 50th, 75th, and 95th percentiles of estimated ambient broadband SPL at locations A, C, and D, for Unweighted, HFC, LFC, PCW, and VHFC weightings in 2018 and 2019 in Milne Inlet and Koluktoo Bay.

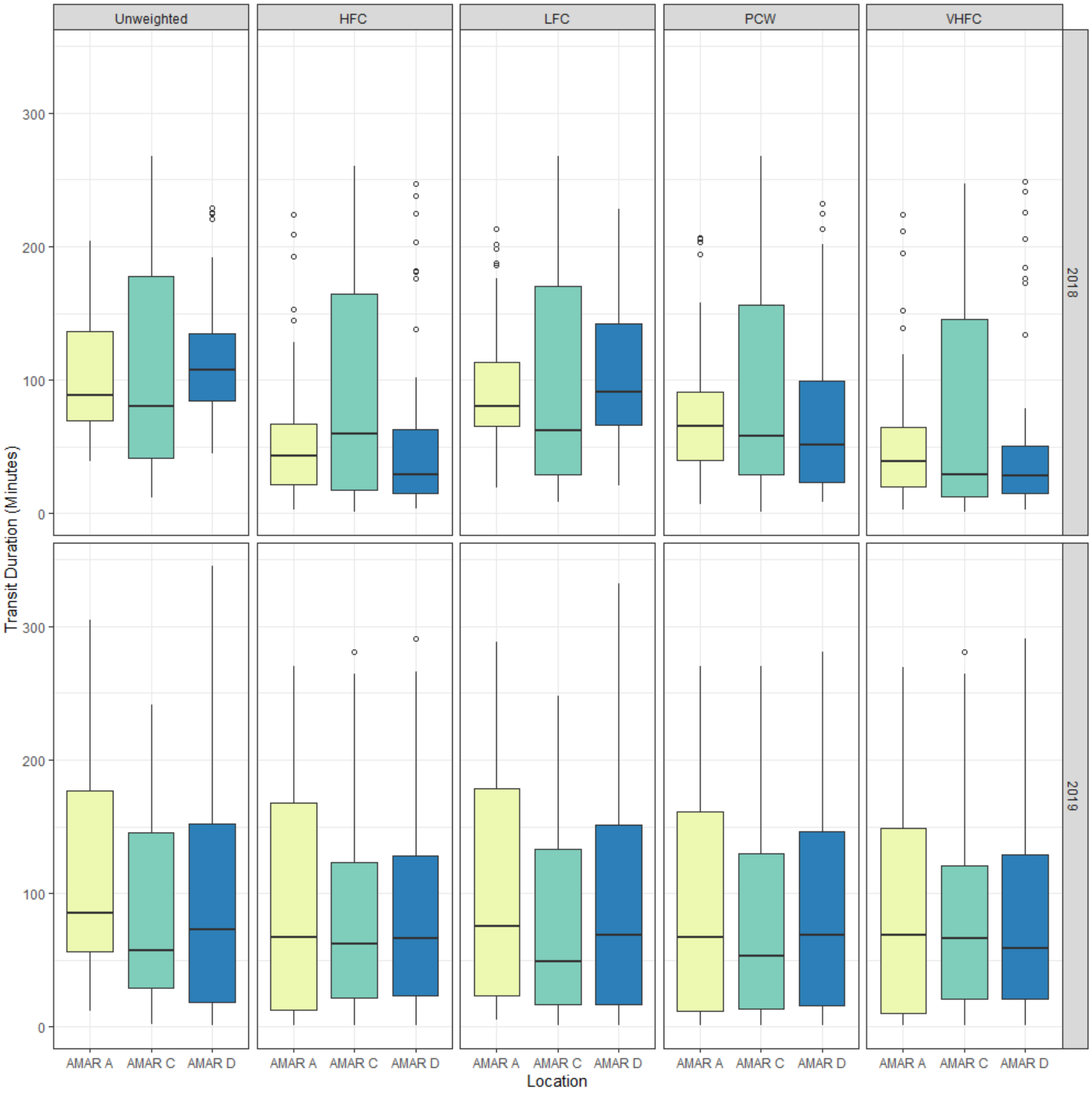

Figure 1.13: Boxplots displaying the 5th, 25th, 50th, 75th, and 95th percentiles of estimated duration of ship noise exposure at locations A, C, and D, for Unweighted, HFC, LFC, PCW, and VHFC weightings in 2018 and 2019.

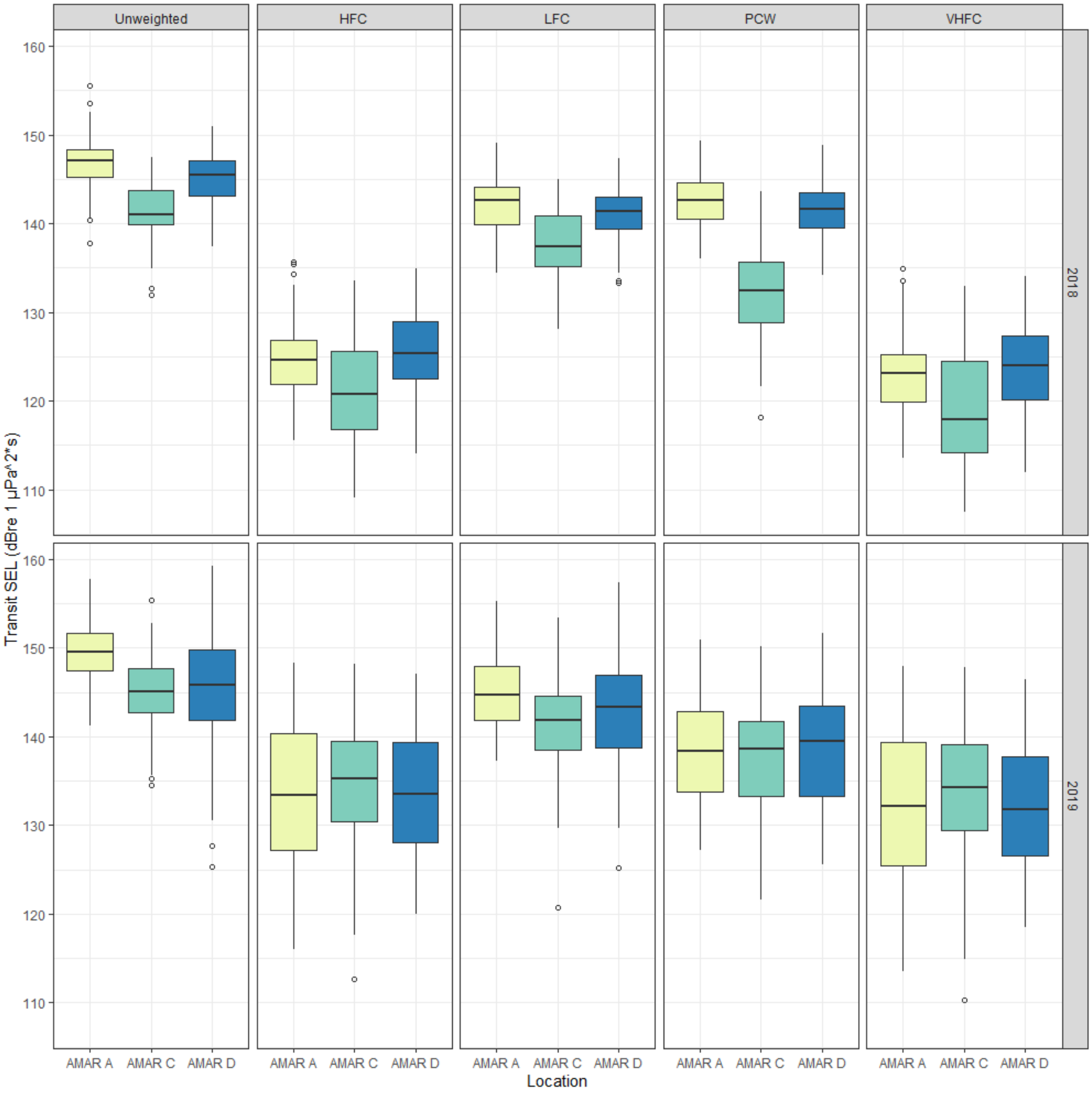

Figure 1.14: Boxplots displaying the 5th, 25th, 50th, 75th, and 95th percentiles of transit SEL during ship noise exposure at locations A, C, and D, for Unweighted, HFC, LFC, PCW, and VHFC weightings in 2018 and 2019 in Milne Inlet and Koluktoo Bay.

Table 1.5: Best linear models for predicting Unweighted, HFC, LFC, PCW, and VHFC SEL levels (dB re 1 $\mu Pa^2 \cdot s$) as determined by backward stepwise model selection. ΔAIC is the difference in AIC values between the selected model and the best model. Adjusted r-squared values were provided for the best model in each weighting.

Weighting	Formula	AIC	ΔAIC	R^2_{adj}
Unweighted	SEL ~ 1	1513.89	134.65	
	SEL~ Year * Location + Speed + Direction + Ambient Broadband	1382.26	3.02	
	SEL ~ Year + Location + Ambient Broadband + Year:Location	1379.24	0	0.27
HFC	SEL ~ 1	1650.74	166.16	
	SEL~ Year * Location + Speed + Direction + Ambient Broadband	1488.48	3.9	
	SEL~ Year + Ambient Broadband	1484.58	0	0.35
LFC	SEL ~ 1	1514.32	89.77	
	SEL ~ Year * Location + Speed + Direction + Ambient Broadband	1426.55	2	
	SEL~ Year + Location + Direction + Ambient Broadband	1424.55	0	0.20
PCW	SEL ~ 1	1562.17	58.13	
	SEL ~ Year * Location + Speed + Direction + Ambient Broadband	1507.27	3.23	
	SEL ~ Year + Location + Ambient Broadband	1504.04	0	0.14
VHFC	SEL ~ 1	1713.18	169.49	
	SEL ~ Year * Location + Speed + Direction + Ambient Broadband	1548.51	4.82	
	SEL ~ Year + Ambient Broadband	1543.69	0	0.35

Discussion

How do Local Marine Mammals Perceive Shipping Noise?

The HFC Broadband SPL representing narwhal hearing did not significantly increase in the presence of shipping, even though unweighted Broadband SPL did significantly increase. The high frequency hearing of odontocetes causes lower sensitivity in frequencies below 1 kHz, where noise from shipping dominates (Arveson and Vendettis 2000). Noise levels did increase when ships were within 1-3 km to the recorders along the shipping route. Veirs et al. (2016) found that in Southern Resident killer whale core habitat, noise from shipping increased by 5-35 dB between 10 kHz and 40 kHz. These high frequency increases occurred up to ~3 km away from the source vessel (Veirs et al. 2016), which is a similar range to what was observed in this study. While narwhal may face lower levels of noise exposure compared to other hearing groups, they will still experience increased noise levels when less than 3 km from an ore carrier.

Other studies have found that noise from shipping can contribute significantly to the high frequency noise audible to odontocete species in areas with heavy shipping traffic (Hermannsen et al. 2014, Cominelli et al. 2018). Avoidant responses have been observed by harbour porpoise and Southern resident killer whales within close range of shipping (Williams et al. 2014, Oakley et al. 2016). This does imply that it is possible narwhal may exhibit a similar response at close distances to ships. Narwhal tagged in Tremblay Sound did exhibited mild avoidance surface behaviour when very close (<1 km) to an ore carrier, and changes in dive duration and surface time were found when an ore carrier was between 1-5 km away (Golder Associates Ltd. 2020a). Narwhal and beluga have also been observed showing avoidance behaviour in the presence of icebreaking vessels (Finley and Davis 1984), however since icebreaking generates significantly more noise with high frequency components compared to normal shipping, these cases are not directly comparable (Cosens and Duek 1993, Arveson and Vendettis 2000, Erbe and Farmer 2000). Ore carriers transiting during the ice-free season have little impact on noise exposure for narwhal during the open water season. The close-range increases in Broadband SPL are consistent with the present understanding of odontocete hearing, and spectral profiles of large shipping vessels at close distances (Arveson and Vendettis 2000, McKinnes et al. 2017, Southall et al. 2019). It also correlates with the distances at which narwhal and other odontocetes begin to elicit responses to large vessels (Williams et al. 2014, Oakley et al. 2016, Golder Associates Ltd. 2020a).

Baleen whales were found to experience the highest Broadband SPL increases and highest SEL levels for times when ships were present. Noise from shipping overlaps with the presumed audible ranges of baleen whales and highlights a concern of exposure risk to this functional hearing group (Tougard and Breedholm 2019). The results from this study support these concerns. When ships were present, broadband SPLs and transit SELs for baleen whales were higher than the other functional hearing groups. Even so, the SELs measured in this study for LFC, as well as all other hearing groups were not sufficient to cause the onset of TTS or PTS to narwhal, bowhead whales, or pinnipeds (Southall et al. 2019) at any location, including on the shipping route. Noise exposure from vessels in these narrow inlets may be limited by the blockage of outside noise by landmasses. If ship traffic increases in the future in Milne Inlet, the impact will be significantly higher for the bowhead whale than the other marine mammal species in the area due to their low frequency hearing.

Phocids also perceive shipping noise to a higher degree than narwhal, but the exposure levels are also lower than what is perceived by low frequency cetaceans. Broadband SPLs as perceived by seals were only significantly higher for a few locations along the shipping route, and only in 2018. The SELs for phocids in water measured in this study were low compared to SEL measurements for seals off the more heavily trafficked British coast (Jones et al. 2017). This could imply that with higher levels of ship traffic the risk of TTS/PTS may also increase for local phocid species.

The use of the weighting functions in this study demonstrates how important it is when assessing impacts of anthropogenic noise, that the hearing capabilities of the subject be considered. Unweighted Broadband SPL is a commonly used metric to assess anthropogenic noise exposure in marine mammals (Erbe et al. 2012, 2018), however this metric can misrepresent perceived noise exposure as it does not account for animal hearing (Southall et al. 2019). When the hearing capabilities of a marine mammal do not overlap with peak frequencies of a noise source, the perceived levels are significantly lower than the unweighted levels, as seen in this study. The use of general weighting functions provides a more accurate representation of marine mammal exposure to anthropogenic noise, and their wider use in studies assessing marine mammal noise exposure is strongly recommended.

How do the unweighted SPLs compare to other studies?

In this study when ships were present, the average unweighted Broadband SPL increased by 7-10 dB along the shipping route. Bulk carriers and other large commercial vessels can increase average Broadband SPL by 20-30 dB, with source levels around 170-183 dB re 1 μPa (Arveson and Vendettis 2000, Jansens and De Jong 2017, McKenna et al. 2017). The Broadband SPL increases observed in this study were not that high, however my noise measurements were taken at a distance from the vessels, so they are unlikely to match those of measured source levels. Ore carriers were operating well below their maximum speed in this enclosed inlet, which may also explain why the observed noise levels are less than in Arveson and Vendettis (2000). The unweighted Broadband SPL increases from shipping in Milne Inlet are less than what is observed in other underwater regions. The shipping route in Milne Inlet observes much less shipping traffic compared to more industrialized areas; transits occurred up to twice a day in Milne Inlet, whereas areas such as the Salish Sea could have up to three vessel transits per hour (Erbe et al. 2012). In more open areas with heavy shipping such as the Baltic Sea, multiple vessels are more likely to simultaneously contribute to received noise levels (Syrjälä et al. 2020). The low density of vessel transits, and the narrow, enclosed geography of the Southern section of Milne Inlet decreases the probability of such interactions occurring.

Vessel slowdowns have been shown to reduce ship noise in marine mammal habitat, even though it leads to longer vessel transit times (Pine et al. 2018, Joy et al. 2019). Higher speeds are associated with increased propeller cavitation, which contribute more noise in higher frequencies (Arveson et al. 2000). It is estimated that increases of one knot can increase noise levels from shipping by 1 dB (Veirs et al. 2016). Speed was not found to be a significant factor in this study, however the speed of ore carriers in Milne Inlet was restricted to nine knots; well below their maximum speeds. The lack of presence of shipping operating at higher speeds may help to explain the lower broadband SPL increases in this study. This suggests the speed restrictions are an effective strategy for mitigating noise from shipping in Milne Inlet.

Two factors that may also influence Broadband SPL from ore carriers during a transit are their orientation and their load. Arveson and Vendettis (2000) also found that source levels of noise were higher when measured from the stern of the ship than the bow. When the vessel is facing away from the recorder, noise levels do appear to be higher (e.g., North of recorder when northbound, South of recorder when southbound). Noise radiating towards the bow is partially blocked by the hull, this a widely observed phenomenon with ship-related noise (Arveson and Vendettis 2000). The load is also important; ore carriers moving northbound in this study were ore-laden and required more energy to reach the same speed as an empty southbound vessel. Northbound vessels tended to have a slightly higher SEL, although the effect was only found to be significant for the LFC weighted SEL. Given that the majority of vessel noise is found under 1 kHz (Arveson and Vendettis 2000), this increase for LFC SEL is expected, and suggests that narwhal and phocids may not detect a difference in noise level between ore-laden and unladen transits.

Ambient Levels

Throughout the noise measurements in this study, the ambient level had a strong influence on the results. The increased ambient levels in 2019 compared to 2018 had a large effect on the Broadband SPL increases, impacted the predictive ability of GAM spatial maps, and in the transit analysis. Both year and ambient level was considered as important variables in stepwise linear model selection for predicting SEL across all weightings. The longer estimated durations of noise exposure during a transit in 2019 may have been influenced by the increased variability in measured ambient Broadband SPL.

Wind speed has a strong effect on ambient sound pressure level above 100 Hz, even in areas with heavy shipping traffic (Kinda et al. 2017). Other contributions to ambient noise can come from seismic activity, presence of ice, and production of biological sounds (Urick 1983, Southall et al. 2020), although these sources are unlikely to be occurring frequently enough to explain the increases in ambient level in 2019. Given the increases in noise level above 100 Hz in 2019, it is possible that increased average wind speeds could be influencing the ambient level between 2018 and 2019. Meteorological data was not available for the study area during the recording period, I recommend future studies to record meteorological data such as wind speed to further investigate this relationship.

Ambient noise levels are increasing in many regions in the Arctic due to with decreased sea ice cover and higher exposure to wind noise (Southall et al. 2020). These studies have mostly occurred in open water environments such as the Beaufort Sea (Southall et al. 2020), but as climate change leads to extended and stormier ice-free seasons in these inlets, the associated increase in the ambient levels may affect the acoustic habitats of marine mammals in Milne Inlet. High ambient levels masked the contribution of unweighted noise from ore carriers at some locations in this study area, particularly ones that are located further away from the shipping route. This masking of the noise of distant vessels may affect the exposure of marine mammals to the shipping, and consequently any response made by the animal.

Study Limitations

This study makes several assumptions; the first and most important is that narwhal hearing is accurately reflected by the HFC weighting function. No audiograms have yet been performed on narwhal, so there is uncertainty whether the HFC weighting used in this study is an accurate representation of narwhal hearing. However, the HFC auditory function was generated using the audiograms of non-porpoise odontocetes including beluga; an animal that shares common ancestry, habitat range, and size to narwhal. Due to their similarity in size, habitat, and phylogeny, it is unlikely that narwhal hearing will deviate significantly from that of a beluga.

Another assumption made in this study is that the narwhal are stationary when ships are passing. This is a limitation of the study due to the use of immobile autonomous recorders, but because it is stationary, it may not reflect how narwhals perceive noise from ore carriers as both the narwhals and the ships move around the area. If a narwhal moves closer or further from a ship, the duration of exposure, maximum perceived broadband SPL, and SEL will all vary.

Although small vessels can contribute significantly to underwater ambient noise levels (Hermannsen et al. 2019), the contribution of noise from non-AIS vessels could not be quantified in this study. Their contribution to the soundscape however may be significant as hunting vessels were a common sight during land-based surveys of the study area.

While the noise levels for HFC and VHFC weighting functions indicate very low noise levels, the ships are not getting close enough to the recorders to reach Broadband SPLs that would be similar to source levels. Narwhals may experience higher noise levels than what have been reported in this study if they are within a few hundred meters of a moving ore carrier. SELs were also only measured when a single ship was present in the study area, and multiple ships in the area may affect noise level exposures. Noise levels are detectable for all species in this study at sufficient distances, and may lead to behavioural disturbances even if they are not high enough to cause auditory effects.

Future Work

This study has shown that the endemic marine mammals in Milne Inlet experience varying levels of ore carrier noise exposure, with narwhals experiencing the least amount of exposure and baleen whales experiencing the highest. Continued passive acoustic monitoring of the area in consecutive years would help in understanding the year-to-year variability in noise levels of Milne Inlet and Koluktoo Bay. Additional years would also assist in determining if 2019 was an anomalous year for noise levels or if it is indicative of a trend towards a noisier environment, as has been observed in other areas of the Arctic (Southall et al. 2020).

Bulk carriers were the most common large vessel to transit through the study area but there were several different types of large vessel that passed through the area including general cargo, oil tankers, and icebreakers. Further study into how these different ship types contribute to the soundscape under the various weightings could highlight vessel types that pose a higher or lower exposure risk to marine mammals in the area.

While the HFC weighting serves as a general predictor of noise level perceived by narwhal, the actual hearing abilities of narwhals remain unknown. *In situ* hearing measurements of narwhal like those performed by Castellote et al. (2014) could be used get a better understanding of the narwhal hearing curve, as well as to verify if the use of HFC weighting function by Southall et al. (2019) is valid for narwhal.

Conclusion

This chapter showed that narwhal detected a fraction of the noise contributions by ore carriers due to their poor hearing sensitivity in low frequencies where shipping noise dominates (Arveson and Vendettis 2000). The Broadband SPL from vessels did not significantly increase for narwhal until the vessels were very close; between 1-3 km from the recorder. Narwhal are not sensitive to the low frequency components of vessel noise that reaches Koluktoo Bay, and did not experience increases in perceived noise level when ships are at the mouth of the Bay, ~6 km away. Baleen whales and seals detect higher levels of vessel noise, can hear ships that are further away, and can detect more vessel noise in Koluktoo Bay than narwhals. None of the marine mammals in the study area received SELs that would exceed TTS or PTS as defined in Southall et al.

(2019). Speed restrictions, enclosure by land, and low density of vessel traffic led to lower increases of noise from shipping compared to other areas (Arveson and Vendettis 2000, Erbe et al. 2012, Veirs et al. 2016).

Chapter 2 Do narwhal react to shipping noise?

Introduction

Noise and Marine Mammal Behaviour

Anthropogenic noise exposure can impact marine mammals in a number of ways including communication masking, hearing loss, and sometimes deafness and mortality (Nowacek et al. 2007). Effects of noise can also be more subtle such as behavioural disturbance, which has the potential to lead to long term consequences for a population. Behavioural disturbance can take many forms, such as changes in vocal behaviour, cessation of foraging activity, or panicked flight from the source in the short-term (Southall et al. 2019), and in the long-term lead to shift in habitat use (Bejder et al. 2006). The consequences of these behavioural changes can vary in severity, from mild annoyance to life threatening (Weilgart 2007).

SPL is the most commonly used sound metric to assess the risk of disturbance to a marine mammal population, but behavioural response to a signal depends on more than just the magnitude of SPL (Southall et al. 2019). Understanding how an animal responds behaviourally to a given stimulus requires an understanding of the physical, ecological, and social contexts in which the individual exists and the exposure occurs (Gomez et al. 2016, Southall et al. 2019). Perception of source proximity and direction, as well as signal resemblance to benign or noxious stimuli, availability of alternative refuges, individual history of exposure, the novelty or familiarity of the individual with the sound, individual physiological condition, the perceived cost of not responding, and the behaviour of nearby individuals are all examples of contextual variables that could influence an animal's response to a given sound (Southall et al. 2019). The complexity of behavioural context and individual variability makes determining a behavioural response to a noise source particularly difficult using SPL alone.

There are a number of factors that may make an animal more or less susceptible to an avoidance response to shipping, including the magnitude and exposure of the noise source, individual experience with anthropogenic noise, and the general nature of the species (Gomez et al. 2016). There are some important considerations regarding the relationships between narwhal and their environment in order to effectively assess an impact on their day-to-day behaviour.

Narwhals and Shipping

Narwhal are regularly hunted by Inuit, and this may give narwhal heightened sensitivity to vessel noise. On one hand this could suggest that ship noise exposure is more likely to illicit a disturbance in narwhal compared to a species that does not associate vessel noise with predation. On the other hand, if narwhal can differentiate the noise profile of the different outboard motorboats and the commercial ships, they may identify their differing noise profiles as threatening or non-threatening and become habituated to the presence of large vessels. If this is the case, then it is possible that narwhal have habituated to the presence of shipping noise in Milne Inlet and may no longer display altered behaviours in the presence of ore carriers.

However, there have also been studies that have documented narwhal and beluga displaying avoidance behaviour in the presence of icebreakers (Finley and Davis 1984). Icebreakers generate high frequency components when icebreaking, which gives them a different noise profile to other large vessels and could contribute to a different response (Cosens and Duek 1993). This shows that there is a variety of responses to large vessels by narwhal reported in the literature.

Narwhal Behaviour in Milne Inlet

To understand how narwhal may respond behaviourally to the presence of a ship, there first needs to be a baseline understanding of narwhal behaviour. Due to the high cost and major logistical challenges of researching in the Arctic, the number of behavioural studies of marine mammals in the region are limited. There are a few studies that have been done that provide a preliminary understanding of narwhal behaviour along the shipping route servicing Baffinland Iron Mines in Milne Inlet, Nunavut (Marcoux et al. 2009, Marcoux 2011, Golder 2020b).

Milne Inlet has been a site for narwhal studies since before the mine was established. Marcoux et al. (2009) conducted 24-hour observations of narwhal situated in Koluktoo Bay. They identified Koluktoo Bay as an important area for narwhal in Milne Inlet, which is further supported by traditional Inuit knowledge of the area (Adrian Ootova, personal communication, Pond Inlet, NU). Marcoux et al. (2009) documented grouping patterns of narwhal in Koluktoo Bay and assessed correlation between narwhal presence and environmental variables. They found that narwhals travelled in clusters of 1-25 individuals, and that these clusters were smaller parts of large herding events that could have up to 642 clusters (Marcoux et al. 2009). There was also a degree of sexual segregation observed. Adult tusked males were primarily seen together. Tuskless females were observed with juveniles, yearlings, and calves, although there was some mixing with males, especially in larger clusters (Marcoux et al. 2009). They found there were some correlations between the entry and exit of narwhal and the tide and circadian cycles. There were inconsistencies between years however, suggesting that while narwal use of Koluktoo Bay is affected by tides, their use of the area is not limited by tidal state (Marcoux et al. 2009). These surveys taken in the same area before the establishment of ore carrier shipping provide some preliminary insights into how narwhal behave in the absence of shipping.

One of the major challenges for detecting changes in narwhal group behaviour is that narwhals are constantly responding to the highly complex and dynamic environment that they live in, and shipping is only one of multiple potential sources of disturbance. Milne Inlet and Koluktoo Bay are both traditional narwhal hunting grounds of the Inuit, and there are often active hunting groups situated on camps along the shore, targeting narwhal as they move in and out of Koluktoo Bay (Adrian Ootova, Pond Inlet, Nunavut, personal communication). While most hunting occurs from land, the Inuit sometimes use their small vessels as hunting platforms. Due to the life-threatening danger that hunting activity poses to narwhal, an antipredator behavioural response is expected to the occurrence of gunshots and nearby small boats.

Another significant predator of the narwhal is the killer whale. Killer whales are a historical predator of narwhal, but in recent years, the number of killer whale sightings in the Arctic has increased due to reduced summer sea ice cover (Higdon et al. 2012). Killer whales are usually present in the Eastern Canadian Arctic during the late Arctic summer when ice is absent from the inlets. They move transiently from inlet to inlet, hunting marine mammals (Higdon et al. 2012).

In response to killer whales, narwhals stay close together and near shore (Breed et al. 2017). In Milne Inlet these predation avoidance events often result in herding events, where narwhal travel en-masse to shallow water such as Koluktoo Bay to avoid predation. Herding does occur in the absence of predators but herding into Koluktoo Bay has been observed in association with killer whale presence (Marcoux et al. 2009).

Inuit hunting and killer whale presence are two examples of major stressors that narwhal may experience in Milne Inlet and are likely to elicit a strong response. If an ore carrier causes a response that mimics one of these two stressors, it could be an indication of a panicked or antipredator response to the vessel. It also highlights the importance of analyzing each potential stressor in isolation of other known stressors to avoid an overlap in narwhal responses. If narwhal do respond to shipping in a similar way as they do to predators, that would indicate there is an effect that could have population level consequences.

Research Objectives.

The objective of this chapter is to determine if narwhals show a change in behaviour in the presence of shipping, and if there is a response, whether it is a similar response to what is observed by narwhal escaping predation by killer whales or hunting activity. An additional objective is to determine if any change in behaviour is related to the HFC Broadband SPL measured in chapter 1. These objectives will be addressed using land-based surveys integrated with passive acoustic monitoring, and AIS ship tracking information.

Materials and Methods

Behavioural Data Collection

Survey Site

Land based surveys were conducted by a field team in a remote field camp on Bruce Head, NU during part of the shipping season in 2019. As part of their agreement with Baffinland, Golder Associates conducted a shore-based narwhal monitoring program that ran from August 5 - September 1 in 2019. The Bruce Head lookout (72.0735ºN, 80.545836 ºW), was located on a ledge at an elevation of 200m above sea level, and had a prominent view of the Behavioural Survey Area (BSA) and Stratified Survey Area (SSA; Golder 2020b). Observers were sheltered from weather by an observation post and used the surrounding ridge to observe the study area. The field camp was set back from the observer platform and was surrounded by electric polar bear fencing.

The field team consisted of three Golder Associates employees, three subcontractors (camp manager, the author, and a marine mammal observer), and six Inuit personnel. With the exception of myself and camp manager, all positions had a staff changeover occur after two weeks. The camp manager and author remained on site for the full five weeks of surveying. The field team was divided into two teams that alternated survey shifts every four hours.

Surveys

Hourly surveys began at 06:00 and ended at 22:00 EST. One team would conduct the surveys between 06:00 to 10:00 and 14:00 to 18:00, and the second team would conduct surveys between 10:00 to 14:00 and 18:00 to 22:00. These were the early and late shifts respectively, and the two teams would alternate between the early and late shifts every day. Every hour two simultaneous surveys were conducted: the Relative Abundance and Distribution (RAD) survey, and the Behavioural Study Area (BSA) survey. Datasets were compiled at the end of the survey season and were provided as Access databases by Golder Associates.

Relative Abundance and Distribution (RAD)

The RAD survey was a count of narwhal in every strata of the stratified survey area (SSA; Figure 2.1). They were conducted hourly by an observer using 10x42 binoculars and a data recorder; who recorded observations onto a datasheet. The observer would run through the strata from A to J, unless a northbound ship was travelling through the area, then the direction of the survey would be reversed beginning from J and ending in A. The observer would list out the Beaufort state between 0 and 10, the amount of glare in the stratum (none, light, or severe) and sightability; i.e. the likelihood of spotting a narwhal in the substratum (excellent, good, moderate, poor, impossible) and would proceed to scan the stratum for narwhals for one minute. If sightability was considered impossible, the substratum would not be surveyed and the surveyors would move on to the next one. The number of narwhal and their cardinal direction of movement (N, NW, W, SW, S, SE, E, NE) were recorded. If there was no clear movement of narwhal, they would be listed as “No Direction”. RADS were done hourly, or when a ship was present they were done continuously until a survey was done for before, during, and after the transit.

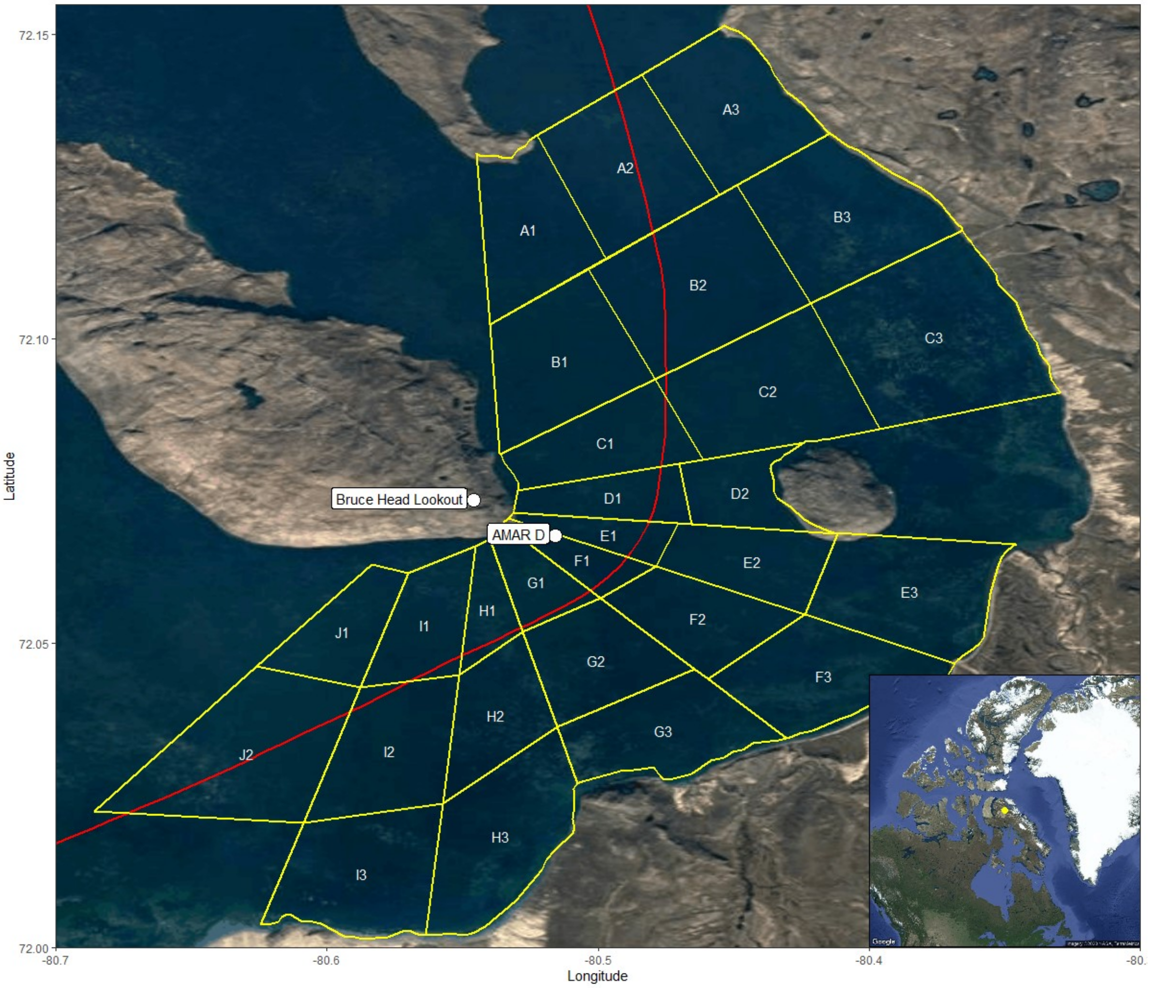

Figure 2.1: Map of SSA outlined in yellow with substrata names in white, and the nominal shipping route in red. Locations of the Bruce Head lookout and location of AMAR 19D are also labeled. Maps sourced from Google (2020).

Behavioural Study Area (BSA)

The BSA survey was designed to collect data on fine scale narwhal behavior as narwhal moved in and out of Koluktoo Bay (Figure 2.2). Narwhal typically move close to shore as they passed around Bruce Head (Adrian Ootova, Pond Inlet, Nunavut, personal communication) often in large numbers, during "Herding Events", providing opportunities to survey group composition and behavior of large numbers of narwhal as they moved into and out of Koluktoo Bay.

The BSA survey area was the strata D1, E1, and F1 up to one km from the tip of Bruce Head (Figure 2.2). Surveys were done for 50 minutes, starting on the hour at the same time as the RAD survey. The BSA required two roles; an observer and recorder (at times there were multiple observers). The observer would report data to the recorder who wrote down the information on a paper datasheet. If a group of narwhal entered the BSA, the observer would report the variables listed in Table 2.1. During a herding event, the survey would continue until the herding event had ended. Behavioural data including, group composition, group travel direction, speed, formation, and tightness were recorded for each group. A group was defined as a cluster of narwhals that were less than one body length apart. Group composition counted the number of adults, juveniles, yearlings, and calves, and whether the adults and juveniles had tusks or not.

If an individual was observed but not clearly identified, it was counted as an unknown. If an individual was counted and identified as adult or juvenile, but it was not known if a tusk was present, it was listed as an adult/juvenile with an unknown tusk. Yearlings and calves were identified based on differing coloration (calves were white, yearlings were greyer and larger), and juveniles were distinguished from adults due to

Figure 2.2: Map of BSA outlined in yellow with the nominal shipping route in red. Locations of the Bruce Head lookout and location of AMAR 19D are also labeled. Maps sourced from Google (2020).

being slightly smaller, dark grey with few white spots and if a tusk was present, it was shorter than the average adult tusk.

Primary and secondary behaviors were also recorded including: travel, foraging, social, and reproductive behaviours (Golder 2020b). A secondary behavior was one that occurred in the presence of the primary behavior (i.e., the behaviour observed first). Other unique behaviours that did not fit the description of primary behaviour types such as diving, logging, nursing, tusking, rubbing, etc. were also recorded when observed (Golder 2020b). Whether the observation was part of a herding event was also recorded.

Non-AIS Anthropogenic Activity

The presence of hunting activity, movement of vessels, and presence of other anthropogenic sources, including helicopters to and from Bruce Head, were also recorded. When any vessel was sighted in the SSA, time of observation, vessel size, its substrata of first sighting, direction of travel, and general activity were recorded. Hunting activity at the tip of the Bruce Head peninsula was recorded when observed during surveys and with two Wildlife Acoustic S4 (in-air) recorders located near the shoreline. When observed in a survey, the time of gunshot, number of shots, target, and whether the target was hit, were all recorded. Hunting activity was recorded both when it was shore-based and vessel-based. The times of gunshot were verified using the manually validated data from the Wildlife Acoustic S4 recorders and were provided by Golder Associates (Golder Associates Ltd. 2020b).

Table 2.1: List of BSA variables collected for narwhal sightings with all potential outcomes and definitions. Variables and entries were taken from Golder Associated Ltd (2020c).

Variable	List of possible entries
Time of sighting	Time (24 Hr)
Sighting Number	# (1,2,3) resetting with each new survey
Group size	# (1,2,3…)
Orientation	Cardinal directions (N, NE, E, SE, S, SW, W, NW)
Group tightness	Tight (<1 body width apart) Loose, (>1 body width)
Group Formation	Parallel, cluster, nondirectional line, no formation
Distance from shore	<300 m, >300 m
Group Composition	# Adults (Tusk/No tusk/ Unknown tusk) # Juveniles(Tusk/No tusk/ Unknown tusk) # Yearlings # Calves # Unknowns
Primary Behaviour	Travel, Milling, Social, Reproductive, Foraging
Unique Behaviours	Breaching (BR), Bubble Rings (BU), Catch Prey (CP), Chase Prey (CH), Diving (DY), Logging (LO), Mounting (MO), Nursing (NU), Rolling (RO), Rubbing (RU), Sexual Display (SX), Spyhopping (SP), Tail Slap (TS), Tusking (TU)
Included in Vac Survey	Yes/No

AIS and Noise

The HFC minute by minute broadband levels from AMAR D in 2019 (hereafter AMAR 19D) calculated in Chapter 1 were used in this study to approximate the noise level of the BSA, and in substrata E1 and F1 of the SSA. The HFC broadband level at AMAR 19D was provided for every sighting in the BSA, and for each RAD count in the SSA. AIS ship information including the proximity of the vessel to the recorder were also provided for every sighting when available.

Definitions of Sighting Context

To isolate the effects of shipping on narwhal behaviour, the presence of specific situational contexts that could significantly affect narwhal behavior were defined. These situational contexts were used to identify and isolate factors that could significantly impact narwhal behavior. Narwhal behaviour during times in which each context was solely present were compared. This was done to compare how shipping may alter behaviour compared to predation and other stressors from anthropogenic activity.

A series of variables were created to define the context of a narwhal observation for analyses of BSA and RAD surveys. In the RAD survey, hourly abundance counts were available, and these contexts were "before", "during", and "after" the presence of vessels, hunting activity, or killer whales. This was done to document the effect of exposure to each stressor on the abundance and distribution of narwhal in the study area, and to see if shifts changed pre and post exposure. For the BSA, the contexts were defined as binary "present" and "absent" since narwhal were moving through the area and would rarely stay in the BSA for sufficient data to be collected for pre/during/post contexts. Further analysis used subsets of the RAD and BSA during times when a single context was present in the absence of all others. The only exception made was for hunting activity, which had a low sample size of "during" cases when all contexts were excluded. Other anthropogenic activity was not excluded for the analysis of hunting activity, as hunting activity was generally associated with small vessel activity.

Hunting

The presence of hunting activity was defined as up to three hours after a gunshot had been fired. Gunshot times derived from the Wildlife Acoustic S4 recorders were used for precise determination of the times of gunshots, and times were also cross validated with the anthropogenic surveys (Golder 2020b).

Killer Whales

Killer whale presence has the potential to impact narwhal behavior just by being in the larger area, and effects on behavior have been observed to last until killer whales leave the area (Breed et al. 2017). As a result, the presence of killer whales needs to be defined with a broad resolution. The presence of killer whales was determined from sightings in the RAD survey, BSA survey, and ad-lib notes. In the RAD survey, killer whale presence was considered "during" between the times of first and last sighting, or first sighting up to three hours after when only one sighting time was available. Before was defined as up to 12 hours before the first sighting, and after was up to 12 hours after last sighting. In the BSA killer whales were considered present between the time of first and last sighting +/- 12 hours when available. When only one sighting time was available, the presence was +/- 12 hours from that time.

Other Anthropogenic Activity

The presence of other miscellaneous anthropogenic activity for which less data was available were also defined. These activities were mostly dominated by the presence of helicopters servicing the Bruce Head field camp and the presence of outboard boats without AIS active in the area. Small boats were a common sight in the study area, and regularly moved in and out of sight of the survey team. Due to this, the defined times of non-AIS vessel also included a 15-minute bracket on either side to account for uncertainty of small vessel activity. This context was not analyzed due to its vague definition, however it was not excluded in the RAD analysis for hunting activity, since small vessel activity was commonly associated with hunting.

Effect of shipping

The presence of large vessels was defined by the interpolated AIS ship presence within 5 km ± 15 minutes of AMAR D as interpolated in Chapter 1. This 5 km range was selected to accommodate the ranges in which narwhal were expected to be able to perceive ship noise based on HFC noise levels from Chapter 1. Sighting within three hours of this context were defined as “before” or “after”.

Statistical Analysis

RAD

Differences in narwhal abundance between before, during, after, and control cases were tested using a zero inflated Poisson model (ZIP). ZIPs are commonly used in ecological count data with large numbers of zeros and use a combination of Poisson regression for non-zeroes and binomial model with logit link for the excess zeroes to model the data (Long 1997). ZIP models were applied for the subsets of the stratified survey data for which contexts of ship presence, hunting activity, and killer whale presence were isolated from all other defined contexts. ZIP models were used to compare the effect of stratum letter, substratum number, and context condition (before, during, after, and NA (Control)) for each of the subsets. The predicted abundance of the model was plotted over the boxplots of the raw abundance data and the differences between the contexts were visually described.

Ship Noise in SSA

A ZIP was applied to a subset of the SSA that included only cases when shipping was isolated from all other contexts. The ZIP was used determine if HFC Broadband SPL at AMAR D had any effect on narwhal abundance in substrata E1 and F1, the two substrata in closest proximity to AMAR D. Backwards stepwise selection was applied to the ZIP model to test whether the variance explained by HFC Broadband SPL during a vessel passage was significant.

BSA

Group size and group behaviour were compared between the control (all contexts were absent) and cases when killer whales, shipping, and hunting activity were present in the absence of other contexts. Comparisons of group size were done with a Welch's two sample t-test. The difference in the prevalence of recorded behaviours was tested between cases when each individual context of killer whales, shipping within 5 km, and hunting were present or absent while all other contexts were absent. The probability of a sighting being part of a herding event, being less than 300 m from shore, moving inbound, having tight spread, when more than one narwhal was present, and the probability of travel as a primary behaviour were tested between the different contexts and the control using a two-sided Z-test of proportions.

Differences in the relative proportion of group speeds were all tested with a chi-squared test for independence. In cases when sample sizes were insufficient to conduct a chi-squared test, the Fisher's exact test was used in its place.

BSA and Noise

Binomial logistic regression was used to examine the effect of Broadband SPLs with the HFC weighting function applied on observed behaviours in the BSA. Using BSA data in the absence of hunting, killer whales, and other anthropogenic activity, a series of binomial models were run to examine the effect of HFC Broadband SPL, ship presence < 5 km ± 15 minutes, and their interactions on the probability of the presence of the following behaviours: herding, general direction (inbound versus outbound), distance from shore (< 300 m versus > 300 m from shore), group spread (tight versus loose), and primary behaviour (travel versus non-travel). The size of groups in the BSA was also examined in relation to HFC Broadband SPL and ship presence with a Poisson-distributed generalized linear model. Group speed was examined with a multinomial logistic linear model from the r package *nnet* (Venables and Ripley 2002). The p-values of these models were assessed with alpha level 0.05 to assess the effect of noise on narwhal behaviour, both in times when ships were within an audible range of AMAR 19D, as well as during times when ships and other activities were absent.

Results

In 2019, RAD and BSA surveys were conducted on 26 days between August 6 – September 1, totalling 139.3 hours of observer effort in the SSA and BSA. In 2019, a total of 14,680 narwhal were counted in the RAD counts. BSA surveys sighted 1,370 groups of narwhal in 2019, counting a total of 5,231 narwhal across 24 days of surveys.

RAD

The number of observational counts per substratum ranged from 284 – 288 RAD counts. When poor and impossible sightabilities were excluded, that range was reduced to 165 – 280 RAD counts, with substrata 3 consistently containing the lowest number of RAD Counts with moderate – excellent sightability. RAD counts saw the lowest abundances in strata A-F, with abundance counts increasing in G-H, and the highest abundances were observed in strata I and J; the closest strata to Koluktoo Bay (Figure 2.3).

Hunting and Killer Whales

Inuit hunting activity did show a trend in narwhal abundance between before, during, and after conditions across substrata (Figure 2.4). Narwhal abundance declined after exposure to hunting compared to before and during counts in some substrata, but not all. Some substrata had increases from before to during, and returned to similar levels after, and substrata H3 observed an increase in narwhal abundance after exposure to hunting activity (Figure 2.4). The ZIP model estimated that across all substrata, abundance decreased from before to during, and decreased from during to after (Figure 2.4, Appendix Table A1).

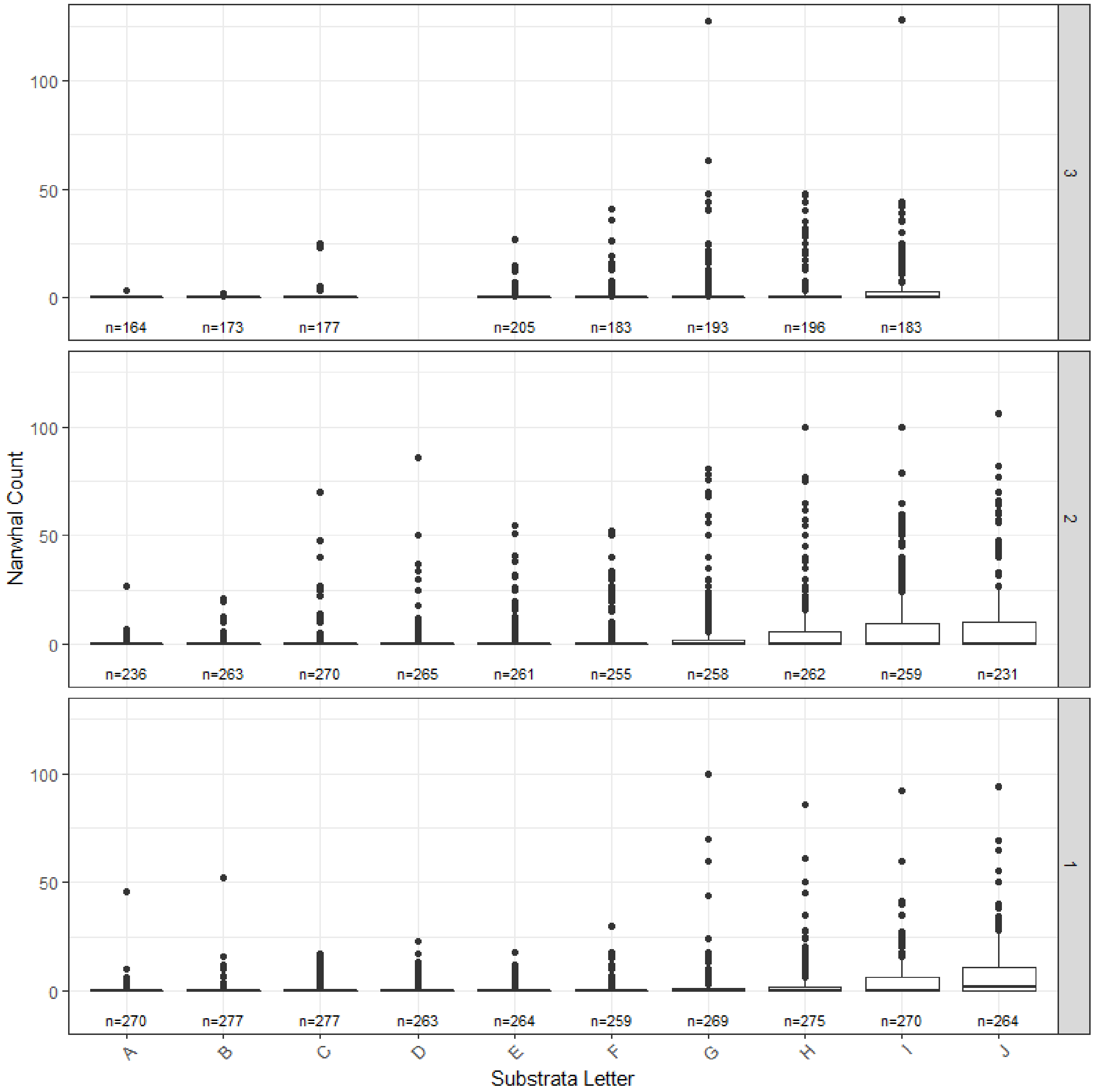

Figure 2.3: Boxplot showing the 5th, 25th, 50th, 75th, and 95th percentiles of narwhal counts from RAD surveys in 2019 for all Substrata excluding surveys with “poor” and “impossible” sightability. Letter and number coordinates match locations in Figure 2.1

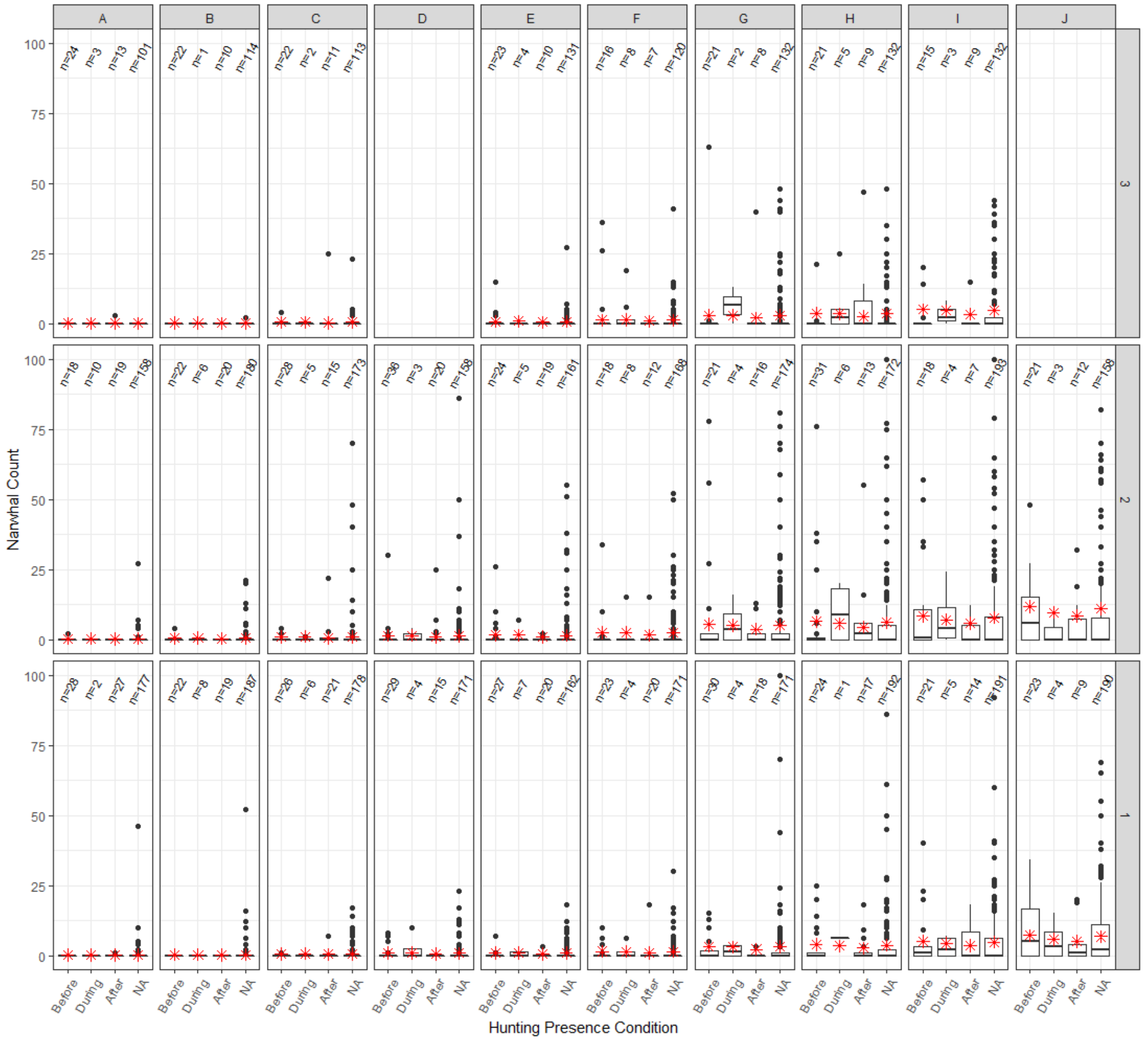

Figure 2.4: Boxplots of narwhal counts in RAD surveys in each substrata during times three hours before, during, and three hours after hunting activity was present in the survey area, as well as the control counts when no other contexts were present (NA). The abundance value predicted by the ZIP model is shown in red for each condition. Letter and number coordinates match locations in Figure 2.1

Narwhal abundance counts after exposure were significantly lower than during, before, and control abundances for the count model. It should be noted that the sample size for the during category was very low for many substrata, even when other anthropogenic activity was not excluded from the analysis.

Killer whale activity also led to a decrease in narwhal abundance in the RAD survey, with after counts being significantly lower in the ZIP model after exposure compared to before and during (Figure 2.5, Appendix Table A2). Strata I and J had the highest abundances before killer whales were present, E - H had highest abundances during killer whale activity, and in all substrata, there were almost no narwhal sighted after killer whales had been present (Figure 2.5). This shows that narwhal shifted their abundance from strata J-I out to E-G, and left the study area after killer whales had been present. The ZIP model estimated across substrata that abundance in the SSA was highest before killer whale activity, reduced during during killer whale activity, and was virtually empty after killer whale activity, with the strongest declines in strata G-J in substrata 1-2 (Figure 2.5). Sample sizes were low, especially for RAD counts after killer whale activity. Substrata C2 and H3 had no surveys available after exposure.

In both cases of hunting and killer whale activity, even though sample size for some survey conditions were low, there was an apparent shift in narwhal abundance post exposure to stressors such as predation from killer whales and gunshots from hunting (Figures 2.4 and 2.5). The differences in counts and abundance (zero inflation in data) in the SSA between before and after conditions were significant for both ZIP models (Appendix Tables A1 and A2).

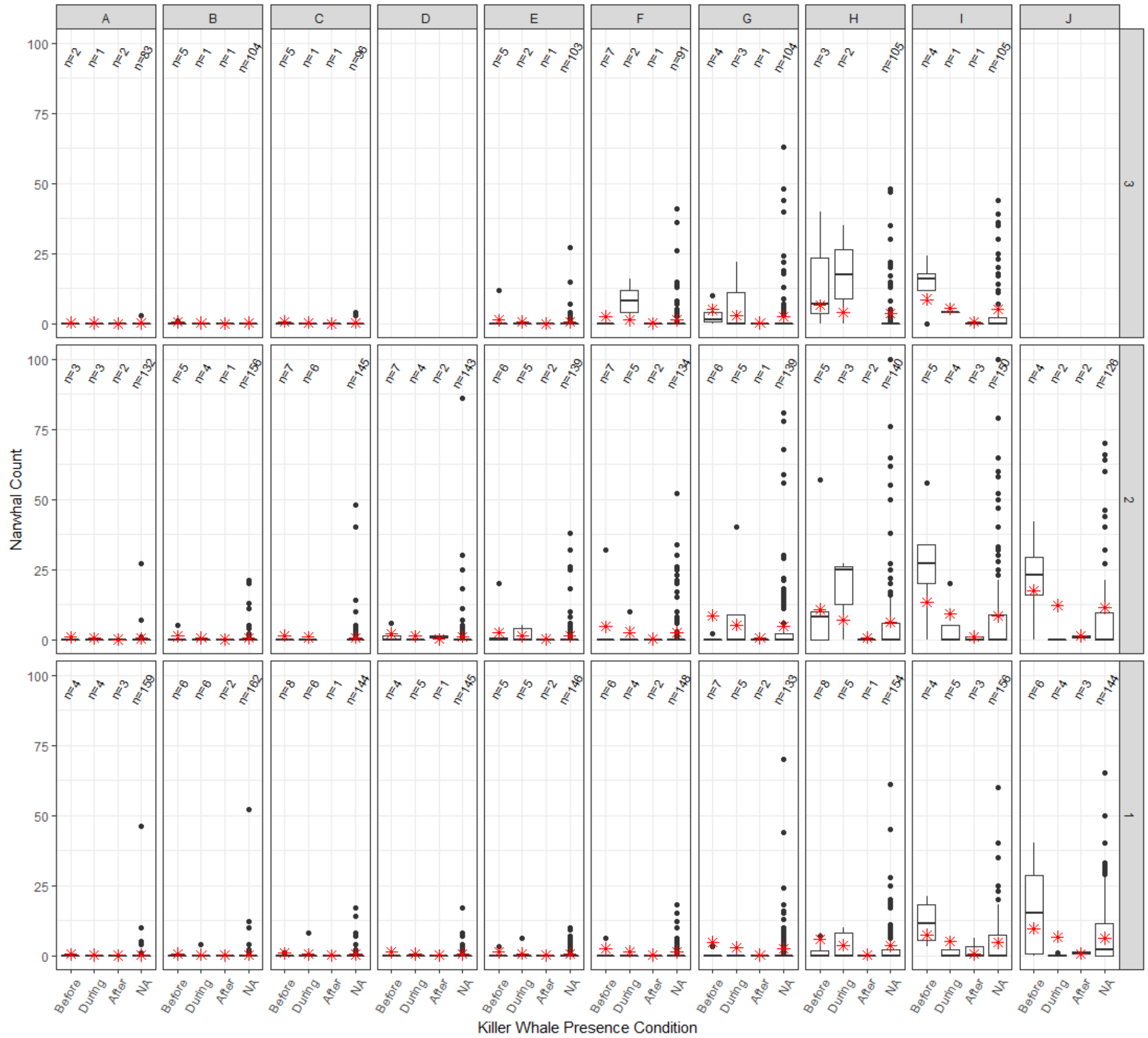

Figure 2.5: Boxplots of narwhal counts in RAD surveys in each substrata during times twelve hours before, during, and twelve hours after killer whales were present in the survey area, as well as a control when no other contexts were present (NA). The abundance value predicted by the ZIP model is shown in red for each condition. Letter and number coordinates match locations in Figure 2.1

Ship Context

In cases before, during, and after the presence of ore carriers in the SSA, the decline in narwhal abundance after exposure did not occur (Figures 2.5, 2.6, and 2.7). Instead, an opposite effect was observed with abundance counts in many substrata increasing after ship presence (Figure 2.5). The ZIP model, for contexts in which only ship conditions were present, found no significant difference in narwhal abundance counts between times before, during, or after exposure (Figure 2.5). The presence of ore carriers did not appear to cause narwhal to leave the SSA. I note that the sample size for abundance counts during exposure were less than either the before or after designations in all strata, likely due to the short duration of time that ships were transiting within 5 km of AMAR D.

HFC Broadband Noise in SSA

The ZIP model used to predict RAD abundance in E1 and F1 from HFC Broadband SPL, location, and ship context found some significant effects of HFC Broadband SPL in some ship contexts. In both the zero inflated and count portions of the model, “during” times of vessel presence and interaction with HFC Broadband SPL was found to be significant. A significant relationship was also found in ‘before” contexts and interaction between “before” and HFC Broadband SPL for the zero-inflated portion of the model (Table 2.2). The zero inflated portion of the model estimates the probability of a non-zero RAD count, whereas the count portion of the model uses a Poisson regression using only non-zeroes. As with the previous ZIP model there was no apparent

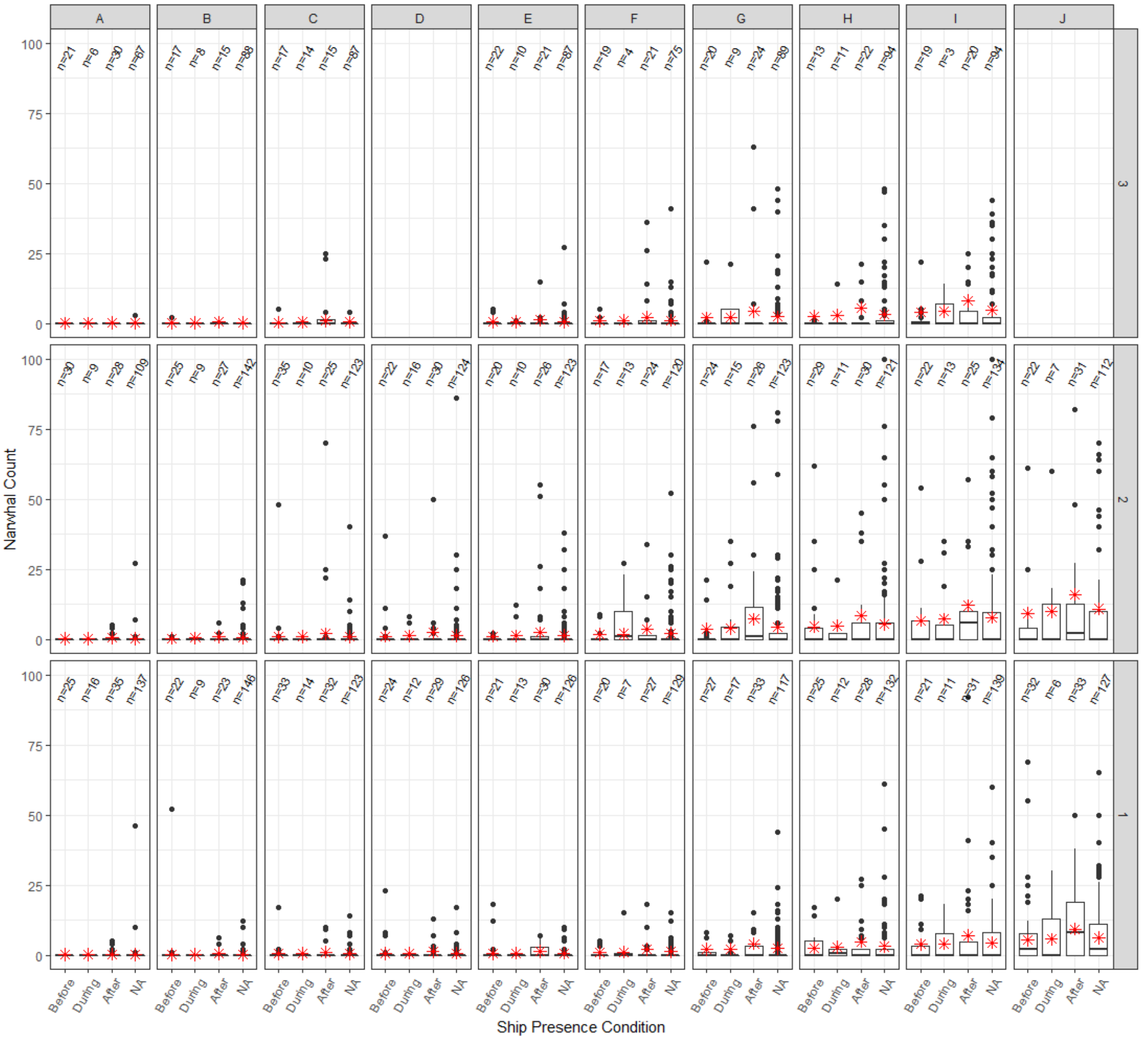

Figure 2.6: Boxplots of narwhal counts in RAD surveys in each substrata during times three hours before, during, and three hours after a ship was present in the survey area, as well as times when no other contexts were present (NA). The mean abundance value predicted by the ZIP model is shown in red for each condition. Letter and number coordinates match locations in Figure 2.1

Table 2.2: Model summary with estimates, standard error, Z and p-values for Zero Inflated Poisson model testing the relationship between RAD narwhal counts and HFC Broadband sound pressure level (SPL) for before, during, and after vessel passages.

Count Model:	Estimates	SE	Z	P-Value
Intercept(E,1, After)	**3.61166**	**1.44856**	**2.493**	**0.0127**
F1	-0.1454	0.15123	-0.961	0.3363
HFC Broadband SPL	-0.021	0.01562	-1.343	0.1792
Before	-2.676	1.96766	-1.36	0.1738
During	**-24.037**	**9.78577**	**-2.456**	**0.014**
NA	-3.0775	1.81299	-1.697	0.0896
HFC Broadband SPL:Before	0.03318	0.02126	1.561	0.1186
HFC Broadband SPL:During	**0.26858**	**0.10448**	**2.571**	**0.0102**
HFC Broadband SPL:NA	0.03075	0.01996	1.54	0.1235
Zero Inflation Model:	Estimates	SE	Z	P-Value
Intercept(E,1, After)	3.77948	3.51014	1.077	0.2816
F1	-0.5735	0.31012	-1.849	0.0644
HFC Broadband SPL	-0.0258	0.03758	-0.686	0.493
Before	**-6.7551**	**6.82021**	**-0.99**	**0.322**
During	**-17.067**	**13.2804**	**-1.285**	**0.1988**
NA	-6.6896	4.36038	-1.534	0.125
HFC Broadband SPL:Before	**0.08**	**0.07363**	**1.087**	**0.2772**
HFC Broadband SPL:During	**0.19459**	**0.14389**	**1.352**	**0.1763**
HFC Broadband SPL:NA	0.08293	0.04757	1.744	0.0812

decline in abundance after a ship had passed. The significant interactions between during HFC broadband SPL and “during” contexts could suggest that noise from shipping is affecting abundance counts when vessels are nearby, however HFC broadband also had a significant interaction with “before” vessel presence in the zero inflated portion of the model (Table 2.2). This suggests that the relationship may not necessarily be causal, although no significant effect was found with HFC Broadband SPL in the ZIP model (Table 2.2). The significant interaction of HFC Broadband SPL and during ship passages estimated a slightly increasing abundance of narwhal with increasing HFC SPL when ships were present, which while statistically significant is not indicative of an avoidant response to vessel noise.

BSA

Of the 1,347 sightings in the BSA, 917 were omitted due to the presence of more than one stressor or due to the presence of other anthropogenic activity. Of the 430 sightings remaining, 20 (4%) occurred within 5 km +/- 15 minutes of an ore carrier, 82 (19%) occurred during hunting activity, 77 (18%) occurred during the presence of killer whales, and 251 (58%) occurred in the absence of all the defined contextual variables (Figure 2.7).

During times when killer whales or hunting were present, there were higher probabilities of herding behaviour, closer distances from shore, inbound movement, and narwhal were less likely to exhibit non-travel behaviour compared to control (Figure 2.7, Table 2.3). When Inuit hunting was occurring, similar narwhal behavioural patterns to the killer whales were observed, although some factors such as the probability of non-travel behaviour, and probability of inbound movement, were not found to be statistically significant (Table 2.3). Narwhal sightings in the presence of ore carriers did not significantly differ from control for all BSA variables with exception to herding, which had a lower probability of occurrence in the presence of shipping (Table 2.3, Figure 2.7).

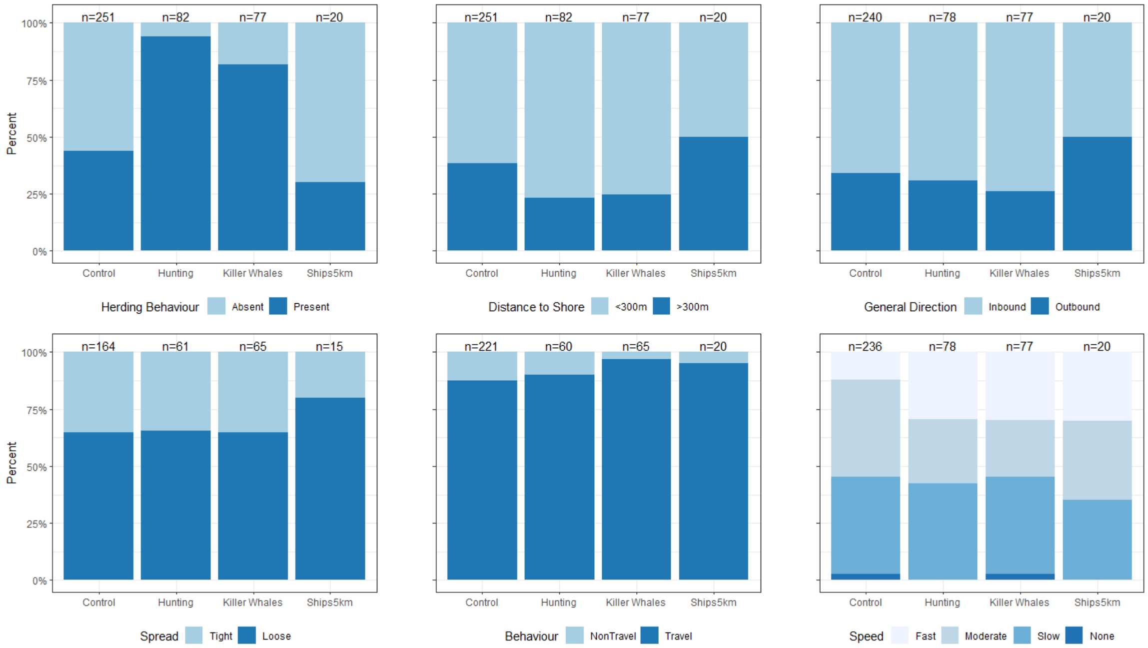

Figure 2.7: The relative proportion of BSA sightings with the assigned behaviour depending on the contextual condition of the sighting. Numbers for each bar represent the number of sightings per group.

Table 2.3: Results from statistical analysis of BSA sightings data under different contextual conditions. Statistically significant relationships are shown in bold text.

Group Size	Contexts Tested	test type	Alternative	t	df	p-value
	Control-Killer Whales	Welch Two Sample T-Test	Greater	1.0128	176	0.1563
	Control-Ships5km	Welch Two Sample T-Test	Less	-0.671	22	0.2545
	Control-Hunting	Welch Two Sample T-Test	Greater	-0.695	173	0.7559
Herding	Contexts Tested	test type		Z	df	p-value
	Control-Killer Whales	**Z-Test**	**Greater**	**4.4986**	**NA**	**<0.0001**
	Control-Ships5km	**Z-Test**	**Less**	**-2.553**	**NA**	**0.0107**
	Control-Hunting	**Z-Test**	**Greater**	**6.7377**	**NA**	**<0.0001**
Proximity to Shore (<300m)	Context	test type		Z	df	p-value
	Control-Killer Whales	**Z-Test**	**Greater**	**4.3373**	**NA**	**<0.0001**
	Control-Ships5km	Z-Test	Less	-0.9244	NA	0.1776
	Control-Hunting	**Z-Test**	**Greater**	**2.1765**	**NA**	**0.0148**
Speed	Context	test type		X-squared	df	p-value
	Killer Whales	**Chi-Squared**	**NA**	**14.962**	**2**	**0.0005**
	Control-Ships5km	Fishers Exact Test	NA	NA	NA	0.1576
	Hunting	**Chi-Squared**	**NA**	**7.8068**	**2**	**0.0202**
Tightness (Tight)	Context	test type		Z	df	p-value
	Control-Killer Whales	Z-Test	Two-Sided	0.50568	NA	0.6213
	Control-Ships5km	Z-Test	Less	1.3317	NA	0.9085
	Control-Hunting	Z-Test	Two Sided	0.0761	NA	0.9393
General Direction (Inbound)	Context	test type		Z	df	p-value
	Control-Killer Whales	**Z-Test**	**Greater**	**2.8579**	**NA**	**0.0021**
	Control-Ships5km	Z-Test	Less	-1.1629	NA	0.1224
	Control-Hunting	Z-Test	Greater	0.1169	NA	0.4535
Travel	Context	test type		Z	df	p-value
	Control-Killer Whales	**Z-Test**	**Greater**	**4.0887**	**NA**	**<0.0001**
	Control-Ships5km	Z-Test	Greater	1.1736	NA	0.1203
	Control-Hunting	Z-Test	Greater	0.6272	NA	0.2653

Group tightness did not change significantly across any of the contexts (Table 2.3). The chi squared and Fisher's exact tests for speed between the stressors and control found significant differences from control for killer whales and hunting, but not for shipping (Table 2.3), even though shipping seemed to have similar proportions to the control contexts for fast group speed (Figure 2.7).

Group sizes for BSA sightings were significantly higher during the presence of killer whales but did not change in the presence of hunting or shipping compared to control (Table 2.3). The presence of ore carriers does not seem to lead to the same behaviours observed in the presence of killer whales or hunting. The group size and probability of herding do not increase in the presence of shipping compared to control (Figure 2.7 and Table 2.3). The distance to shore, patterns in group speed, tightness, and general direction of movement in and out of the inlet do not differ between times when ore carriers were present and the control (Figure 2.7 and Table 2.3). It should also be noted that the number of narwhal sightings that occurred when ships were less than 5 km from AMAR D were much lower than the sample sizes for all other contexts. This limits the statistical power of the tests performed and may explain why some visually distinct differences in Figure 2.7 that are significant for the other contexts are not statistically significant for shipping in Table 2.3.

BSA and noise

During times when ships and other activities were absent, there were significantly decreasing trends in the probability of herding behaviour, groups travelling inbound, and groups < 300 m from shore with increasing HFC broadband SPL (Figure

2.8, Table 2.4). Group size also appears to slightly decrease with increasing HFC Broadband levels (Figure 2.8, Table 2.4).

In relation to the presence of shipping and noise level interactions with shipping, no significant effect was found in any of the behavioural variables analyzed. The 95% confidence intervals for times when ships were present (red) are consistently wider than those of the natural behaviour (blue) and overlap in all variables (Figure 2.8). The low sample size (*n* = 20) of the sightings during ship presence may be the likely culprit for these high levels of uncertainty. It's also worth noting that there is an absence of sightings data for noise levels higher than ~105 dB re 1µPa HFC and lower than ~83 dB re 1µPa HFC when ships are present (Figure 2.8), further limiting the possibility for an observable change in narwhal response to high noise levels during times when ships were present. Even when the ships were nearby, the perceived noise levels by the narwhal were very low.

The multinomial model that assessed speed in relation to HFC Broadband SPL and ship presence found no significant relationship between HFC Broadband SPL, ship presence, or interaction for slow, medium, or fast group speeds. In Figure 2.8, the visualized trends show that fast group speeds are the least common of the three in natural settings, and there is a higher mean probability of fast-moving narwhal during times when ships are present, however the wide 95% confidence intervals overlap with the ships-absent data. While there is a visible increase in probability of slow group speeds with increasing HFC Broadband SPL, and a simultaneous decrease in probabilities for moderate and fast group speeds, the confidence intervals in these results are very wide and reflect low statistical power (Figure 2.,9 Table 2.5). Low sample sizes for sightings during times when ships were present seem to be resulting in high levels of uncertainty of the actual trends, and thus produce non-significant effects of HFC Broadband SPL and ship presence within 5 km ±15 minutes on narwhal speed in the BSA (Table 2.5).

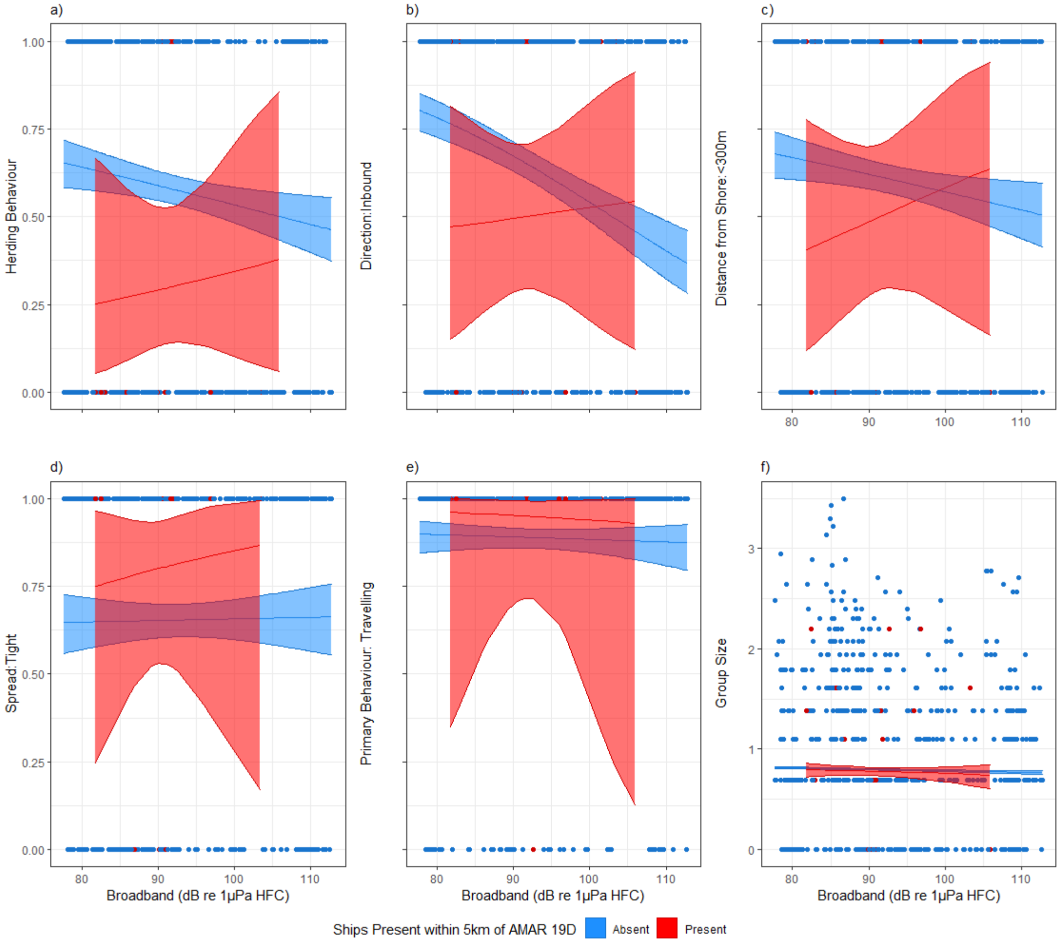

Figure 2.8: Predicted values with 95% confidence intervals from binomial logistic regression (a-e) and Poisson distributed generalized linear model (f) for BSA data in 2019 during times when hunting, killer whales, and other anthropogenic activities were absent. Values are predicted on the y axis over Broadband SPLs (dB re 1 µPa HFC) on the x axis. Each model shows the estimated probability of a) herding behaviour, b) inbound direction, c) < 300 m distance from shore, d) tight spread, and e) travelling as primary behaviour; f) is the counted group size transformed with natural log to match the output of the Poisson distributed generalized linear model.

Table 2.4: Summary of binomial logistic and Poisson distributed generalized linear models for models shown in Figure 2.8.

Behavioural Variable	Model Family	Category	Estimate	SE	Z value	p value
Herding	Binomal Logistic	**Intercept**	**2.370**	**0.779**	**3.044**	**0.0023**
		HFC Broadband SPL	**-0.022**	**0.008**	**-2.679**	**0.0074**
		Ships5km5min	-5.494	7.027	-0.782	0.4342
		HFCBroadband SPL:Ships	0.047	0.076	0.619	0.5361
Distance to Shore (<300m)	Binomal Logistic	Category	Estimate	SE	Z value	p value
		Intercept	**2.36705**	**0.78636**	**3.01**	**0.0026**
		HFC Broadband SPL	**-0.0208**	**0.00841**	**-2.474**	**0.0134**
		Ships5km5min	-5.9609	6.62986	-0.899	0.3686
		HFC Broadband SPL:Ships	0.06007	0.07226	0.831	0.4058
General Direction (Inbound)	Binomal Logistic	Category	Estimate	SE	Z value	p value
		Intercept	**5.73148**	**0.86225**	**6.647**	**<0.0001**
		HFC Broadband SPL	**-0.0557**	**0.00917**	**-6.071**	**<0.0001**
		Ships5km5min	-6.8378	6.51308	-1.05	0.2940
		HFC Broadband SPL:Ships	0.06775	0.07093	0.955	0.3400
Spread (Tight)	Binomal Logistic	Category	Estimate	SE	Z value	p value
		Intercept	0.44935	0.97114	0.463	0.6440
		HFC Broadband SPL	0.00203	0.01042	0.195	0.8460
		Ships5km5min	-2.27	10.7051	-0.212	0.8320
		HFC Broadband SPL:Ships	0.03366	0.11932	0.282	0.7780
Primary Behavior as travel/nontravel	Binomal Logistic	Category	Estimate	SE	Z value	p value
		Intercept	2.73001	1.25226	2.18	0.0293
		HFC Broadband SPL	-0.007	0.01335	-0.523	0.6012
		Ships5km5min	2.67424	14.4051	0.186	0.8527
		HFC Broadband SPL:Ships	-0.0197	0.15519	-0.127	0.8988
Group Size	Poisson	Category	Estimate	SE	Z value	p value
		Intercept	**2.20216**	**0.19556**	**11.261**	**<0.0001**
		HFC Broadband SPL	**-0.0091**	**0.00212**	**-4.278**	**<0.0001**
		Ships5km5min	0.28064	1.76849	0.159	0.8740
		HFC Broadband SPL:Ships	-0.0044	0.01938	-0.227	0.8210

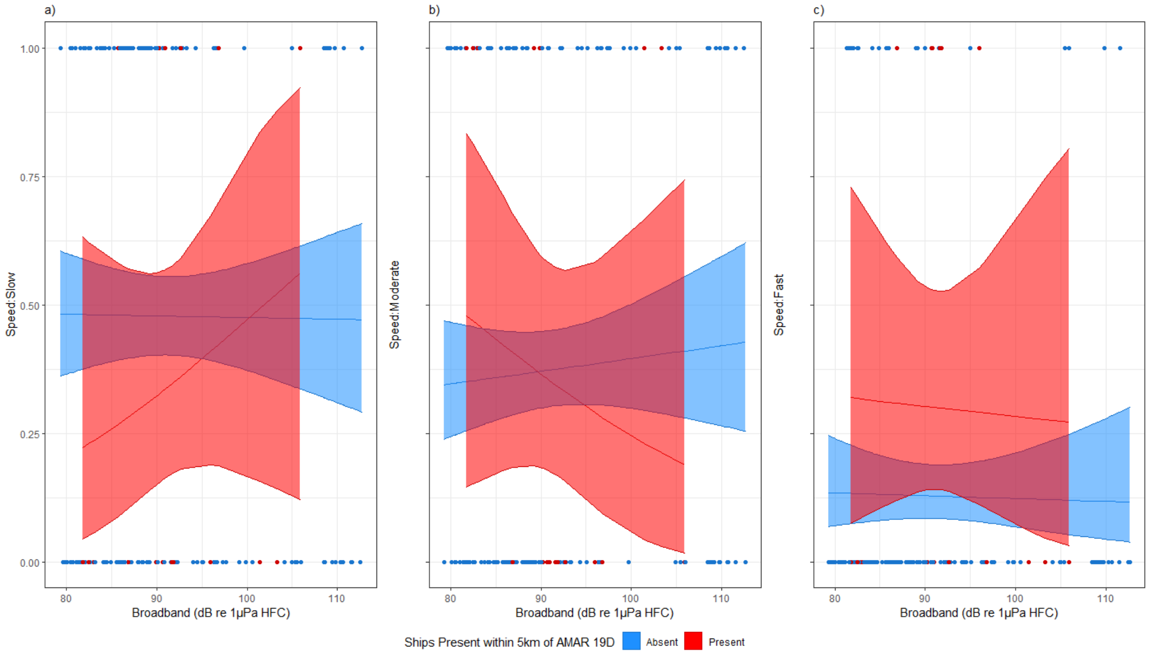

Figure 2.9: Predicted probabilities ± 95% CI for a) slow, b) moderate, and c) fast group speeds for BSA sightings in 2019 in the absence of hunting, killer whales, and other anthropogenic activity with times with ships present within 5 km ± 15 minutes in red, and all other times in blue.

Table 2.5: Summary results for multinomial logistical model testing the impact of ship presence within 5 km ± 15 mins, HFC Broadband SPL, and interaction on the speed of narwhal groups in the BSA. Slow speed was used as a reference factor for the model and hence has no values of its own.

Speed	Category	Estimate	SE	Z value	p value
Fast	Intercept	-0.9811	2.4548	-0.3997	0.6894
	HFC Broadband SPL	-0.0036	0.0269	-0.1354	0.8922
	Ships5km5min	5.0486	8.4651	0.5964	0.5509
	HFCBroadband:Ship5km15min	-0.0421	0.0918	-0.4592	0.6461
Moderate	Intercept	-0.9016	1.6694	-0.5400	0.5892
	HFC Broadband SPL	0.0072	0.0182	0.3950	0.6928
	Ships5km5min	7.9850	8.3235	0.9593	0.3374
	HFCBroadband:Ship5km15min	-0.0845	0.0908	-0.9308	0.3520

Discussion

This study set out to determine if narwhal were responding to shipping in a manner similar to their response to other stressors. A significant response to killer whales and hunting was detected which was expected. However, a similar response was not observed in the presence of shipping or its related noise in either the RAD or BSA survey data, with the effects being often muddled by low statistical power from small sample sizes.

Hunting and Killer Whales

The findings of the SSA and BSA analyses showed a distinct pattern of behaviour before, during, and after exposure to killer whales and hunting activity. After these two stressors occur, there is reduction in the abundance of all narwhal in the SSA. In the case of the killer whales, the decline is very dramatic, with almost no narwhal present in the SSA, and a few in Strata I and J. Strata I & J are the closest to Koluktoo Bay, suggesting these remaining narwhals may be stragglers making their way to Koluktoo Bay. In the BSA, narwhal travelling closer to shore were more likely to be travelling, moving inbound towards Koluktoo Bay, to be moving faster, and were more likely to be herding. This response is similar to narwhal behaviour observed by Breed et al. (2017) in Admiralty Inlet when killer whales were nearby. Breed et al. (2017) also found narwhal returned to normal after the killer whales left the area. It is uncertain when narwhal behaviour returned to normal in this study since the narwhal had left the study area for an extended period of time after the killer whales left. Many marine mammal species respond with antipredator behaviour to killer whale presence and calls (Allen et al. 2014, Isojunno et al. 2016), and this strong response was expected.

During Inuit hunting activity, narwhal seemed to display similar changes in behaviour albeit less extreme; their abundance in the SSA declined slightly after hunting activity in the SSA, and in the BSA herding was more likely to occur, with the narwhals being closer to shore. The correlation in the BSA may be because herding narwhal close to shore are ideal targets for hunting activity at Bruce Head. The hunting activity could be a response to, rather than a cause for, the narwhal behaviour in the BSA. That said, the decrease in abundance after hunting activity across the SSA is likely a response to hunting activity. The effect of hunting on narwhal abundance in the SSA however seems to be less extreme than for killer whales, indicating that narwhal close to the event may flee in response, but other narwhal further away from the hunting event may not.

Shipping and Noise

When it came to shipping, patterns of abundance varied between different substrata in the SSA, but generally did not resemble the responses seen in the presence of hunting and killer whales. Narwhal abundance did not decline after a vessel has passed the SSA in any substrata, in fact it generally increased. This indicates that narwhal do not flee the area in response to shipping like they do in the presence of predation risk. The ZIP model used to test the effect of HFC broadband SPL in substrata E1 and F1 did not find a decrease in narwhal abundance or presence with increasing noise levels. The RAD analysis for shipping was limited by only analyzing the abundance of narwhal in the SSA at a broad resolution before, during, and after exposure. This broad resolution cannot detect mild responses at close range of the ships. While no large-scale response was observed by the presence of shipping, the possibility of a mild avoidant response to shipping cannot be ruled out. Additionally, for the RAD surveys, sightability was inevitably lower in farther strata, and they were the first substrata to reach poor or impossible sightability in the presence of bad weather. The abundance counts of narwhal in these strata may be underrepresented.

In all analyses of BSA behaviour in relation to HFC broadband SPL, the high uncertainty prevented any significant differences to be detected, even though some differing trends from the control are present. The results of this study indicate that in the presence of ships, narwhal don't flee the SSA nor engage in antipredator responses in the BSA. It is presently unclear what role that HFC broadband SPL may have due to the limitations of the sample sizes in this study and the low noise levels recorded. However, the lack of response to ship presence in the SSA and BSA suggests that exposure to ship noise is unlikely to cause major disruptions to important life functions such as foraging.

While more detailed group behaviour was available in the BSA than the RAD, this area was not necessarily representative of narwhal behaviour across the SSA. The BSA was close to shore and was not located directly on the shipping route. As a result, there were extremely few sightings of narwhal in the BSA with a ship less than 1 km from AMAR D. The lack of observed response to ships in this study does not rule out the possibility of behavioural changes by narwhal at very close distance, where broadband SPL is expected to increase. Studies that utilize movement data from tagging such as Golder Associates Ltd. (2020a) or monitoring surface behaviour near ships with drones may provide better data for fine scale movements of narwhal in response to shipping at close distances. Difference between group types (e.g., groups with/without calves) were not considered in this study, although effects may vary depending on the composition of narwhal groups. There are multiple other hunting locations along the shore both north and south of the BSA that cannot be seen from the survey platform. It is thus possible for narwhal entering the BSA to have been recently exposed to unknown hunting activity not recorded in the surveys.

Robust analysis of a behavioural response by marine mammals to noise from shipping is notoriously difficult to achieve. Replicates in these types of analyses are often either spatially or temporally segregated, observed responses may sometimes be falsely attributed to acoustic stimulus when an unmeasured environmental parameter was responsible, and the conclusions of such analyses are commonly generalized (Erbe et al., 2018). Responses by marine mammals to anthropogenic noise vary considerably both in received SPLs and in the severity of exposure (Gomez et al. 2016, Southall et al. 2019). Different populations, sound sources, and environmental contexts contribute to this variability, but the variability in response is also seen within populations depending on individual experience, age, gender, health, and motivation (Erbe et al, 2018). This study made efforts to compare behavioural responses to other biologically meaningful stimuli such as predation by killer whales and Inuit hunting, however there may be additional environmental factors that may explain some of the observed variability in narwhal abundance in Milne Inlet. Marcoux et al. (2009) did not find a relationship between tidal or circadian cycles and narwhal movement patterns in Koluktoo Bay, however other factors such as prey availability may play an important role in narwhal movement patterns in the area.

Some odontocete species have been observed responding to noise from shipping. Southern resident killer whales have been shown to exhibit mild avoidance behaviour in the presence of ship noise at around 130 dB re 1 µPa unweighted (rms; Williams et al. 2014). In addition, 120 dB re µPa unweighted has been identified as an informal criterion for an acoustic effect on marine mammals, however response thresholds have been observed to occur both above and below this criterion (National Research Council, 1994). Many studies also use unweighted broadband SPL, which chapter 1 demonstrated can misrepresent the perceived noise levels by marine mammals in some cases. The use of unweighted Broadband SPL alone to predict the response of marine mammals to anthropogenic noise has been criticized as insufficient since it does not account for the complex individual contexts in which these exposures occur (Gomez et al. 2016, Southall et al. 2019).

When looking for responses in behaviour to other kinds of vessel traffic, odontocetes seem to exhibit a stronger response to smaller vessels than large ones (Ng and Leung 2003). Large ships generally move more slowly, they follow a relatively fixed path, and they generate most of their noise at frequencies where cetaceans with HFC or VHFC weightings have poor sensitivity (Arveson and Vendettis 2000, McQuinn et al. 2011). Smaller vessels can also approach cetaceans more rapidly and create more noise with high frequency components (Hermannsen et al. 2019). As a result, they pose a higher risk of behavioural disturbance to odontocetes than large vessels, even if the unweighted Broadband SPL is the same (Ng and Leung 2003, McQuinn et al. 2011, Lundquist et al. 2012). Non-AIS vessels (outboard motorboats) were not directly analyzed in this study, but hunting activity was often associated with the presence of small vessels. There is likely to be an effect of small boat presence on narwhal behaviour, especially since many of these outboard boats are used to actively hunt narwhal.

Icebreaking activity has been shown to coincide with avoidance responses in narwhal and beluga (Finley and Davis 1984, Cosens & Dueck 1993). Icebreaking does not occur during the open water season but may occur on the shoulder seasons depending on sea ice conditions. The shipping season in Milne Inlet extends into October, when sea ice begins to form, and narwhal begin to migrate towards their winter habitat. This is a particularly vulnerable time for narwhal, as the development of sea ice can lead to lethal entrapments (Heide-Jørgensen et al. 2002, Westdal et al. 2017). It has been suggested that seismic testing could increase the chance of ice-entrapment for narwhal (Heide-Jørgensen et al. 2013). If so, disturbance from other anthropogenic noises could lead to similar increases in risk.

The lack of large scale behavioural response in the short term does not exclude the possibility of subtle responses in close range of ships, or long-term effects of vessel traffic on narwhal. Animals that do not avoid vessels may be still subject to increased stress levels during exposure (Weilgart 2007, Forney et al. 2017). Long term exposure to vessel noise has led to shifts in habitat use in other odontocete species, displacing them from what could be important habitat (Bejder et al. 2006). Narwhal show high site fidelity to Milne Inlet, returning to the same inlets and bays every year (Marcoux et al. 2009, Adrian Ootova, Pond Inlet, Nunavut, personal communication). This high site fidelity has been a reason for the traditional hunting activity by the local Inuit, but also means that they could be particularly vulnerable to long-term exposure (Forney et al.

2017). Displacement of narwhal from this habitat could have significant consequences for the local communities. The presence of large vessels in the open water season appears to pose little immediate threat to narwhal due to the low measured noise levels and lack of observed response, but nonetheless due to the importance of the population to the local community, and the risk of long-term impacts as seen in other marine mammal populations (Bejder et al. 2006), it is recommended that monitoring of narwhal in the shipping lanes is continued.

Study Limitations

Sample sizes were limited in several contextual situations, making analysis of individual substrata difficult. In the RAD, both hunting activity and killer whales had zero sightings for contextual conditions in some substrata. In the BSA, there are far fewer narwhal sightings during ship presence within 5 km of AMAR 19D compared to the other contexts.

The low sample sizes observed in the RAD and BSA surveys can be considered a by-product of the fact that some of the other contexts are common occurrences at this study site. Killer whales were only present for three of the 26 days of surveys, but hunting and other anthropogenic activities were a near daily occurrence, especially when narwhal were nearby. The frequent presence of other stressors makes determining the effect of the ore carriers difficult, since any potential effect is likely to be masked by the presence of more imminent threats to the narwhal. Additionally, the ZIP models did not take account for temporal dependence of sightings, which violates the model assumptions. To improve the statistical power of the analyses used in these studies, additional years of data would be required to increase the number of cases when ships and narwhal were present in the absence of other stressors, as well as to mitigate the effect of temporal dependence in the data.

Future Work

This study was unable to utilize the full extent of the survey database, as most years did not have AIS, acoustic recordings, and land-based survey data simultaneously available. The only remaining year with available data from all three sources was 2015, but it was not included in analysis due to time constraints and the low number of vessel transits relative to later years. Including data from 2015 and future years will improve the ability of this analysis to determine the effect of ore carrier vessels on narwhal behaviour in Milne Inlet, especially in the BSA. With higher sample sizes it will also be possible to further analyze the effect on group composition of narwhal response to these stressors, in particular the presence of calves and yearlings, which was not explored in this study.

Conclusion

My aim in this chapter was to determine if the presence of shipping, and its associated noise was causing a change in behaviour of narwhal near the shipping route in Milne Inlet. Narwhal were found to not respond to shipping, although they were found to change behaviour in the presence of killer whales and Inuit hunting activity by vacating the area and herding close to shore. I found that narwhal detected little noise during times when ships were present. Overlap of other anthropogenic effects led to low sample sizes for many analyses. Continued monitoring of narwhal in Milne Inlet is recommended to further increase sample size and to look for long term impacts.

Summary

This study set out to investigate the effect that the recent introduction of large vessel traffic had on the acoustic habitat of narwhal and other local marine mammal species in their summer habitat in Milne Inlet, and if narwhal responded behaviourally to noise associated with shipping traffic. In chapter 1, I found that narwhal detected low levels of noise from the ore carriers due to their poor hearing sensitivity below 1 kHz where shipping noise dominates (Arveson and Vendettis 2000). The HFC broadband SPL from vessels did not significantly increase for narwhal until the vessels were within a few kilometers of the recorder. Baleen whales and seals detected higher levels of vessel noise and could hear ships from further away. Baleen whales in Koluktoo Bay could perceive noise from shipping when narwhal and phocids could not. Ambient levels varied between the four study years and affected many of the analyses performed. None of the marine mammal groups received SELs during transits that would exceed TTS or PTS thresholds as defined in Southall et al. (2019).

In chapter 2, land-based surveys were used to determine if narwhal responded to ships by comparing exposure to ships with other stressors like killer whales and hunting. Narwhal were found to not respond to shipping, although they were found to respond quite dramatically to the presence of killer whales and Inuit hunting activity by vacating the area and herding close to shore. There was no evidence for a deleterious effect on narwhal behaviour by noise from shipping, however many analyses had sample size issues due the frequent presences of other stressors.

The low noise levels documented in this study suggest a very low risk to narwhal from shipping noise. Popper et al (2020) suggests that mitigation measures be only used when risks are evident and when noise levels are high enough to lead to population level consequences. However, Risch et al. (2021) argue that just because a population effect is not observed, that regulatory measures are not “over precautious” because population effects are difficult to detect, and often simple mitigation strategies can effectively reduce the impact of anthropogenic noise. While the risk to narwhal from shipping noise appears to be low in this area, their importance to the local Inuit communities as a key source for food and culture necessitate additional precautions when it comes to assessing the impact of anthropogenic noise on their populations. Even without shipping, narwhal still live in a high-risk environment and remain one of the most vulnerable Arctic species to climate change (Laidre et al. 2008). As climate change reduces sea ice cover, shipping traffic in the Arctic is expected to increase (Aulanier et al. 2017). Waiting for population level effects to arise before implementing mitigation efforts would have significant consequences not just for narwhal, but also for the local Inuit communities. With precautionary mitigations and continued monitoring, the risk from anthropogenic shipping to the narwhal population would be minimized.

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Appendix

Table A1: Results for Zero Inflated Poisson Model for RAD counts with respect to hunting activity from chapter 2. A-J indicate stratum, 1-3 indicate substratum number, and after, before, during, and NA indicate contextual condition.

Count Model						Zero Inflation Model					
		Estimates	SE	Z	P-Value			Estimates	SE	Z	P-Value
A,1, After	**Intercept**	**1.46335**	**0.0965**	**15.165**	**< 2e-16**	**A,1, After**	**Intercept**	**3.4295**	**0.26989**	**12.707**	**< 2e-16**
	B	0.11923	0.11369	1.049	0.294317		B	-0.2882	0.29942	-0.963	0.335753
	C	**0.3156**	**0.10183**	**3.099**	**0.00194**		**C**	**-0.8201**	**0.27623**	**-2.969**	**0.002987**
	D	**0.39664**	**0.10064**	**3.941**	**8.11E-05**		**D**	**-1.0703**	**0.27708**	**-3.863**	**0.000112**
	E	0.1286	0.09801	1.312	0.189501		**E**	**-1.5141**	**0.25846**	**-5.858**	**4.67E-09**
	F	**0.27177**	**0.09541**	**2.848**	**0.004394**		**F**	**-1.8634**	**0.25302**	**-7.365**	**1.77E-13**
	G	**0.75552**	**0.09198**	**8.214**	**< 2e-16**		**G**	**-2.2825**	**0.24737**	**-9.227**	**< 2e-16**
	H	**0.66076**	**0.09157**	**7.216**	**5.36E-13**		**H**	**-2.6671**	**0.24436**	**-10.914**	**< 2e-16**
	I	**0.75004**	**0.09113**	**8.231**	**< 2e-16**		**I**	**-2.9462**	**0.24352**	**-12.098**	**< 2e-16**
	J	**0.97105**	**0.09103**	**10.668**	**< 2e-16**		**J**	**-3.2157**	**0.24933**	**-12.897**	**< 2e-16**
	2	**0.49617**	**0.01838**	**26.992**	**< 2e-16**		2	-0.0146	0.07934	-0.183	0.854445
	3	**0.38345**	**0.02682**	**14.295**	**< 2e-16**		**3**	**0.60852**	**0.10642**	**5.718**	**1.08E-08**
	Before	**0.2794**	**0.04507**	**6.199**	**5.68E-10**		Before	-0.2969	0.18461	-1.608	0.107822
	During	-0.179	0.1208	-1.482	0.138433		During	-0.0648	0.41173	-0.157	0.874934
	NA	**0.14422**	**0.03937**	**3.663**	**0.000249**		**NA**	**-0.2802**	**0.15255**	**-1.836**	**0.066292**

Table A2: Results for Zero Inflated Poisson Model for RAD counts with respect to killer whales from chapter 2. A-J indicate stratum, 1-3 indicate substratum number, and after, before, during, and NA indicate contextual condition.

Count Model						Zero Inflation Model					
		Estimates	SE	Z	P-Value			Estimates	SE	Z	P-Value
A,1, After	Intercept	0.00831	0.3135	0.027	0.978857	A,1, After	**Intercept**	**3.86051**	**0.57848**	**6.674**	**2.50E-11**
	B	-0.1075	0.12253	-0.878	0.380152		B	-0.4095	0.35722	-1.146	0.251689
	C	**-0.2691**	**0.11733**	**-2.294**	**0.021806**		**C**	**-0.8801**	**0.33728**	**-2.609**	**0.009069**
	D	-0.0293	0.11343	-0.258	0.796324		**D**	**-1.0418**	**0.34203**	**-3.046**	**0.00232**
	E	**-0.3242**	**0.10932**	**-2.966**	**0.003019**		**E**	**-1.5062**	**0.31753**	**-4.744**	**2.10E-06**
	F	0.06737	0.10351	0.651	0.515125		**F**	**-1.8763**	**0.31047**	**-6.043**	**1.51E-09**
	G	**0.40149**	**0.10009**	**4.011**	**6.04E-05**		**G**	**-2.3104**	**0.3048**	**-7.58**	**3.45E-14**
	H	**0.38283**	**0.09917**	**3.86**	**0.000113**		**H**	**-2.7457**	**0.30048**	**-9.138**	**< 2e-16**
	I	**0.4557**	**0.09848**	**4.628**	**3.70E-06**		**I**	**-3.1183**	**0.29865**	**-10.441**	**< 2e-16**
	J	**0.64461**	**0.09862**	**6.537**	**6.29E-11**		**J**	**-3.321**	**0.30621**	**-10.846**	**< 2e-16**
	2	**0.55705**	**0.02213**	**25.168**	**< 2e-16**		2	-0.0996	0.09411	-1.059	0.289669
	3	**0.37145**	**0.03163**	**11.744**	**< 2e-16**		**3**	**0.45384**	**0.12526**	**3.623**	**0.000291**
	Before	**2.07896**	**0.30039**	**6.921**	**4.49E-12**		Before	-1.0743	0.54309	-1.978	0.047919
	During	**1.9652**	**0.30457**	**6.452**	**1.10E-10**		During	-0.4814	0.57113	-0.843	0.399322
	NA	**1.87369**	**0.29804**	**6.287**	**3.24E-10**		NA	-0.5128	0.50615	-1.013	0.311038

Table A3: Results for Zero Inflated Poisson Model for RAD counts with respect to shipping. . A-J indicate stratum, 1-3 indicate substratum number, and after, before, during, and NA indicate contextual condition.

from chapter 2.

Count Model						Zero Inflation Model					
		Estimates	SE	Z	P-Value			Estimates	SE	Z	P-Value
A,1, After	**Intercept**	**1.74387**	**0.09261**	**18.83**	**< 2e-16**	**A,1, After**	**Intercept**	**2.79115**	**0.30622**	**10.424**	**< 2e-16**
	B	0.12595	0.11741	1.073	0.283397		B	-0.3368	0.35044	-2.472	0.287303
	C	**0.34635**	**0.10365**	**3.342**	**0.000833**		**C**	**-0.8966**	**0.34445**	**-2.92**	**0.001987**
	D	**0.41326**	**0.103**	**4.012**	**6.02E-05**		**D**	**-1.1065**	**0.33854**	**-4.355**	**0.000149**
	E	0.08747	0.10099	0.866	0.386418		**E**	**-1.488**	**0.31903**	**-6.16**	**5.78E-08**
	F	**0.19774**	**0.09816**	**2.015**	**0.043954**		**F**	**-1.9213**	**0.3149**	**-7.148**	**7.31E-13**
	G	**0.5951**	**0.09441**	**6.303**	**2.92E-10**		**G**	**-2.3535**	**0.30982**	**-8.787**	**< 2e-16**
	H	**0.54797**	**0.0939**	**5.835**	**5.36E-09**		**H**	**-2.7406**	**0.30789**	**-9.95**	**< 2e-16**
	I	**0.77334**	**0.09307**	**8.309**	**< 2e-16**		**I**	**-3.0206**	**0.30765**	**-10.936**	**< 2e-16**
	J	**0.9691**	**0.09295**	**10.426**	**< 2e-16**		**J**	**-3.2631**	**0.31345**	**-11.775**	**< 2e-16**
	2	**0.50992**	**0.01984**	**25.708**	**< 2e-16**		2	-0.0982	0.08578	-0.6	0.241835
	3	**0.47197**	**0.02862**	**16.489**	**< 2e-16**		**3**	**0.60264**	**0.11406**	**5.064**	**1.26E-07**
	Before	**-0.2928**	**0.03384**	**-8.653**	**< 2e-16**		**Before**	**0.5901**	**0.12227**	**0.556**	**3.18E-05**
	During	**-0.2403**	**0.04421**	**-5.435**	**5.47E-08**		**During**	**0.55649**	**0.17761**	**0.858**	**0.002547**
	NA	**-0.1496**	**0.02168**	**-6.903**	**5.10E-12**		**NA**	**0.55913**	**0.10234**	**6.416**	**4.77E-08**

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