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Tusâven? Acoustic observation of baleen whale species composition and seasonal presence in the Torngat Area of Interest, Nunatsiavut, Canada

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Tusâven? Acoustic observation of baleen whale species composition and seasonal presence in the Torngat Area of Interest, Nunatsiavut, Canada

A Thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Marine Biology

by

Kayla Sunshine Haas

Committee in charge:

John Hildebrand, Chair
Simone Baumann-Pickering
Kaitlin Frasier
Joshua Jones

2025

The Thesis of Kayla Sunshine Haas is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2025

DEDICATION

I would first like to thank my friends and family for their unwavering support and encouragement throughout my journey as a student and researcher. Their belief in me has shaped the person I am today, and I am deeply grateful for their guidance and support.

I would also like to dedicate this paper to baleen whales and the message they share with the world. Baleen whales were once driven to the brink of extinction, targeted relentlessly by commercial whaling for the resources their bodies provided. It seemed like humans desire for profit would never stop, and these magnificent beings, suffered greatly. Their numbers dwindled, entire populations collapsed, and some species were lost forever. Yet, against all odds, the story of baleen whales did not end there. Through the unrelenting efforts of activists, conservationists, and biologists who refused to stay silent, awareness grew. Laws were changed, protections were put in place, and voices, both human and whale, rose above the waves. But it wasn't just human intervention that kept their story alive, it was the whales themselves, their resilience, their adaptability, their refusal to disappear. Their songs echoed across oceans, defying the silence that extinction would have brought.

Throughout my master's journey, I carried their message with me: to never give up, to move forward despite the challenges, and to find my own voice in a world that can often feel overwhelming. Like the whales, I've learned that even when the odds seem impossible, persistence matters. This work, this degree, and my passion for marine biology are all part of my own song, a tribute to the whales and to all who fought, and continue to fight, for their place in our world.

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LIST OF ABBREVIATIONS

TAOI	Torngat Area of Interest
MPA	Marine Protected Area
PAM	Passive Acoustic Monitoring
GPL	Generalized Power-Law detector
SIC	Sea Ice Concentration
DVM	Diel Vertical Migration
HARP	High-frequency Acoustic Recording Package
XWAV	wav. File Format
LTSA	Long-term Spectral Average
SPL	Sound Pressure Level
AMSR2	Advanced Microwave Scanning Radiometer
IWC	International Whaling Commission
NARW	North Atlantic Right Whale

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I would first like to give thanks to my committee members, John Hildebrand, Katlin Frasier, and Simone Baumann-Pickering, for their unwavering support, insightful feedback, and guidance throughout this process. It has been an honor to have such accomplished scientists on my committee, and their expertise has been so important in shaping this thesis. I am especially grateful to my thesis advisor, Joshua Jones, for his continuous encouragement and mentorship. From late nights coding in the lab to field trips to go see whale bones, his dedication, patience, and kindness have made a lasting impact on my academic journey. I feel incredibly lucky to have had the opportunity to learn from him. Also, a heartfelt thank you to Rodd Laing and Michelle Saunders from the Nunatsiavut Government Department of Lands and Natural Resources for their generous funding and support, and to Sid Pain from Oceans North, whose knowledge about the Torngat Area of Interest played a role in inspiring this research.

I would also like to give my appreciation to Ian Cosgrove for his work in creating the call parameter measurement tool discussed in this paper. His dedication to developing a tool that provides valuable insights into species calls in this region has helped set this work apart from previous studies. Additionally, I am grateful to Jack Ewing for his assistance with coding and statistical analyses used to examine flow noise and diel patterns in this study. On a personal note, I would also like to thank Nina Folz, my long-time friend throughout my academic journey. From meeting as sophomores in college to navigating the challenges of research and graduate school together, having a friend to share this experience with has been a true gift, and I am incredibly grateful for her support. I am deeply thankful to everyone who has supported and contributed to this project, and I look forward to carrying these lessons forward in my future.

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ABSTRACT OF THE THESIS

Tusâven? Acoustic observation of baleen whale species composition and seasonal presence in the Torngat Area of Interest, Nunatsiavut, Canada

by

Kayla Sunshine Haas

Master of Science in Marine Biology

University of California San Diego, 2025

John Hildebrand, Chair

Nunatsiavut is a transition zone between Arctic and lower-latitude marine mammals in the southeastern Canadian Arctic. However, knowledge of baleen whale species and their habitat use in the Torngat Area of Interest (TAOI), northern Nunatsiavut, is limited. This study examined the seasonal presence and acoustic behavior of bowhead, fin, humpback, and sei whales in the TAOI through underwater sound recordings collected offshore from Saglek Bank between October 2022 and September 2023. Species-specific calls were identified by visually analyzing spectrograms every 30 minutes and included fin whale 20Hz downsweeps, sei whale 90Hz downsweeps, humpback whale song, and bowhead whale frequency modulated calls. A call parameter measurement tool was applied to measure signal characteristics, including contour creation and receive levels. The relationships between acoustic presence and environmental factors, such as sea ice concentration and solar elevation angle were examined. Fin whale 20Hz downsweeps were the most frequently detected calls, occurring from October to mid-January and again from June through the end of the deployment in September. Sei whale 90Hz downsweeps were detected during ice-free periods, from October to early January and again from late July to September. Humpback whale songs were only detected in the fall of 2022, during October and November, while bowhead whale frequency-modulated calls were recorded intermittently in the spring and summer, from late May to August. While we did not have enough acoustic detections to confidently observe if there was a diel calling pattern in bowhead and sei whale calls, both fin and humpback whales had a peak in acoustic activity during the night. These findings provide a new understanding of the acoustic presence of baleen whale species, highlighting the TAOI's ecological significance for these whales and the importance of addressing environmental factors in monitoring low-frequency vocalizations.

INTRODUCTION

The Labrador Sea is an area in the eastern Arctic that provides a crucial marine ecosystem for many animals that capitalize on the nutrient-rich waters from the cold offshore Labrador Current (Coté et al., 2019). This includes different species of baleen whales, suborder Mysticeti, that utilize this environment's physical and biological properties to aggregate, forage, and breed (Clarke et al., 2023). Documented presence of baleen whales in the Arctic includes fin whales, blue whales, minke whales, sei whales, bowhead whales, North Atlantic right whales, and humpback whales (Davis et al., 2020; Laidre et al., 2010; Nieukirk et al., 2004; Ramagosa et al., 2020; Unpublished Andres). It is reported that some of these whale's travel near the shallow-water areas of Saglek Bank in the northern Labrador Sea, which is part of the Inuit territory of Nunatsiavut (DFO 2011; Unpublished Andres). Northern Labrador has been inhabited and utilized by humans for nearly 10,000 years, and the Inuit have thrived in this region for a long time. They continue to uphold their traditions on their lands and waters through changing times (Torngat Area of Interest Steering Committee, 2024).

The Torngat Area of Interest (TAOI; Fig 1 area outlined in red) is a sub-arctic region on the northern Labrador Shelf in Nunatsiavut territory. TAOI comprises two oceanic environments: the coastal area with fjords and bays and the continental shelf. The Nunatsiavut territorial government is currently tasked with assessing the Torngat Area of Interest to establish an Indigenous Protected Area and a national marine conservation area under the Canada National Marine Conservation Areas Act (Torngat Area of Interest Steering Committee, 2024). The coastal environment of Labrador offers abundant marine resources, including fish, seals, whales, and other marine organisms. These animals hold significant importance for the Labrador Inuit due to their traditional reliance on marine resources for sustenance, cultural practices, and economic activities (Parks Canada, 2024; Dewailly et al., 1993). So, the adjacent ocean's current physical and biological conditions directly impact their well-being, making this project crucial. One of the intentions of their evaluation is to determine the seasonal presence of baleen whales in this area of the Arctic, which would significantly contribute to the management of Nunatsiavut's marine waters. Whales aid in many vital systems in the Arctic ecosystem, contributing to the marine food chain, marine biogeochemical cycling, and as a traditional food source for the Inuit of Nunatsiavut (Parks Canada, 2024; Pearson et al., 2022; Roman et al., 2014).

The Arctic is experiencing rapid warming, up to four times the global average, leading to significant declines in sea ice and longer open-water seasons (Crawford et al., 2021; IPCC, 2022). This increased accessibility has resulted in heightened human activities, such as vessel traffic, which are expected to place more pressure on Arctic marine species at both individual and population levels (Dawson et al., 2018; Stevenson et al., 2019; Moore et al., 2012; Pirotta et al., 2019). As key ecological indicators, marine mammals are particularly vulnerable, making it critical to understand their distribution and habitat use to identify important areas, establish baseline data, and inform conservation efforts (Kiszka et al., 2015). In this context, marine protected areas (MPAs) play a crucial role in conserving biodiversity, restoring habitats, reducing human impacts, and sustainably managing marine ecosystems (Brooks et al., 2022; Arctic Council, 2021). MPAs have been shown to mitigate the effects of climate change by minimizing stressors on local wildlife, highlighting their importance as pressures from both climate change and human activities continue to increase (IPCC, 2022). Therefore, establishing additional MPAs in the Arctic is vital for effective conservation.

Understanding the migration patterns and ecological needs of marine species, such as baleen whales, becomes increasingly important as the Arctic undergoes rapid changes due to increased ocean warming and human activity. The migration of baleen whales is commonly understood as a strategy to capitalize on the high productivity of polar waters during summer for feeding and accumulating energy reserves, followed by a migration to warmer, lower-latitude regions for breeding and calving (Kellogg, 1928; Stevick et al., 2003). This distinct separation between feeding and breeding grounds is typical of capital breeders, whose large body size enables them to store significant energy reserves, facilitating long-distance migrations (Brodie, 1975; Aguilar & Lockyer, 1987; Lockyer, 1986).

Several factors influence the timing and extent of whale migrations. Whales may travel to lower latitudes to find mates, reduce heat loss for calves, avoid killer whale (Orcinus orca) predation, or breed and give birth in warmer, safer waters during winter and spring (Corkeron & Connor, 1999). Alternatively, they might leave high-latitude feeding grounds when sea ice reduces productivity or access to food (Brodie, 1975; Corkeron & Connor, 1999; Clapham, 2001). Some baleen whales migrate up to 10,000 km annually, traveling to the eastern Canadian Arctic in summer and fall to forage in nutrient-rich feeding grounds where nutrient upwelling, sunlight, and stable water temperatures support the growth of their preferred prey, such as copepods, krill, and small fish (Kellogg, 1929; Baumgartner et al., 2003; Tarling, 2003). However, some individuals may remain in high-latitude feeding grounds, and variations in migration patterns may depend on factors such as species, gender, age, and reproductive state (Brown et al., 1995; Geijer et al., 2016), suggesting that whale movements are more complex than previously understood.

The dynamic interactions between seasonal changes to the environment and marine species highlights the need to understand how these factors influence whale behavior and distribution. To further explore these connections, advancements in acoustic monitoring technology have provided researchers with powerful tools to study marine mammals in remote polar regions (Southall et al., 2012; Wiggins and Hildebrand, 2007). The accessibility of long-term acoustic recording devices has enabled researchers to study marine mammals' acoustic behavior and seasonal presence in previously difficult areas to access using ships, aircraft, or on-ice methods (Jones et al., 2022; Hildebrand, 2009). This wealth of acoustic data offers new insights into species distribution, movement patterns, reproductive behavior, and population ecology (Oestreich et al., 2024). Building on these technological advances, the Whale Acoustics Laboratory at The Scripps Institute of Oceanography has conducted year-round continuous underwater sound recordings in the Torngat Area of Interest to assess the seasonal utilization of this sub-Arctic region by marine mammals. Researchers have investigated the seasonal presence and acoustic behavior of different marine mammal species by analyzing a full year of acoustic recordings from a location 20 km offshore in the TAOI.

To efficiently handle such extensive datasets as the one discussed in this paper, there has been an increasing demand for detection methods that go beyond basic presence/absence metrics, which are typically limited by the labor-intensive nature of manual analysis. The Scripps Whale Acoustics Lab has developed a generalized power-law (GPL) detector that utilizes detection threshold parameters robust enough to handle long-term deployments under varying ocean noise conditions without requiring operator adjustments (Helble et al., 2012).

This technique significantly reduces analysis time while providing detailed acoustic presence/absence data and call unit parameters, such as call duration and slope, that are challenging to obtain manually. Initially designed to detect nearly all humanly audible humpback call units, the GPL detector shows potential for broader applications across various marine mammal vocalizations, making it a valuable tool for species detection and a precursor to classification techniques (Helble et al., 2012).

By leveraging such advancements in detection algorithms, passive acoustic monitoring (PAM) can now provide valuable data for examining the simultaneous occurrence of multiple species across seasons. In the North Atlantic, distinct call types are reliably associated with the species studied in this paper and are commonly used to assess their presence. In this study, we analyze patterned song notes produced by humpback whales (Payne & McVay, 1971; Kowarski et al., 2019; Clark & Clapham, 2004), 90 Hz downsweeps from sei whales (Nieukirk et al., 2020; Tremblay et al., 2019; Baumgartner et al., 2008), 20 Hz downsweeps from fin whales (Morano et al., 2012; Thompson et al., 1992; Watkins et al., 1987), and frequency-modulated calls from bowhead whales (Clark & Johnson, 1984; Cummings & Holliday, 1987; Stafford & Clark, 2021) to explore large-scale species distribution and behavior in this region. Many of these vocalizations are sex-specific and associated with mating, such as humpback whale songs (Clark & Clapham, 2004) and 20 Hz downsweeps repeated from fin whales (Thompson et al., 1992), and are often produced during certain seasons. Although we may fail to detect species when they are silent or using different call types, these well-documented vocalizations enable us to track broad distribution patterns during the times when the animals are actively vocalizing. Enhancing our knowledge of baleen whale habitat use and acoustic behavior is vital for future research and monitoring efforts, ultimately supporting effective environmental resource management in Nunatsiavut.

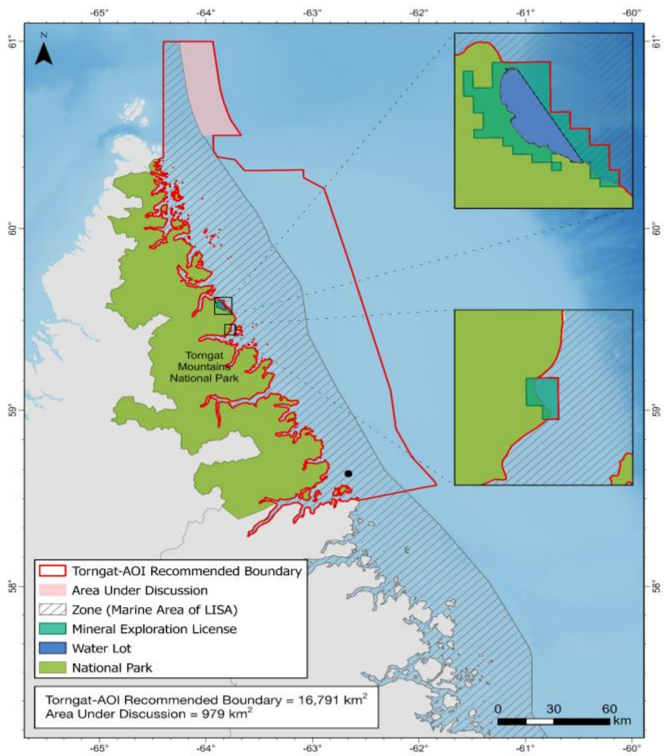

Figure 1. Site of HARP approximately 20 km off the coast of the Torngat Mountains National Park along the Labrador Shelf. The black dot is the HARP, and the region outlined in red represents the marine area of interest in the TAOI. (Map: Nunatsiavut Government)

Humpback whales: Humpback whales (*Megaptera novaeangliae*) are a cosmopolitan species found in both offshore and coastal regions across the globe, except in the very high Arctic (Heide-Jørgensen & Laidre 2007; Kennedy et al., 2014). Humpbacks undertake one of the longest migrations of any mammal, with some populations traveling up to 15,000 kilometers each year (Ford & Reeves 2008; Kettemer et al., 2022). In the North Atlantic, two main populations migrate seasonally from winter breeding grounds to feeding areas spanning from the Gulf of Maine to Norway during spring, summer, and fall (Katona & Beard, 1990; Clapham, 2018). In winter, they migrate south to calve and mate in places like the Caribbean and Cape Verde (Heenehan et al., 2019; Stevick et al., 2016; Stevick et al., 1999; Stevick et al., 2003). Throughout most of the year, humpbacks are typically found in small groups of 2-5 individuals, though larger groups occasionally form for cooperative feeding (Félix & Novillo, 2015). Their primary diet in the North Atlantic includes euphausiids (krill) and small schooling fish such as capelin, Atlantic herring, sand eels, and mackerel (Gong et al., 2014; Heide-Jørgensen & Laidre 2007; Magnusdóttir et al., 2014; Víkingsson et al., 2015). For over a thousand years, Greenland Inuit have hunted humpback whales using traditional methods. These whales were vulnerable to early whalers, and large-scale commercial whaling in the 18th and 19th centuries severely depleted their populations. However, after the International Whaling Commission (IWC) banned commercial whaling in 1982, humpback populations began to recover, though limited traditional hunting by Indigenous groups continues today ("Humpback Whale" noaa.gov; IWC; NAMMCO).

Bowhead whales: The bowhead whale (*Balaena mysticetus*) is endemic to Arctic and sub-Arctic waters, residing in these northern regions year-round and closely tied to the presence of sea ice (Stevenson and Hartwing, 2010; Reeves et al., 1983; Heide-Jørgensen et al., 2006; Quakenbush et al., 2010). This association is believed to provide them refuge within pack ice from predators and is a large part of their ecology (Higdon and Ferguson, 2009). In the summer, they migrate to the high Arctic as the ice retreats, and in winter, they move southward as the ice advances (Shelden et al., 1995; Harwood et al., 2017). Their name comes from the distinct bow-shaped curve of their upper jaw, which enables them to break through thick sea ice to create breathing holes, demonstrating their remarkable adaptations to the harsh

Arctic environment (“Bowhead Whale” noaa.gov). Their diet mainly consists of zooplankton, such as copepods (Calanus finmarchicus), euphausiids (krill), and other small crustaceans (Sheffield and George, 2021; Blackwell et al., 2022; Laidre et al., 2010).

In the Northwest Atlantic, a distinct bowhead whale population known as the Eastern Canada–West Greenland (ECWG) stock resides near West Greenland, the eastern Canadian Arctic, and Baffin Island (Doniol-Valcroze et al., 2020; Laidre et al., 2015). Historically, bowhead whales were abundant further south along the Labrador and northern Newfoundland coasts, where Basque whalers hunted them (Cumbaa, 1986). Slow-swimming and highly valued, they were nearly driven to extinction by European and American whalers over four centuries, from the 1500s to the 1900s. Despite significant declines from historical whaling, the ECWG stock is now protected and recovering, with Canadian hunting regulated by Fisheries and Oceans Canada (DFO). Subsistence hunting of bowheads remains vital for Inuit communities in Canada, Greenland, and Alaska, providing traditional food, supporting livelihoods, and preserving cultural heritage (“Bowhead Whale” noaa.gov; IWC; NAMMCO; DFO). The Inuit refer to the bowhead whale as "Apvik."

Fin whales: The fin whale (*Balaenoptera physalus*), is the second-largest whale species on Earth, surpassed only by the blue whale (“Fin Whale” noaa.gov). This cosmopolitan species primarily inhabits temperate to polar latitudes and is mostly pelagic, favoring open-ocean waters, although it is occasionally seen in coastal areas (Heide-Jørgensen & Laidre 2007; Edwards et al., 2015; Watkins et al., 1987). Fin whales in the Northwest Atlantic migrate to lower latitudes in winter, but their wide pelagic distribution means that specific migration routes and calving grounds remain poorly understood. Evidence suggests they travel from the Labrador Sea and Davis Strait to breeding grounds in mid-Atlantic waters, including areas off New England and North Carolina (Silva et al., 2013; Edwards et al., 2015). Their migration patterns appear to adapt to prey availability, with some individuals staying in regions where food is accessible year-round (Hamilton et al., 2009; Oleson et al., 2014). In Arctic waters, fin whales primarily feed on euphausiids, copepods, and pelagic fish such as capelin, juvenile herring, and sand lance during the summer (Mitchell, 1975; Woodley & Gaskin, 1996; Sigurjónsson & Víkingsson, 1997). In early whaling eras, fin whales were difficult to hunt due to their speed and preference for open waters. However, new technologies in the late 1800s allowed large-scale hunting and led to heavy exploitation. Today, fin whales are protected under international agreements, though limited hunting continues in Greenland under the International Whaling Commission's "aboriginal subsistence whaling" provision (“Fin Whale” noaa.gov; IWC; NAMMCO).

Sei whales: The sei whale (*Balaenoptera borealis*), the third-largest species of baleen whale (“Sei Whale” noaa.gov). This species has a nearly cosmopolitan distribution but is absent from the high Arctic, tropics, and Indian Ocean (Mizroch et al. 1984). Sei whales are migratory and inhabit deep offshore environments, typically traveling alone or in small groups (Pike et al., 2019; Prieto et al., 2012). However, they are one of the least known baleen whale species, as their elusive nature, unpredictable annual movements, and frequent misidentification as Bryde’s or fin whales have led to limited data on their distribution (Reeves et al., 2002; “Sei Whale,” NAMMCO; Davis et al., 2020). Much of our understanding of their distribution comes from historical whaling records, which may no longer be reliable, particularly regarding their largely unknown winter habitats (Davis et al., 2020). In the western North Atlantic, sei whales are believed to range from mid- to low-latitudes up to Labrador and Davis Strait, migrating northward from southern New England to eastern Canada (Kellogg, 1929; Olsen et al., 2009; Prieto et al., 2014; Mitchell & Chapman, 1977). Recent satellite tagging in the Azores during spring and early summer has revealed migration to the Labrador Sea, suggesting a migratory corridor between these regions (Olsen et al. 2009; Prieto et al. 2014). In Nova Scotia, sei whales primarily feed on euphausiids (krill) and copepods, particularly Calanus finmarchicus, as well as fish, and crustaceans, with diet varying seasonally (Flinn et al., 2002; Sigurjónsson & Víkingsson, 1997; Prieto et al., 2012). Historically, sei whales were heavily hunted in the 1900s after larger baleen whale populations were depleted ("Sei Whale," NOAA). Today, they are listed as endangered under the Endangered Species Act and classified as depleted under the Marine Mammal Protection Act ("Sei Whale," IWC). Despite the International Whaling Commission's ban on commercial whaling, sei whales are still occasionally taken under special permits for scientific research and aboriginal subsistence hunting ("Sei Whale," NAMMCO).

MATERIALS AND METHODS

i. Acoustic data collection

One High-frequency Acoustic Recording Package (HARP; Wiggins and Hildebrand, 2007) was deployed 20 km off the coast of Saglek Bay (58°41.93' N, 62°31.08' W) from October 12, 2022, to September 9, 2023 (Table 1). The HARP was located at a depth of 153m on the Labrador shelf, and continuously sampled underwater sounds at 200 kHz during its deployment, recording for one minute out of every 60 minutes in subsequent sessions. The acoustic recordings captured a bandwidth of 5 Hz to 5 kHz.

Initially, the hydrophone comprised six cylindrical transducers (Benthos AQ-1) wired in series, providing a sensitivity of −187 dB re: V/μPa with 55 dB of preamplifier gain. A two-stage hydrophone was used in the 2022-23 period, integrating the low-frequency stage from previous years with six cylindrical transducers and approximately 50 dB of preamplifier gain. Additionally, a high-frequency stage featured a spherical omnidirectional transducer (ITC-1042, www.itc-transducers.com) with a sensitivity response of −200 dB re: V/μPa (± 2 dB) from 1 Hz to 100 kHz and about 80 dB of preamplifier gain, the combined sensitivity of both stages aligned with published HARP specifications (Wiggins and Hildebrand, 2007). All acoustic recordings were formatted into XWAV files for analysis and decimated using an eighth-order Chebyshev type I filter to reduce data to 10.67 k samples/s (new bandwidth: 10 – 5333 Hz), thereby minimizing computational requirements. Analyses were performed using the Triton program in MATLAB (MathWorks Inc., Natick, MA), which computed and displayed long-term spectral averages (LTSA) and standard spectrograms, facilitated audio playbacks, and logged call detections (Wiggins and Hildebrand, 2007).

Table 1. Deployment metadata, including recording times, sampling period, position, and depth for the HARP used to collect acoustic data. One single-channel HARP was deployed at this site.

Deployment Metadata	
Deployment name	NUNAT_SB_03
Start date (UTC)	October 12, 2022
End date (UTC)	September 9, 2023
Recording duration	332 days
Sample rate	200 kHz
Latitude	58°41.93' °N
Longitude	62°31.0827' °W
Depth	153 m

The data analysis involved a meticulous process of visually inspecting spectrograms to identify baleen whale calls during the year-long deployment. This process, which required a trained observer to distinguish whale vocalizations from other sounds within a 10-300 Hz frequency range, ensured the accuracy of our findings. Calls with visually clear parameters in the spectrogram (clear contour shape, start and end time, minimum and maximum frequency) were manually logged and subjectively sorted into distinct signal type categories based on visual inspection (Table 2). Detected calls were recorded in Microsoft Excel, detailing parameters such as frequency range and duration, and subsequently categorized by consulting published literature on characteristic calls of various baleen whale species. The resulting acoustic data provides valuable insights into species distribution, seasonal patterns, behavior, and population ecology.

ii. Detection and Classification of Calls

Trained analysts examined 30-minute Long-Term Spectral Average (LTSA) windows with a temporal resolution of 1 second and a frequency resolution of 2 Hz to identify the distinctive calls of various species, including fin whales, humpback whales, minke whales, sei whales, North Atlantic right whales, blue whales, and bowhead whales, by comparing them with a previously described vocalization for each species. Based on published literature, it is known that different species can produce similar call types (Davis et al., 2020; Nieukirk et al., 2004; Tremblay et al., 2018). Additionally, acoustic detection ranges vary significantly depending on factors such as the whale's location, ambient noise levels, environmental conditions, vocal behavior, and the frequency and amplitude of the vocalization (Wiggins et al., 2016; Širović et al., 2007; Stafford et al., 2007). To address this challenge, baleen whale calls were first categorized based on the signal parameters of the calls, including frequency range, duration, and signal characteristics. These signal types include 30-14 Hz down sweep, 50- 30 Hz down sweep, 90-30 Hz down sweep, 20 Hz pulse, frequency-modulated calls, songs, pulse train, 18 Hz tonal, and upsweep. Whenever probable calls fitting the parameters of one of the signals were identified, a corresponding 120-second spectrogram with a 2000-point FFT, Hanning windows, and 90% overlap was reviewed to confirm their presence and recorded. The acoustic presence or absence of low-frequency whale calls was determined every 30 minutes during the recordings. For each logged call, a two-minute XWAV time series and a JPEG graphical file were saved, showing the 30-minute LTSA window and a 120-second spectrogram of the call detection, frequently with additional calls. For the 332 days of the deployment, 7,764 logged low-frequency signals were stored in an Excel workbook for further analysis.

Following data collection, the accompanying 120s spectrogram image of each call was verified by an experienced independent analyst, K.S. Haas, who assigned each signal type to the corresponding baleen whale species based on established signal parameters in published literature. Any misidentifications were reassigned to the correct species or removed from the detection database. This process, known as 'labeling,' involved determining whether the signal matched the known parameters of the species' call, examining if similar calls occurred nearby in time, and checking for the presence of different species' calls within 20 minutes of the signal of interest. When similar calls were consistently produced within a continuous time frame, sometimes lasting for hours, these signals were attributed to a specific species. This method improved confidence in species identification, as analyzing each spectrogram twice in detail ensured a more accurate assessment of vocalization types.

iii. Baleen whale species identification

Only calls identified with high confidence were included in this study (Table 2), along with medium confidence calls that, after additional analysis, could be reliably attributed to a specific species. High-confidence calls were those identified with certainty regarding the species that produced them. These included fin whale 30 Hz downsweeps and sei whale 90 Hz downsweeps, which were attributed to their respective species with 100% certainty.

Medium-confidence calls were those with a strong inference about the species producing the call but with some remaining uncertainty. These included humpback and bowhead whale vocalizations, which can sometimes be difficult to differentiate due to overlap in their acoustic characteristics and limited research distinguishing them. Additionally, bowhead whale vocalizations can be mistaken for sea ice noise, further complicating identification (Jones et al., 2020). After the initial analysis, there was confidence that the detected humpback whale songs and bowhead whale frequency modulated calls were classified correctly. To be certain, all saved spectrograms for each respective call were further aliased and compared to published literature again. Bowhead whale songs were excluded from further analysis due to overlap with humpback whale song. Instead, we focused on detecting their frequency-modulated calls, which are more distinct and easier to identify as Bowhead whale vocalizations.

Low-confidence calls were those identified as biological in origin but without sufficient certainty to assign them to a specific species. These calls were categorized based on frequency ranges: XL for calls between 0 and 100 Hz, XM for calls between 100 and 200 Hz, and XH for calls between 200 and 300 Hz. These labels will be analyzed in future analyses beyond the scope of this study.

Table 2. Baleen whale species of interest call type characteristics and signal parameters. The maximum frequencies of humpback and bowhead whale vocalizations are set to the upper limit of the spectrogram analysis in the table.

Species	Frequency Range	Duration	Description	Signal Type	References
Fin whale	15 - 30 Hz	0.5 - 1 s	Short downsweep, singlet or doublet calls	20 Hz down sweep	(Watkins et al., 1987); (Simon et al., 2010); (Thompson et al., 1992)
Sei whale	30 - 90 Hz	1 - 2 s	Concave downsweeps, that occur alone, in pairs, or in groups of three to five downsweeps.	90 Hz down sweep	(Nieukirk et al. 2020); (Baumgartner et al. 2008)
Humpback whale	50 - 300 Hz	0.5 - 5 s	Highly variable sounds including cries, grunts, squeaks, and moans, organized, and repeated to create full songs	Song	(Kowarski et al. 2019); (Clark & Clapham's 2004) ; (Risch et al., 2012)
Bowhead whale	20 - 300 Hz	1 - 5 s	Calls descending, ascending, or relatively constant in frequency, ranging from brief 0.5 s grunts to longer 4-5 s moans	Frequency Modulated Calls	(Jones et al., 2022); (Clark and Johnson, 1984); (Cummings & Holliday, 1987); (Stafford 2022)

Fin whales: Fin whales produce vocalizations typically consisting of pulsed tones sweeping from 25–44 Hz down to 15–20 Hz over 0.5–1 second (Morano et al., 2012; Thompson et al., 1992; Watkins et al., 1987). These calls, reported in this paper as 20 Hz downsweeps, are the most commonly observed fin whale vocalization worldwide (Figure 2a;

Edds-Walton, 1997). 20 Hz downsweeps are also produced by males to attract females when produced in regular sequences that form a type of stereotypical song (Watkins et al., 2000; Širović et al., 2017; Rice et al., 2020). Additionally, 20-Hz calls produced at an irregular pattern are thought to serve as a social function, such as maintaining contact between group members (McDonald et al., 1995; Edds-Walton, 1997). The calls can occur in bouts of single or doublet calls, repeated over extended periods (Simon et al., 2010; Širović et al., 2004; Kuna & Nabelek, 2021).

Sei whales: Passive acoustic monitoring along the east coast of Canada suggests that sei whales are present and vocalizing throughout the summer and fall months (Davis et al., 2020). Sei whales produce low frequency downsweep calls with an average maximum frequency of 80 Hz down to 30 Hz over 1.0-2.0 seconds (Figure 2b; Baumgartner et al., 2008). These calls are typically concave in shape and occur in pairs, but triplets or singles can also be observed (Nieukirk et al., 2020; Tremblay et al., 2019; Baumgartner et al., 2008; Rankin and Barlow, 2007). They are believed to be a type of contact call used to maintain group cohesion, but it is currently unknown whether these vocalizations are sex-biased or how they may vary across regions and seasons.

Humpback whales: The humpback whale song is one of their most well-known and complex vocalizations, consisting of a series of variable sounds organized into units, phrases, and themes (Payne & McVay, 1971). Humpback songs range from 20 to 1000 Hz and last between 0.5 to 5 seconds, often incorporating grunts, squeaks, and moans (Figure 2c; Clark & Clapham, 2004; Stimpert et al., 2011). Since only males are known to produce these songs, it is widely believed they serve as a male display during the breeding season (Dunlop et al., 2008; Tyack, 1981). These songs evolve throughout the winter-spring display season, with individuals within a population synchronizing changes in song structure (Payne & Payne, 1985; Guinee & Payne, 1988). An individual song can last up to 30 minutes and be repeated continuously for up to 24 hours. The vocal categories used were primarily adapted from prior studies in humpback whale acoustics (Kowarski et al., 2019; Clark & Clapham, 2004). Non-song vocalizations, such as cries, cry sequences, non-patterned calls, and grunt sequences, were excluded from the analysis due to their overlap with sounds produced by other species. Instead, units in song fragments and full songs were labelled as songs. Songs were included if they exhibited repetition, with continuous complexity and structure, ranging from a single phrase or subphrase to multiple themes repeated in sequence.

Bowhead whales: Bowhead whales are highly vocal and utilize a range of acoustic signals for essential biological functions, including reproduction, group cohesion, socializing, and migration (Stafford and Clark, 2021). They produce a variety of simple, narrow-band, frequency-modulated calls between 20–500 Hz, such as upsweeps, downsweeps, moans, grunts, constants, and undulating calls with repetitive frequency fluctuations and harmonics that can last anywhere from 0.5 to 5 seconds (Figure 2d; Clark and Johnson, 1984; Cummings & Holliday, 1987; Stafford & Clark, 2021). Frequency-modulated calls are made during the summer foraging, fall and spring migration periods, including marginal ice conditions in the spring and early summer, as well as during freeze-ups in October and November (Jones et al., 2022; Clark and Johnson, 1984; Würsig & Clark, 1993).

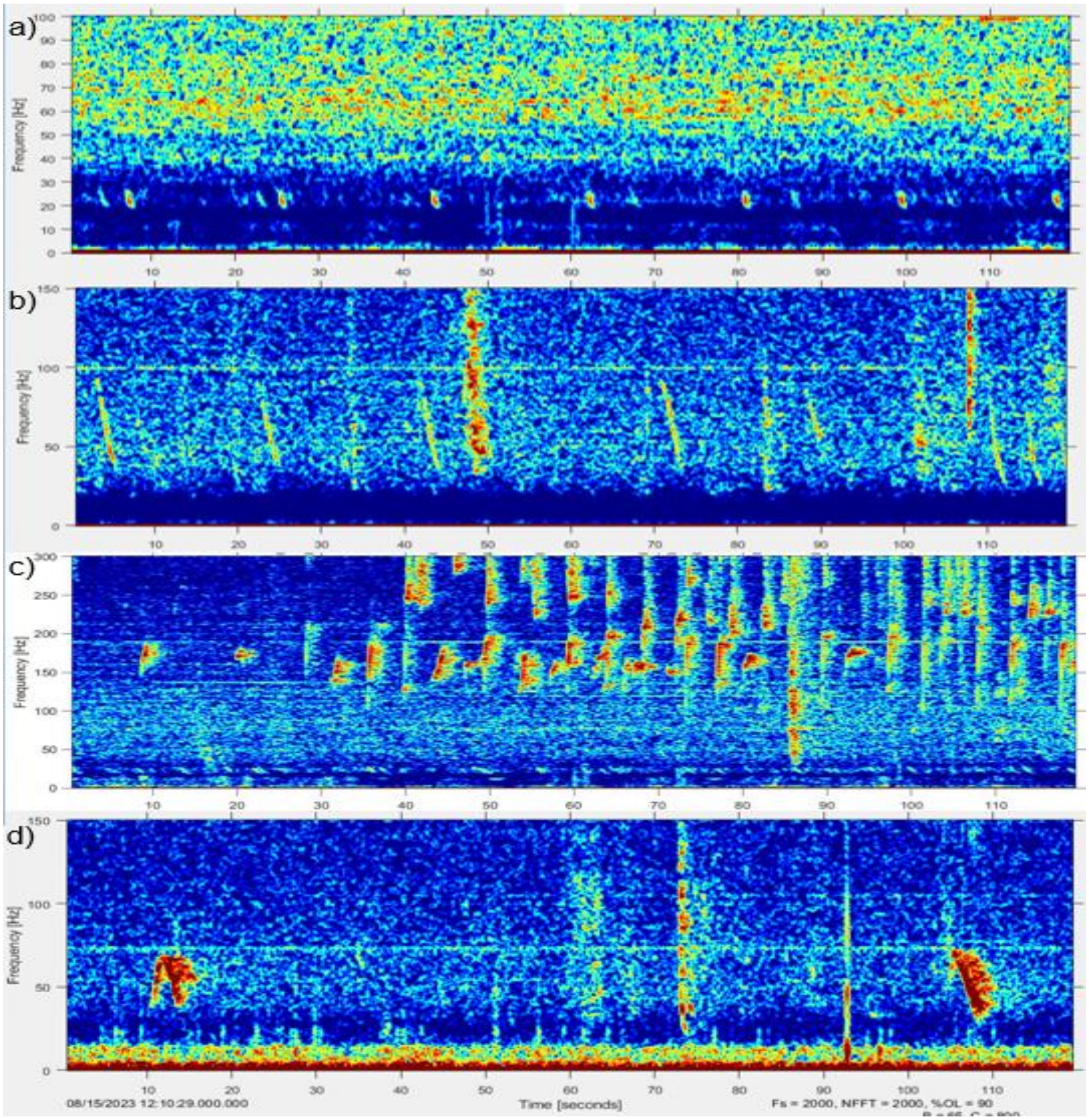

Figure 2. Spectrogram examples of (a) fin whale 20 Hz downsweep, (b) sei whale 90 Hz downsweeps, (c) humpback whale song, and (d) bowhead whale frequency-modulated calls

iv. Time Series of Acoustic Presence:

We analyzed all 120-second XWAV call detections from the 2022-23 recordings to identify species' vocal repertoires and explore seasonal changes in calling behavior. Only calls with clear parameters visible in the spectrograms were included in the analysis. Signals were matched to published call types, and their key characteristics were logged. Then, the monthly proportion of total calls for each type to assess seasonal variations was calculated. A time series was generated to evaluate the seasonal presence of each species in the TAOI. This was combined with an analysis of monthly sea ice concentrations and day/night cycle during the survey, investigating their potential influence on baleen whale presence and behavior.

v. Call Parameter Measurement Tool

After careful analysis of the year-long deployment, the distinguishable call types from four different baleen whale species were selected for further investigation based on the confidence level of species acoustic presence assigned by the manual inspector (K.S.H). These included fin whale 30 Hz downsweeps, sei whale 90 Hz downsweeps, humpback whale songs, and bowhead whale frequency-modulated (FM) calls. These calls were chosen due to their distinctive acoustic characteristics, allowing for reliable species identification. Once the species were assigned to specific signals, student researcher Ian Cosgrove created a workflow to build standardized measurement parameters for each call type. The workflow used 75-second time windows containing each manually annotated call and applied a generalized power-law (GPL) detector algorithm (Helble et al. 2012) for contour creation, which we call the call parameter measurement tool in this study. The tool utilized 75-second windows to improve the accuracy of species presence, give the analyst more context of the soundscape surrounding the call, and identify nearby calls of the same type. Signals within these windows were extracted from background noise, generating isolated contours of potential calls. The analyst (K.S.H) reviewed these contours, paired the original annotation to a specific call, and had options for further annotation, labeling, and inclusion of additional similar signals for measurement. The tool measured parameters such as call duration, frequency bandwidth, received level, etc. allowing for data aggregation across a large number of calls and allowing for a comprehensive and quantitative evaluation of their acoustic characteristics. Also, it allowed for the collection of data across numerous calls, simplifying a complete evaluation of their acoustic characteristics while reducing the limitations of labor-intensive manual analysis.

The call parameter measurement tool was particularly useful for stereotyped sounds, such as fin and sei whale downsweeps, which are consistent in frequency and duration. However, the detector was not used for more variable calls like humpback whale songs and only tested on bowhead whale FM calls due to their wide variability in frequency, duration, and structure. The -3dB endpoint method was chosen for the receive level and sound exposure level, as in Wiggins and Hildebrand 2020, and was used for each call type to keep the methods consistent. The output from the call parameter measurement tool was not used in the analysis or results comparing baleen whale acoustic presence to environmental factors. Instead, this tool was utilized to extract precise measurements of fin and sei whale downsweeps, which could not be reliably achieved through manual detection alone.

vi. Sea Ice Measurements

To evaluate the influence of sea ice on the acoustic presence of fin, sei, humpback, and bowhead whales, we estimated median daily sea ice concentrations within a 20 km radius around the recording site between 2022 and 2023. Advanced Microwave Scanning Radiometer 2 (AMSR2) sea ice maps, with a 3.12 km spatial resolution, were obtained from the University of Bremen (Melsheimer & Spreen, 2019; Spreen et al., 2008). Using custom MATLAB code, we calculated median daily sea ice concentrations for all AMSR2 grid values within a circular mask centered on the recording location. The 20 km mask radius was chosen as a conservative estimate for the specific study site to ensure reliability and consistency in the data. While low-frequency sounds, such as those produced by baleen whales, can often travel well beyond this distance, even in shallow waters where our hydrophone is located, this radius provides a practical and standardized boundary for analysis (Wiggins and Hildebrand, 2020; Xu et al., 2021). More importantly, it serves as a valuable seasonal indicator, offering insights into the ocean environment and seasonality of baleen whales. By focusing on this localized area, we can assess how the sea ice concentration may influence whales' departure and arrival to this region, providing critical information about habitat use and environmental conditions. An additional mask was applied to exclude pixels within 1 km of the shoreline to minimize the effects of terrestrial snow and ice. MATLAB was used to compute the daily arithmetic mean, variance, and median of sea ice concentrations, expressed as a percentage of the total mask area. Median values were favored due to overestimated ice concentration at grid points near land, especially during late summer ice-free periods when mean values sometimes indicated over 5% ice cover, while median values more accurately reflected 0% ice cover.

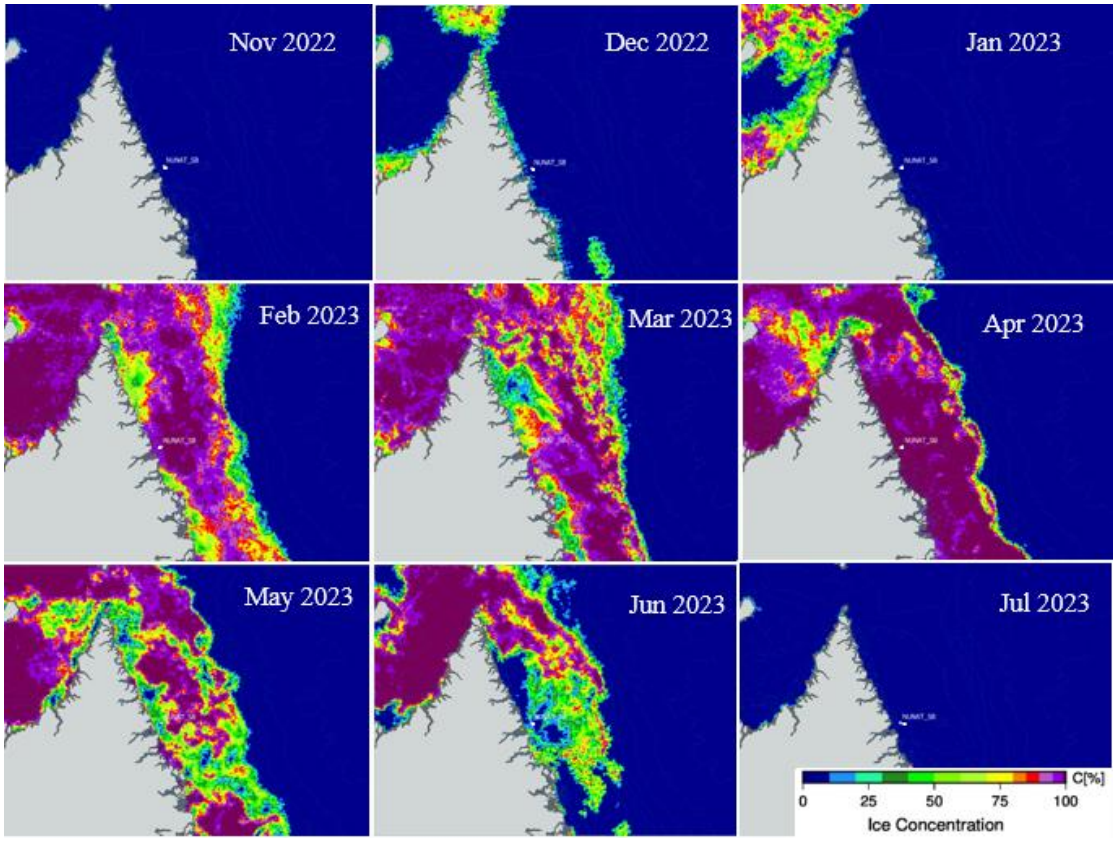

Figure 3. Map showing monthly sea ice concentration (SIC) around the recording site from November 2022 to July 2023. Months with 0% SIC are excluded. The site is marked with a small white dot, and percent SIC is represented on the color bar scale.

vii. Solar Elevation Angle Measurements

The solar elevation angle, which accounts for atmospheric refraction, was determined based on the deployment's timing and location using the NOAA Sunrise/Sunset and Solar Position Calculators. These tools rely on equations from *Astronomical Algorithms* by Jean Meeus (Meeus, 1998). The calculator provides sunrise and sunset times with an accuracy of about one minute for locations between ±72 degrees latitude and within ten minutes for areas beyond that range. Since the study site is at 58.6988 degrees latitude, it falls within the accurate range. This data was used to assess how solar elevation angle influences the acoustic presence of baleen whales at the site every 30 minutes.

To investigate diel patterns in whale acoustic detections, we used Matlab to analyze the number of detections during the day and night for fin and humpback whales. Sei and bowhead whales were not included in this part of analysis due to a limited number of detections. The analysis involved categorizing detections into "day" or "night" based on solar elevation data. Positive solar elevation values indicated daytime, while negative values represented nighttime. For each species, we calculated the total number of detections during the day and night. A chi-squared test was used to determine whether the differences in detections between day and night were statistically significant. This test was chosen because it compares observed counts (detections) to expected counts under the assumption of no diel pattern. A bar chart was created to visually display the results, showing the number of detections for each species during day and night.

viii. Statistical Analysis

To further explore what factors may be influencing baleen whale vocalization patterns in the Arctic, we ran statistics on certain variables compared to species presence. The variables include the normalized time of day and Advanced Microwave Scanning Radiometer 2 (AMSR) sea ice concentration data (Melsheimer & Spreen, 2019). The predictor variables of percent ice cover, sun elevation angle, day of year, and year were considered for analysis in explaining fin whale and humpback whale acoustic presence. Fin whale and humpback whales were chosen due to the large number of calls recorded in the data. Sun elevation angle (accounting for atmospheric refraction) was obtained for the coordinates of our recording location based on the formulas from Meeus (1998) used in the NOAA Solar Calculator (gml.noaa.gov/grad/solcalc). Due to extended periods of constant daylight or darkness at this latitude, normalized time of day was not included as a predictor for diel presence. All data processing and preliminary analyses were performed using MATLAB, while the statistical analyses were conducted in R.

RESULTS

From October 2022 to September 2023, about 8,000 hours of data from the deployment was examined for baleen whale vocalizations. The analysis identified over 7,760 sounds of fin, sei, humpback, and bowhead whales, as well as sounds that were biological in origin but could not be definitively attributed to a specific species. The most common baleen whale call recorded was a series of short, down-swept pulses in the 15-30 Hz range that were identifiable as fin whale 20 Hz downsweep calls.

i. Fin whales and Sea Ice Concentration

There were an initial 4,809 detections of fin whale 20Hz downsweep calls recorded in the data and our analysis of their vocalizations revealed a distinct seasonal pattern. Acoustic detections of fin whales were first recorded on October 12, 2022 at the start of the deployment (Figures 5a and 6a). Detections were highest during the open water period in October, with fin whale daily acoustic presence reaching a peak of 22 hours per day, and a secondary peak occurred briefly in November. During this period, fin whale 20 Hz downsweeps were observed to be highly repetitive and continuous, forming a constant band of acoustic energy between 15–30 Hz, which masked the detection of individual calls (Figure 4). However, their calls became increasingly sporadic through November and December. Daily acoustic presence sharply declined from late December to mid-January, coinciding with the onset of sea ice formation, ceasing entirely by January 18, 2023, when the sea ice concentration was above 90% (Figure 5a).

Fin whale calling activity resumed sporadically on June 7, 2023, when the sea ice concentration was about 20% in the area and then rapidly increased during July as the open-water period set in. Notable increases in acoustic presence were observed at the end of July and early September, reflecting the species' utilization of the region during these ice-free periods until the deployment concluded on September 9, 2023. Figure 5a illustrates fin whale daily acoustic presence relative to sea ice concentration, showing vocalizations detected mostly during open-water periods and marked absences during ice-covered times. Interestingly, fin whales were detected even with some sea ice present, suggesting that the waters near Nunatsiavut is a frequented region for fin whales and their departure coincides with high sea ice concentrations, which may limit access to the region.

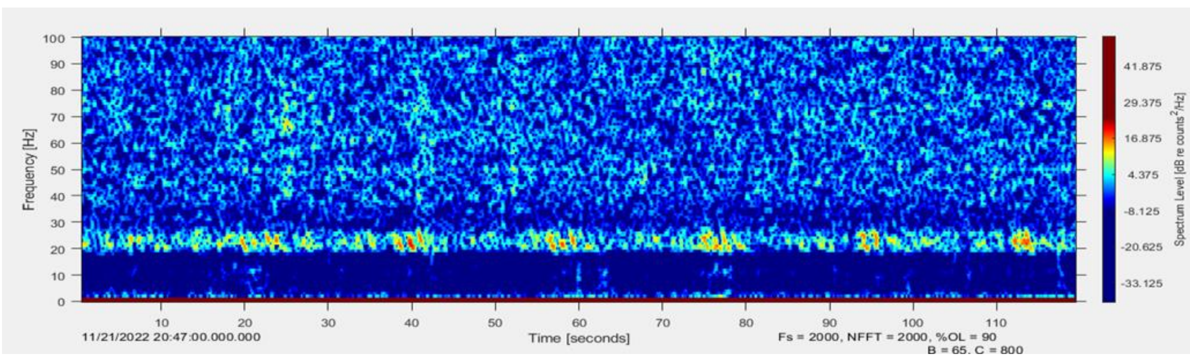

Figure 4. Spectrogram showing a constant band of acoustic energy between 15-30 Hz produced by fin whales in the fall. This masked individual downsweeps and appeared as a yellow horizontal line in the spectrogram.

ii. Fin whales and Day/Night Cycle

Throughout the year, fin whales were detected frequently, with some acoustic events lasting longer than 24 hours, making it challenging to visually distinguish a clear diel pattern in their calling behavior (Figure 6a). This may also be influenced by the timing of the winter solstice in December, which results in shorter daylight hours, which may skew the interpretation of daytime versus nighttime calling activity. Similarly, the summer solstice in June could lead to extended daylight hours, affecting the distinction between day and night detections. From a visual standpoint, the fin whale calling data suggest a potential diel pattern with calling occurring both at night and during the day but without a definitive indication of higher calling rates at one time over the other.

To address the challenge of trying to visually distinguish a day/night calling pattern, a chi-squared test was used to determine whether the differences in detections between day and night were statistically significant. The test found that fin whale detections were significantly higher at night compared to daytime. A total of 597 detections occurred during the day, while 934 detections were recorded at night (Figure 7). A chi-squared test revealed a statistically significant difference between day and night detections ($\chi^2 = 82.04$, $p<0.001$).

iii. Sei whales and Sea ice Concentration

There were 87 acoustic detections total for sei whale 90 Hz downsweeps. Their calls were detected intermittently with the first being recorded on October 14, 2022 (Figure 5b and 6b). Call rates peaked at a modest 3.5 hours per day at the end of November, and then declined sharply after that, with only two acoustic detections recorded in December and one in January. The final call of the open-water season was detected on January 6, 2023, about a day before the onset of sea ice formation (Figure 5b). No sei whale calls were recorded during the ice-covered period. Acoustic activity resumed during the open water period on July 21, 2023, with sporadic detections of sei whales throughout the summer, continuing until the deployment concluded in September 2023. This seasonal pattern suggests that the oceanic region near Nunatsiavut serves as a summering area for sei whales and that their presence is primarily influenced by the availability of open water, with vocal activity limited to ice-free periods.

iv. Sei whales and Day/Night Cycle

Our data revealed acoustic detections of sei whale 90Hz downsweeps occurred during both daytime and nighttime hours, suggesting that sei whales in this region may not exhibit a strong diel preference for calling activity (Figure 6b). However, the limited number of detected calls restricted our ability to perform statistical analyses, and the unique environmental challenges of high-latitude regions, further complicated the interpretation of diel patterns. These factors made it difficult to draw definitive conclusions about any diel trends in sei whale vocal behavior.

v. Humpback Whales and Sea Ice Concentration

Figure 5c illustrating the seasonality of humpback whale songs by month and their relationship to sea ice reveals a notable pattern in humpback whale acoustic presence. Acoustic detections of humpback whale song were first recorded on October 14, 2022. Their vocalizations were detected during the open water period of October through November, with vocal activity varying throughout the day, leading to a total of 1,266 acoustic detections of their songs being labeled. A distinct peak in song production was observed at the beginning of November, lasting 16 hours per day, during which songs were very persistent and prolonged. Following this peak period, a gradual decline in song detections occurred. Calling rates steadily decreased until no further vocalizations were recorded after November 30, 2022, approximately a month before sea ice began forming in the area. This pattern suggests a brief but concentrated humpback whale acoustic presence during the fall months of October and November.

vi. Humpback Whales and Day/Night Cycle

Humpback whales were only acoustically detected in October and November. However, a slight diel pattern is observed in their calling behavior (Figure 6c). When the solar elevation is below 0° (indicating nighttime), humpback whale acoustic detections were a bit more frequent, with longer singing durations at night compared to daytime. We analyzed humpback whale detections during the day and night, based on acoustic recordings in Nunatsiavut, Canada. The diel plot shows the concentrated number of humpback whale songs related to the region's diel cycle. Out of the total 458 acoustic detections, 107 detections occurred during the day, compared to 351 detections at night (Figure 7). A chi-squared test for independence revealed a significant difference in detections between day and night ($\chi^2 = 135.61$, $p<0.001$), indicating a strong nocturnal pattern in acoustic presence.

vii. Bowhead Whales and Sea Ice Concentration

Acoustic detections of bowhead whale frequency-modulated calls were first recorded on May 28, 2023 (Figure 5d). No detections were recorded during the fall or winter months. It is worth noting that the absence of detections during the winter period may be due to the similarity in acoustic signatures between the whales' frequency-modulated calls and the pressurized noise produced by sea ice (Jones et al., 2022). This overlap made distinguishing between bowhead whale vocalizations and ice-generated sounds difficult. As a result, only 28 acoustic detections of bowhead whale frequency modulated calls were labeled with confidence in the data set, although there may be more in the deployment.

The timing of high-confidence detections of bowhead whale calls starting in late May matched with when the sea ice concentration ranged from 50% to 13% in the Nunatsiavut area

(Figure 5d). Acoustic activity increased in June as ice levels decreased from 10% to 0%. This rise continued until reaching a peak calling rate of 2.5 hours in July when sea ice concentration was at 0%. Additionally, there was one detection in August. However, it is unclear why bowhead whales were still detected in July and once in August, despite the absence of ice during these months. This is because bowhead whales are traditionally considered ice-associated species (Moore and Reeves, 1993), with their range typically confined to areas with seasonal ice cover. These results indicate that bowhead whale FM calls were detected intermittently near our HARP, suggesting a mostly spring and summer presence in the Nunatsiavut area. Their calls were absent during winter months, possibly due to increased sea ice coverage and overlap with ice noise. Acoustic detections began in late May as sea ice levels decreased, continuing sporadically into July and August despite the absence of sea ice.

viii. Bowhead Whales and Day/Night Cycle

Our data showed that most detections of bowhead whale frequency-modulated calls occurred during the daytime (Figure 6d). However, the small number of detected calls limited our ability to confidently identify a diel pattern in their calling behavior or conduct statistical analyses. The unique environmental challenges of high-latitude regions, such as the extended daylight due to the summer solstice, added further complexity to interpreting diel patterns. These factors made drawing clear conclusions about any diel trends in bowhead whale vocal behavior challenging.

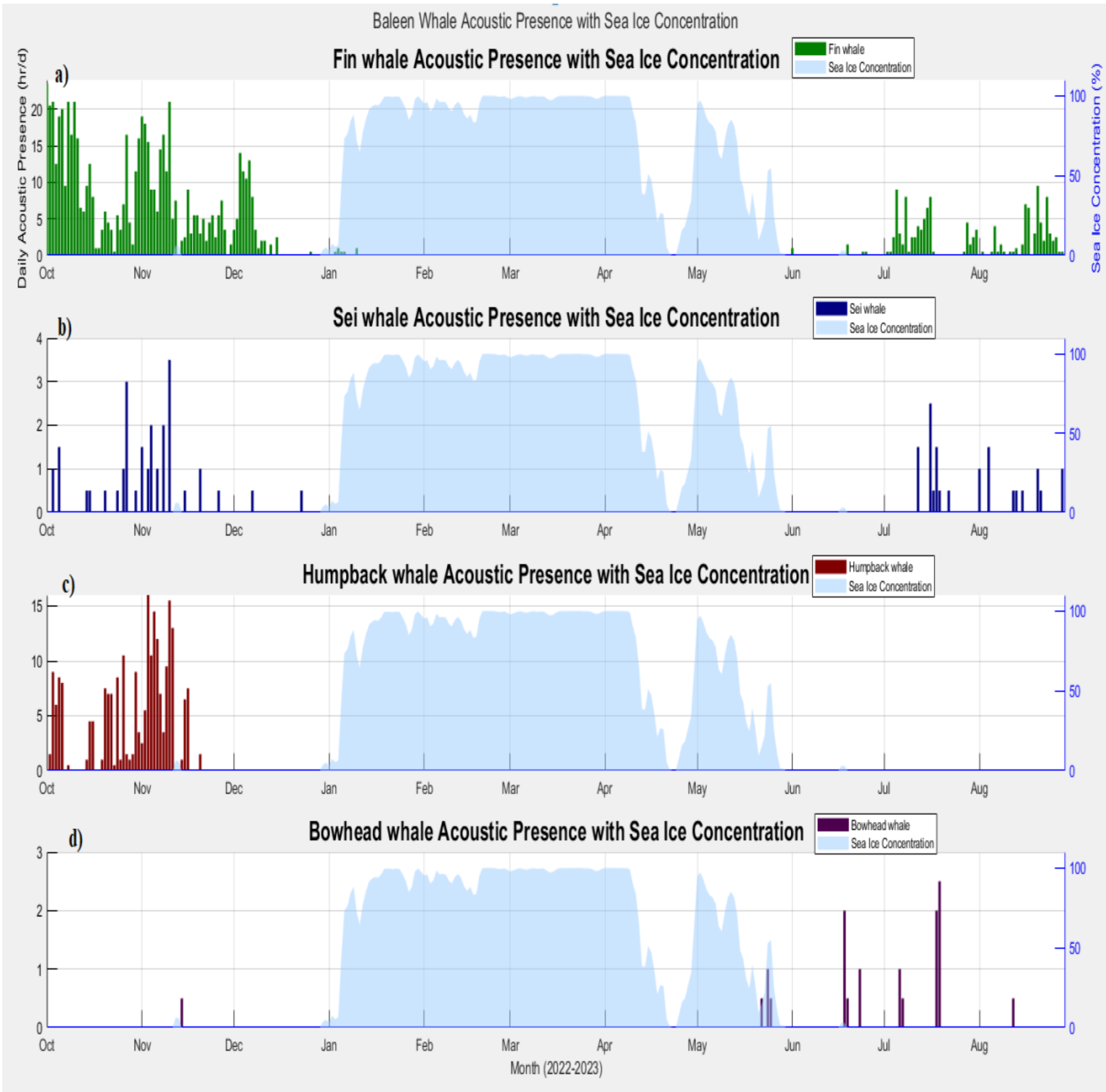

Figure 5. Barplot showing the acoustic presence of each baleen whale species in relation to the sea ice concentration (SIC) around our hydrophone with confirmed acoustic presence for (a) fin whales; (b) sei whales; (c) humpback whales; (d) bowhead whales. The x-axis represents the month of the year, while the y-axis on the right shows the percentage of SIC, and the y-axis on the left shows daily acoustic presence for each species, measured in hours per day (0-24 hr/d). It's important to note that this represents the total hours of calling activity rather than the number of individual whales detected, providing a measure of how frequent calls were over time. Also, the y-axis was minimized for humpback (0-16 hr/d), sei (0-4 hr/d) and bowhead whales (0-3 hr/d) to better focus on their calling rates.

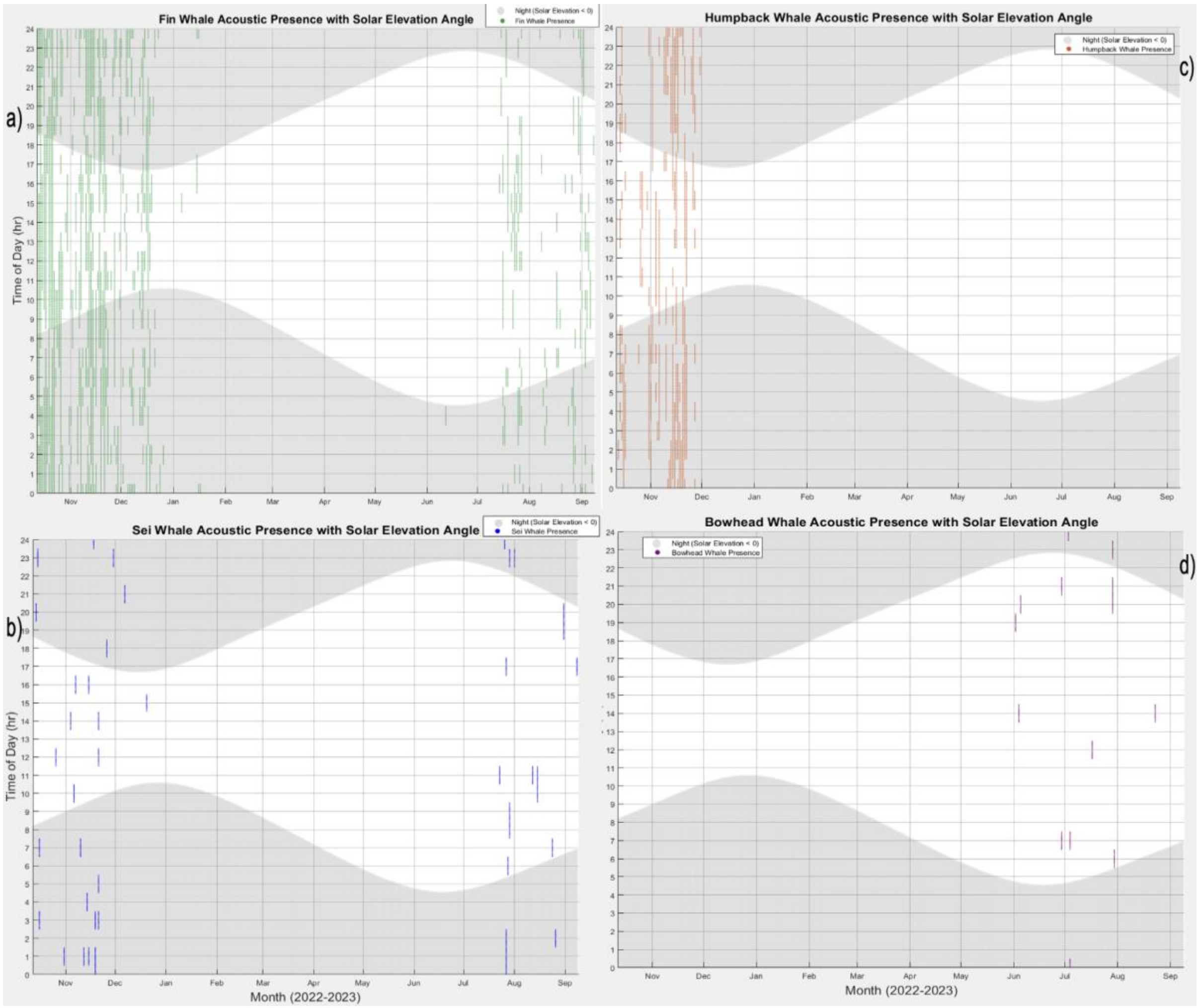

Figure 6. Plot shows the hourly acoustic presence of (a) fin whales; (b) sei whales; (c) humpback whales; (d) bowhead whales in relation to solar elevation angle, from October 2022 to September 2023. The x-axis represents the months of the year, while the y-axis shows the time of day in hours (0–24). The gray shaded region indicates night and the white region indicates day.

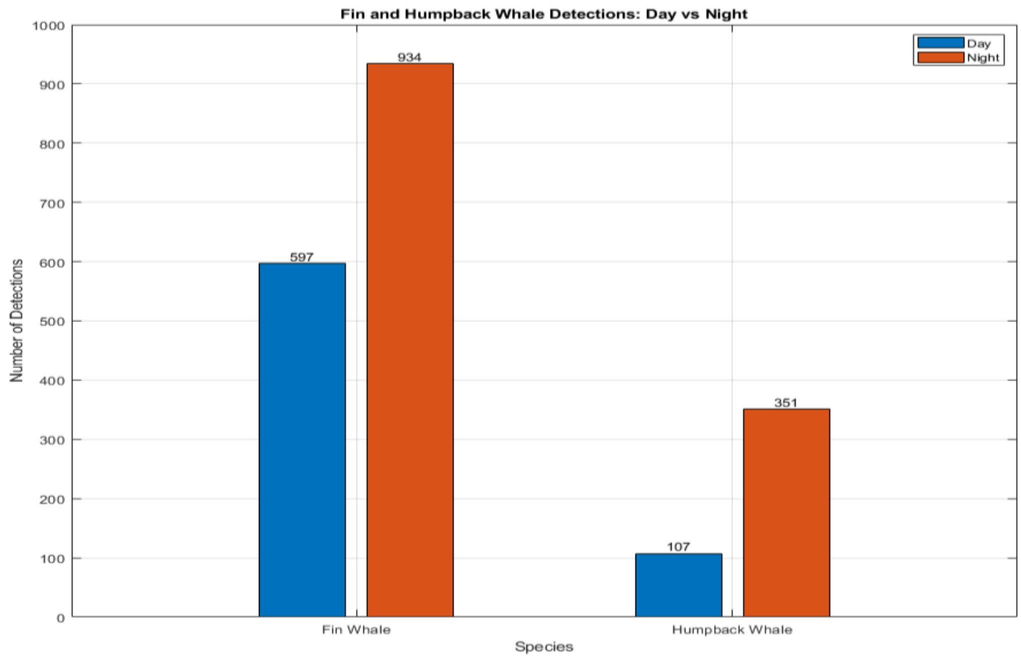

Figure 7. Bar plot showing the total acoustic detections of Fin whales and Humpback whales during the day compared to the night. The x-axis represents the total number of detections. Error bars are absent as detections represent total counts rather than statistical estimates.

ix. Call Parameter Measurement Tool results

Over 6,400 fin and 200 sei whale downsweep contours were processed, yielding 11 standardized measurement parameters. These measurements and detection time series provide a baseline for understanding whale vocalizations and will guide future algorithm development for detecting calls in complex acoustic environments. The measurements that were outputted include the mean, standard deviation, and range (min-max) for each call duration (s), slope (Hz/s), start and end frequency (Hz), minimum and maximum frequency (Hz), peak frequency (Hz), peak-to-peak receive level at -3 dB (dB re 1 μPa), RMS receive level at -3 dB (dB re 1 μPa), and sound exposure level at -3 dB (dB re 1 $\mu Pa^2/Hz$) (Table 3). The -3dB endpoint method was chosen for the receive level and sound exposure level, as in Wiggins and Hildebrand 2020, and was used for each call type to keep the methods consistent. As noted before, the call parameter measurement results were not used to analyze or compare baleen whale acoustic presence with environmental factors. Instead, this tool was used to accurately measure fin and sei whale downsweeps, which couldn't be reliably done manually. From these findings, we can determine if there are any clear acoustic distinctions between the two species vocalizations which confirms the potential of these parameter measurements to contribute to the training and development of an automated detection algorithm. When comparing the slope of fin whale 20Hz downsweeps and sei whale 90Hz downsweeps, clear differences are observed in their mean and standard deviation. Fin whale 20Hz downsweeps showed a consistent slope with a mean of -4.4 and minimal variation of ±1.8, while sei whale 90Hz downsweeps exhibited greater variability of ±6.2, with a distinct mean slope of -9.7 (Figure 8). The two species RMS Receive Level [-3 dB] (dB re 1 µPa) is also shown. Although both species' vocalizations share the same standard deviation (±3.3), their mean RMS received levels are different. The fin whale 20Hz downsweeps have a mean RMS received level of 94.3, while the sei whale 90Hz downsweeps have a higher mean RMS received level of 101.7. This suggests that, in the future, this dataset could be used to train an automated detection algorithm capable of scanning new long-term deployments and autonomously identifying multiple species' calls based on these differences in call measurements.

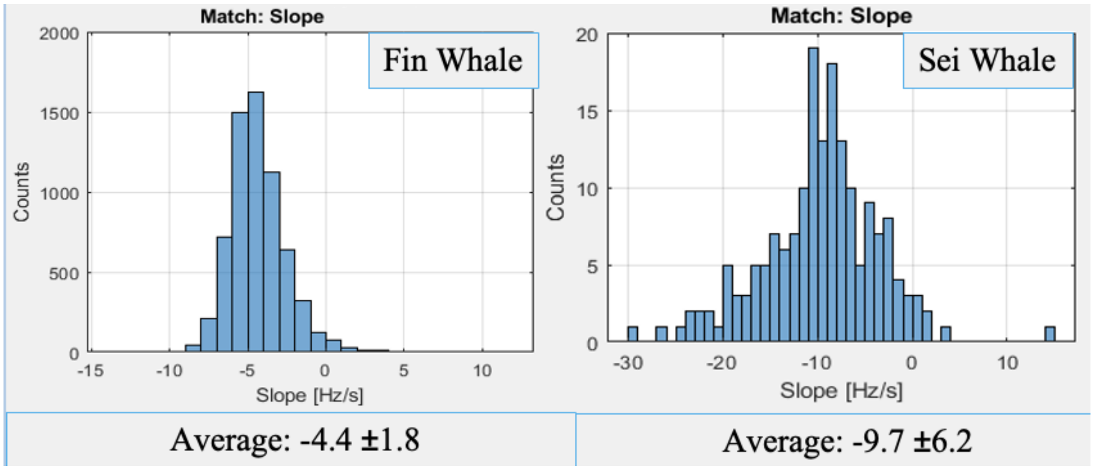

Figure 8. These two histograms illustrate the slope distribution for each species' call, highlighting distinct means and standard deviations.

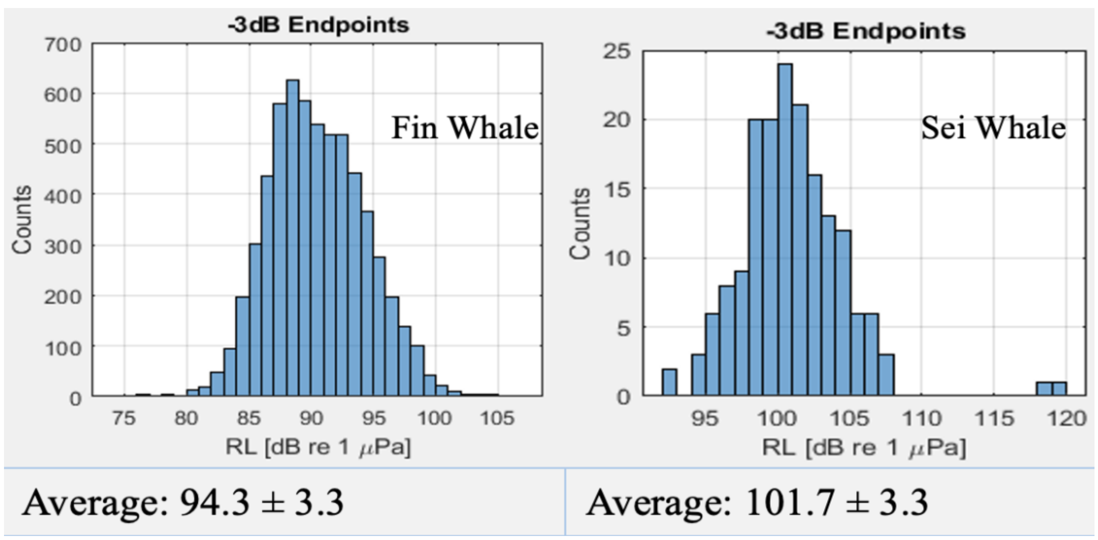

Figure 9. These histograms illustrate the different RMS Receive Level [-3 dB] (dB re 1 µPa) for each species' call.

Table 3. The measurements that were outputted from the call parameter measurement tool used to collect measurements of fin and sei whale calls in this study. It includes the mean, standard deviation, and range (min-max) for each call duration (s), slope (Hz/s), start and end frequency (Hz), minimum and maximum frequency (Hz), peak frequency (Hz), peak-to-peak receive level at -3 dB (dB re 1 µPa), RMS receive level at -3 dB (dB re 1 µPa), and sound exposure level at -3 dB (dB re 1 µPa²/Hz).

Species call	Fin whale 20Hz downsweep		Sei whale 90 Hz downsweep	
Call measurement	Mean ± Standard Deviation	Range (min-max)	Mean ± Standard Deviation	Range (min-max)
Duration (s)	1.1 ± 0.3	0.4 - 2.7	2 ± 1	0.9 - 6.7
Slope (Hz/s)	-4.4 ± 1.8	-13.4 - 11.3	-9.7 ± 6.2	-29.2 - 15
Start freq. (Hz)	24.8 ± 1.8	16 - 39.5	67.8± 0.3	33 - 89
End freq. (Hz)	21.1 ± 2.1	15 - 39.5	55.5 ± 10.7	30 - 86.5
Min. freq. (Hz)	18.8 ± 1.8	15 - 36	42.1 ± 9.7	30 - 61
Max. freq. (Hz)	27.7 ± 2	20 - 40	77.4 ± 8.9	46 - 88
Peak freq. (Hz)	24.7 ± 6	13 - 42	62.8 ± 10.3	31 - 88
Peak-to-peak Receive Level [-3 dB] (dB re 1 µPa)	87.6 ± 1.8	82.9 - 98.8	91 ± 1.6	87.4 - 100
RMS Receive Level [-3 dB] (dB re 1 µPa)	94.3 ± 3.3	85.4 - 113.7	101.7 ± 3.3	94.6 - 119.6
Sound exposure level [-3 dB] (dB re 1 µPa²/Hz)	113.1 ± 4	103.4 - 140.1	119.1 ± 4.5	110.7 - 141.1

DISCUSSION

This study presents the first documented record of the seasonal movements of multiple baleen whale species in the Torngat Area of Interest, Nunatsiavut, Canada, and examines their relationship with environmental factors. All four baleen whale species of interest were acoustically detected near the waters of Nunatsiavut during the 2022–23 deployment. Fin, sei, and humpback whales were present during the fall and early winter months (October 2022 to January 2023). Additionally, fin, sei, and bowhead whales were detected during the spring and summer months (May to September 2023), suggesting their widespread presence throughout the Nunatsiavut region. When interpreting our observations, it is important to recognize the limitations within the dataset, including the inability to detect non-vocalizing animals or those producing vocalizations different from the ones analyzed in this study, as well as varying detection ranges across species and seasons. Despite differences in vocal behavior across species, such as the similarity between humpback and bowhead whale songs or the limited understanding of sei whale vocalizations, we detected vocalizations from each species throughout the entire deployment. These findings provide a broad overview of the temporal distribution of these species in Nunatsiavut, contributing valuable insights into the biological and ecological importance of this region.

i. Fin Whale Seasonal Acoustic Presence

We reported on the acoustic detection and patterns of fin whale 20Hz downsweeps in the waters near the Torngat area of interest in Nunatsiavut, Canada. Fin whales were detected in this region throughout most of the open-water period, indicating an extended presence, with their absence aligning with the high sea ice concentrations observed from January to June.

This is consistent with other studies that show fin whale catches and sightings are more frequent during the summer than in the winter at latitudes above 50°N in regions such as Labrador-Newfoundland (Hay, 1982) and the Northeast Atlantic (Jonsgard & Norris, 1966).

The characteristic 20Hz downsweeps of fin whales became increasingly sporadic as the fall to winter season progressed, before detections ceased altogether by January, which coincided with the complete coverage of surface waters by sea ice. Despite the seasonal decline, fin whales lingered in the region longer than other baleen whale species (Figure 4a). Their vocalizations were the last baleen whale acoustic activity detected, persisting until January 18, 2023, just before sea ice became close to 100% in the region. The detection of fin whales at the start of the winter season when the sea ice concentration was above 0% suggests that not all fin whales may migrate to lower latitudes at the start of the breeding season, which typically starts in November (Ramp et al., 2024). This pattern is similar to the behavior of fin whales in the North Pacific (Oleson et al., 2014). For Arctic waters, Simon et al., 2010 pointed towards secondary oceanographic effects on prey availability rather than the physical presence of sea ice as a limiting factor in fin whale distribution. Historical catch data indicates that migration is not obligatory for fin whales (Mackintosh 1942), and migration timing can vary by sex and age class (Laws 1961).

In the fall, the fin whale 20Hz downsweeps were highly repetitive and continuous, forming a constant energy band around the 30-15 Hz frequency range (Figure 6). This resulted in the masking of individual downsweeps and the appearance of a continuous band of sound (yellow horizontal line) in that frequency range, illustrating the persistent nature of their calling at that time. This energy broadband could have been influenced by factors such as an increasing number of callers, changes in call rate and intensity by individuals, or changes in sound propagation linked to environmental factors like calling depth or topography (Wiggens and Hildebrand, 2020). As stated before, male fin whales may produce 20Hz downsweeps in regular sequences to attract females, creating a type of stereotypical song (Romagosa et al., 2021; Watkins, 1981). The increase in repetitive calling in the fall may reflect males ramping up their acoustic activity in preparation for the winter breeding season. Similar findings on blue whales (*Balaenoptera musculus)* and fin whales (*Balaenoptera physalus*) suggest that balaenopterid singing during the feeding season is more prevalent than once thought (Clark & Gagnon, 2022; Croll et al., 2002).

Based on a comprehensive analysis of historic whaling records, mark recovery tags, visual sightings, and acoustic recordings, Mizroch et al. 2009 and Escajeda et al., 2020 indicates that fin whale movement patterns are likely far more complex and variable than the traditional model of a direct annual migration to lower latitude breeding grounds (Kellogg 1929). Instead, some could remain at high latitudes or delay migration to exploit food resources unavailable in mating areas (Silva et al., 2013; Simon et al., 2010). The strategy of delayed migration may be advantageous for male fin whales by allowing them access to non-migratory females who either remain on feeding grounds or migrate later, a behavior similarly observed in humpback whales (Clark & Clapham, 2004; Mattila et al., 1987). Additionally, studies indicate that not all fin whales migrate south to mate; some initiate mating activities at high latitudes before undertaking their migration (Simon et al., 2010). The high occurrence of repetitive 20Hz downsweeps in the fall suggests that fin whales may display flexible behaviors in this region, likely shaped by individual needs and environmental factors such as food availability and reproductive opportunities. This highlights the need for further research to better understand their variable migration patterns.

Fin whales were also the second species to return to this region in the spring, with 20Hz downsweeps resuming on June 7, 2023. This timing aligns with the fin whale's known winter migration to lower-latitude waters and their annual return to high-latitude feeding grounds during the summer months (Mitchell, 1975; Watkins et al., 1987; Woodley & Gaskin, 1996). Fin whale calling activity resumed on June 7th and rapidly increased during July as the open-water period set in. Significant decreases in acoustic presence were observed in late July and early August. The decline in acoustic activity during these periods could indicate that fin whales were absent from this region at the time. Alternatively, their calling activity may reflect a shift to prioritizing foraging during times of seasonal phytoplankton blooms, which occur in spring and fall under favorable light and nutrient conditions (Hill et al., 2018; Wihsgott et al., 2019). This supports the hypothesis that fin whale 20 Hz downsweeps are unrelated to feeding behavior (Burkhardt et al., 2021; Širović et al., 2013). Burkhardt et al. (2021) suggests that the absence of 20 Hz downsweeps during feeding periods, despite the availability of abundant prey, indicates that fin whales do not produce 20 Hz downsweeps while feeding. This explanation could also apply to the observed decreases in acoustic activity during late October and November in the previous fall. This suggests that during presumed periods of high primary productivity, often linked to the timing of phytoplankton blooms, fin whales produce 20Hz downsweeps less frequently, likely prioritizing feeding over maintaining contact or engaging in mating behaviors.

Our analysis revealed that fin whale calling rates at the start of the deployment in October and November 2022 were significantly higher and more repetitive compared to the summer months of 2023, suggesting that the 20Hz calls during the fall months were likely associated with mating behaviors. This underscores the importance of the Nunatsiavut region as not only a critical feeding ground but also a potentially significant area for early breeding and social interactions; and highlights the need for further research to better understand seasonal variations in fin whale 20 Hz calling patterns.

ii. Fin Whales and Diel Activity

Our analysis revealed a significant difference in fin whale vocal activity between day and night. During the study period, 597 detections were recorded during the day, compared to 934 detections at night. The chi-squared test confirmed this difference as statistically significant (chi^2 = 82.04, p<0.001), strongly suggesting that fin whales are more vocally active at night. This diel pattern could be influenced by several ecological or behavioral factors.

Diel calling patterns have been observed in many baleen whale species, including fin whales, with differences in peak calling activity linked to feeding behaviors and prey availability (Pilkington et al., 2018; Simon et al., 2010; Širović et al., 2013). Foraging and vocalizing are both energetically expensive behaviors so typically baleen whales vocalize more when they are not foraging (Gough et al., 2022). Fin whales are thought to call less during the day while actively foraging on prey, such as krill and small fish, which form dense aggregations at depth. At night, these prey species undergo diel vertical migration, dispersing into shallower depths, potentially reducing the efficiency of lunge feeding and leading to increased vocal activity (Lampert, 1993; Sigurjónsson and Víkingsson, 1997; Stafford et al., 2005). This nighttime calling behavior has been observed in fin whale populations across various regions. For example, Širović et al. (2013) found that fin whales in the Gulf of California produced more 20 Hz downsweeps at night, while Pilkington et al. (2018) reported site-specific diel patterns in Canadian Pacific waters with higher nighttime calling rates. Burnham (2019) also noted a trend toward increased nighttime calls near Vancouver Island, though this was not statistically significant.

These findings are consistent with observations reported in other studies on diel patterns in fin whale calling, which similarly observe increased vocal activity at night. Understanding these patterns is important for conservation and management efforts, as it can help identify critical feeding or communication times and areas for fin whales.

iii. Sei Whales Seasonal Acoustic Presence

We analyzed the acoustic patterns of sei whale 90 Hz downsweeps in the waters near the Torngat Area of Interest in Nunatsiavut, Canada. Our study focused on examining how these vocalizations may be related to key environmental factors, including sea ice concentration and solar elevation, during the 2022–2023 observation period. By comparing acoustic detections to these variables, we aimed to better understand the potential drivers of sei whale acoustic presence in this high-latitude region, where environmental conditions vary dramatically across seasons.

Sei whales exhibited distinct seasonal movements, with peak occurrence near the study area during summer and fall months. Typically, sei whales have been documented traveling as far north as the Davis Strait and Labrador Sea during summer (Mitchell, 1974) and begin their southward migration in September and October (CETAP, 1982). However, our study found sei whales in the Labrador Sea later than expected, with detections continuing beyond October and a peak of their acoustic occurrence in November. The last detection of sei whale 90 Hz downsweeps in the region occurred in January, approximately one day before sea ice began forming in the area. Leading these observations to suggest that sea ice may have influenced the migration timing of sei whales in the Labrador Sea during that year. However, unlike other baleen whale species, sei whales exhibit irregular annual migration patterns and there is limited scientific literature directly addressing the specific behavior of sei whales leaving regions upon the onset of sea ice (Davis et al., 2020; Jonsgård and Darling, 1977).

Sei whale migrations are complex and variable, with documents of their distribution shifting significantly from year to year, even within the same region. For instance, Schilling et al. (1992) used photo identification to document an irregular influx of sei whales into the southern Gulf of Maine in 1986, highlighting the sporadic nature of their movements. Similar patterns have been documented globally, with historical catch data revealing instances where large numbers of sei whales reappearing in certain areas after decades-long absences (Jonsgård & Darling, 1977). In their study on the biology and distribution of sei whales in the eastern North Atlantic, Jonsgård and Darling highlighted the species' unpredictable migratory patterns and year-to-year variability in feeding ground occupancy. They attributed these irregular movements to shifting environmental conditions and prey availability, emphasizing the unpredictable nature of sei whale distribution and the challenges it poses for their study and conservation. So, it appears likely sei whales appear to have been present in the Labrador Sea from October 2022 to January 2023, potentially influenced by variations in environmental conditions, one of which possibly being the introduction of sea ice.

Their acoustic detections resumed in July 2023, in alignment with previous research (Mitchell, 1975). This indicates that this is probably when sei whales migrate back into this region after their annual migration to their breeding grounds (Mitchell, 1975; Olsen et al., 2009). The presence of sei whales in this region beyond October underscores the need for further research into the environmental factors driving these shifts and the potential flexibility in their migration behavior. Additional studies are also necessary to better understand sei whale acoustic behavior and interpret their acoustic patterns. Currently, only one call type is known for sei whales, with limited knowledge regarding whether it is produced by both sexes or its seasonal use (Davis et al., 2020).

iv. Sei whales and Diel Activity

Our data indicated that sei whale acoustic detections occurred both during the day and at night. However, due to the limited number of calls and challenges in interpreting diel patterns influenced by the winter and summer solstices, we were unable to confidently establish any distinct pattern in vocalizations. Baumgartner & Fratantoni (2008) investigated sei whale vocalization rates in the Gulf of Maine using ocean gliders, focusing on relationships between vocalizations, oceanographic conditions, and the vertical distribution of their prey, Calanus finmarchicus. This calanoid copepod is known for diel vertical migration, moving to shallower depths at night and deeper during the day (Baumgartner et al., 2003; Lampert, 1993). Their results indicated that sei whale vocalizations were more frequent during the day when C. finmarchicus was deeper and less common at night when the copepods migrated closer to the surface. These observations suggest that sei whale vocalization behavior may be driven by the availability of C. finmarchicus in surface waters, which could affect their feeding efficiency. Historical accounts of baleen whale feeding behavior support the hypothesis that sei whale diel vocalizations are governed by prey availability. Ingebrigtsen (1929) noted that sei whales exhibited skim feeding on copepods primarily during dusk and dawn, which aligns with copepod availability in surface waters. When copepods are near the surface, sei whales prioritize feeding, potentially leaving less time for social vocalizations. Despite our limited data, this suggests that the diel variation in sei whale vocalizations could be shaped by prey distribution and corresponding changes in feeding and social behaviors.

v. Humpback Whale Seasonal Acoustic Presence

The analysis of humpback whale acoustic activity showed a very concentrated seasonal presence in October and November. For a long time, it was believed that humpback whale singing was limited to their breeding grounds, but more recent research has documented singing along migratory routes and in feeding areas (Au et al., 2000; Cates et al., 2019; Clark & Clapham, 2004; Kowarski et al., 2018). Mattila et al., 1987 documented isolated instances of humpback whale songs on a North Atlantic feeding ground, primarily during autumn. Their findings align with this study's observation of heightened song production in late autumn. According to their study, song occurrence was rare in spring but relatively common in autumn, which they attributed to the mixing of individuals from different feeding areas, a hypothesis that aligns with the temporal patterns identified in this study. In a review of humpback whale social ecology led by Clapham (1996), he discussed observations by Mattila et al., 1987 and McSweeney et al., 1989 that suggest that humpback singing in high latitudes may serve as a low-cost advertisement of fitness by males and a means for females to assess potential mates. Another hypothesis for humpback whale songs being heard on feeding grounds could be because of seasonal increases in male testosterone levels (Cates et al., 2019; Clark & Clapham, 2004; Wingfield & Marler, 1988). Singing activity in spring and autumn may reflect lingering mating behaviors associated with elevated testosterone levels, either at the onset of the breeding season in autumn or as it tapers off toward its conclusion in spring (Clapham, 2000). This hypothesis is further supported by findings of high sperm levels in two male humpback whales killed off eastern Canada in October and November (Mitchell, 1973). Additionally, male intrasexual competitive behavior observed on feeding grounds in late autumn (Weinrich, 1995) likely represents another indication of this extended breeding activity. All in all, though, the results from this study found that humpback whales sing in the Labrador Sea region during the autumn and that humpback whale songs are much more common in high latitudes than previously believed.

The presence of humpback whale song in this dataset was detected from October through November but abruptly stopped at the beginning of December, about a month before sea ice began to form in the area. This gap between the decrease in song production and the onset of sea ice indicates that the migration of humpback whales from the region is likely not driven by the growth of sea ice "pushing" the animals out. Instead, other factors may influence their departure before ice formation begins. The cessation of humpback whale calls in relation to ice growth aligns with observations by Ramp et al., 2015, who noted that humpback whales have adapted their seasonal movements to shifts in productivity within key feeding grounds in the North Atlantic. They suggested that the timing of seasonal migrations is likely driven more by the depletion of krill stocks or the fulfillment of enough energy reserves for the season rather than by the advancement of pack ice. That study also determined that over 26 years (1984–2010), humpback whales tended to arrive earlier at a summer feeding area in the North Atlantic and that this change was likely related to warmer sea surface temperatures and earlier sea ice break-up, which in turn might bring about a quicker onset of spring blooms, heightened primary production and the occurrence of crucial prey earlier in the season (Ramp et al., 2015). So, it can be strongly inferred that oceanographic conditions affecting prey availability may influence the departure of humpback whales from this region before the onset of sea ice formation. Other papers have also pointed toward secondary oceanographic effects on prey availability rather than the physical presence of sea ice as a limiting factor in whale distribution (Findlay et al. 2017; Simon et al. 2010). Notably, no humpback whale songs were detected during the spring months in our study. This absence may be due to a lack of humpback whales in the region during spring-summer 2023. Visual surveys conducted near Newfoundland since the late 1980s by researchers from the Whitehead lab at Dalhousie University have consistently reported that humpback whales are more commonly sighted during the late summer of August and September than in June and July (Hooker et al., 1999; Whitehead, 2013). These historical findings align with our observations, where humpback whales were detected more frequently in late summer to early fall, with no detections in spring. This supports the idea that humpback whale presence in the region is seasonally influenced, peaking in late summer through fall.

vi. Humpback whale and Diel activity

Our analysis revealed a significant difference in Humpback whale vocal activity between day and night. From the concentrated amount of humpback whale songs recorded in October and November, a distinct yet slight diel pattern emerged. During the study period, 107 detections were recorded during the day, compared to 351 detections at night. The chi-squared test confirmed this difference as statistically significant (chi^2 = 135.61, p<0.001), strongly suggesting that Humpback whales are more vocally active at night.

This nighttime pattern of singing observed in our study aligns with previous research on humpback whale vocal behavior across various regions, suggesting that this diel pattern may be a species-wide characteristic. Similar patterns have been observed in feeding grounds (Kowarski et al., 2018; Magnúsdóttir et al., 2014), breeding grounds (Au et al., 2000;

Cholewiak, 2008; Kobayashi et al., 2021), and along migration routes (Shabangu and Kowarski, 2022). This diel pattern could be influenced by several behavioral or ecological factors. One possible explanation is that increased calling at night is linked to feeding behavior, as seen in fin whales, where vocal activity rises in response to prey distribution (Pilkington et al., 2018; Širović et al., 2013). However, Au et al. (2000) observed humpbacks singing more at night than in the day on the breeding grounds of Hawaii during a time when the animals were fasting; showing that this behavior may not be driven by foraging. The study proposed that this diel pattern results from humpback whales relying on both visual and acoustic cues during the day but only acoustic cues at night. Increased singing at night suggests a shift toward acoustic sexual advertisement as a primary mating strategy, rather than physical competition, which relies on visual cues and is more effective during daylight. This behavior could explain the observed trend across different environments (Kowarski et al., 2018; Parks et al., 2014).

It is important to note that during this time of year in the region, there are significantly more hours of darkness than daylight due to the approaching winter solstice in December, which may skew our observations of increased singing at night. Nevertheless, the observed diel pattern, both in our findings and in previous studies, supports the idea that nighttime offers optimal conditions for humpback whale vocalizations in the Labrador Sea, and that this day/night pattern in calling activity may be related to social behavior, likely due to the reliance on acoustic cues for mating in the absence of light.

vii. Bowhead whale seasonal acoustic presence

The bowhead whale frequency-modulated calls in our dataset were detected sporadically throughout the deployment. The stock these bowhead whales are believed to be a part of is the eastern Canadian-western Greenland Stock, as this population of bowhead whales is widely distributed across the eastern Canadian Arctic and Baffin Bay to the west coast of Greenland in the Labrador Sea (Heide-Jørgensen et al., 2003; Chambault et al., 2018). During the fall and winter months, no bowhead whale calls were detected. One possible explanation for this is that bowhead whales are known to closely follow the advancing and retreating sea ice edges (Stevenson & Hartwig, 2010; Reeves et al., 1983; Harwood et al., 2017; Heide-Jørgensen et al., 2006). However, distinguishing their vocalizations from the sounds of moving, pressurized sea ice is difficult. The lack of detections during this time could be due to the similarity between the whales' frequency-modulated calls and the acoustic noise generated by sea ice (Jones et al., 2022). Bowhead whale detections observed in late spring to early summer when the SIC fluctuated between 50% to 10% coincides with the presence of marginal sea ice in the area. The marginal ice zone is the transition area between open ocean and pack ice, where waves and swells interact with the ice (U.S. National Ice Center, 2020). These conditions, characterized by open ice edges and breathing holes, provide an optimal habitat for bowhead whales (George et al., 1989). This seasonal pattern aligns with the species' preference for remaining near ice edges while maintaining access to open water.

The continued detection of bowhead whale frequency-modulated calls during the open water periods of July and August is unexpected given their known behaviors (George, 2009; Moore and Reeves, 1993). However, recent studies suggest this may not be entirely surprising, as the rapidly changing Arctic environment driven by climate change is likely influencing bowhead whale distribution and behavior. Bowhead whales are known to exhibit flexibility in movement patterns and habitat selection, influenced a lot by oceanographic conditions including sea surface temperatures and sea ice thickness (Chambault et al., 2018). Tracked movements of the eastern Canadian-western Greenland bowhead whale stock from feeding grounds in Disko Bay during April and May of 2009 and 2010 showed that all 78 tagged whales left Greenland waters and migrated northwest towards the Canadian Arctic Archipelago during May and June (Heide-Jørgensen & Laidre, 2021; Heide-Jørgensen et al., 2021). In July and August, these whales were primarily distributed around Baffin Island and within the waters of the Canadian Arctic Archipelago (Heide-Jørgensen & Laidre, 2021). Baffin Island and the waters of the Canadian Arctic Archipelago are located north of our hydrophone in Nunatsiavut. This means that while it is unusual to hear bowhead whales this far south in the summer, given the proximity of Baffin Island to Nunatsiavut, the bowhead whale detections in July and August are not entirely unexpected, suggesting that their summer distribution may have shifted further south during 2023. It has also been documented that bowhead whales were harvested in the Hudson Strait in August by Nunavik hunters, indicating the possibility of some summer residency in the area (Stephenson & Hartwig, 2010). This observation is consistent with our findings of bowhead whale detections during the summer months near the coast of Nunatsiavut, which lies just south of the entrance to the Hudson Strait.

Given the increasing warming in the Arctic and the decrease in seasonal sea ice (Rantanen et al., 2022; Zhang et al., 2018), we may observe new distribution shifts driven by changing environmental conditions. Sea ice's role in bowhead ecology is complex, as it influences the broader structure of Arctic ecosystems by regulating the extent, timing, and thickness of ice and sea surface temperatures, which in turn affects primary production (Arrigo & van Dijken, 2015). As climate warming progresses, sea ice loss has become a symbol of the changing Arctic, and bowhead whale populations now regularly inhabit open-water regions from late summer through autumn (Druckenmiller et al., 2018). Bowheads show no difficulty in migrating or feeding in open waters, even when the nearest sea ice is hundreds of kilometers away. In fact, George et al., 2015 reported that bowhead whale body condition improved from 1989 to 2011, showing a positive correlation with summer sea ice loss in the western Beaufort Sea. Also, preliminary data from 2018 to 2019 further indicate further improvements in body condition (Stimmelmayr et al., 2020). Moore and Laidre, 2006 suggested that increased primary productivity, followed by secondary productivity, may enhance bowhead whale feeding opportunities in summer and fall.

Bowhead whales mainly feed on zooplankton, such as copepods and euphausiids, which are closely linked to primary production (Sheffield and George, 2021). This, along with their relation to sea ice, makes bowheads an important indicator species for Arctic environmental change (Moore and Laidre, 2006). Indeed, primary productivity in the Beaufort sector of the Arctic Ocean increased by 53% from 1998 to 2012 due to declining summer sea ice and extended ice-free periods, a trend that has continued since 2012 (Arrigo & Van Dijken, 2015; Frey et al., 2017). This adaptability is crucial as high-latitude habitats are changing quickly due to rising ocean temperatures and declining ice (Chambault et al., 2018). As the Arctic continues to warm and sea ice shrinks, we may see further shifts in bowhead whale behavior and distribution. These changes show the whales' ability to adapt but also emphasize the need for ongoing monitoring and research to understand the ecological impacts of a rapidly changing Arctic environment.

viii. Bowhead whale and Diel activity

Due to the limited number of bowhead whale detections, it was challenging to establish a diel pattern in calling activity. However, the concentrated number of calls observed in July suggested an increase in vocal activity during the day compared to nighttime. Several previous studies have examined the seasonal and spatial patterns of bowhead whale acoustic activity, there is limited research specifically discussing increased daytime vs. nighttime acoustic detections. For instance, Halliday et al. (2018) in the northern Amundsen Gulf reported year-round acoustic presence of bowhead whales, with increased activity in spring and summer, but did not observe strong diel patterns in their study. Similarly, Blackwell et al., 2007 in the western Beaufort Sea, reported an absence of consistent diel patterns throughout the year and Thomisch et al., 2022 in the Fram Strait observed bowhead whale acoustic presence during autumn and winter months but did not detail time-of-day variations. One reason for the lack of a clear diel pattern in many studies could be that bowhead whales are known to feed during winter (Citta et al., 2015), as well as sing extensively in winter months (Tervo et al., 2009; Stafford et al., 2012; Clark et al., 2015). This suggests that singing and feeding behaviors are not mutually exclusive for bowhead whales, unlike other whale species (Baumgartner & Fratantoni, 2008; Matthews et al., 2001).

While our findings hint at a potential increase in bowhead whale vocal activity during the day in July, the limited number of detections and lack of observed diel patterns in other studies highlights the need for more research to better understand the relationship between bowhead whale vocal behavior, feeding, and time of day, particularly in the context of their unique Arctic habitat.

ix. Bowhead vs. Humpback whale song

One of the challenges in this study was differentiating between humpback whale song and bowhead whale song in the data. Bowhead whales and humpback whales both sing complex songs that change over breeding seasons (Payne and McVay 1971; Stafford et al., 2018; Tervo et al., 2011). Currently, no study focuses solely on distinguishing between the songs of these two species and in a region like the waters near Nunatsiavut, where both species are believed to be present, this can make it difficult to reliably tell them apart. While our study did not aim to distinguish between bowhead and humpback songs, focusing instead on identifying bowhead frequency-modulated calls and humpback whale songs, there remains a concern that some of the recorded humpback songs may have been bowhead songs. Fortunately, previous studies have made efforts to differentiate between the two, and we can also use the time of year a song was recorded to help determine which species most likely produced it. Bowhead whale songs usually consist of many song types within a single season, most notably in the winter (Stafford et al., 2018; Stafford et al., 2012), while humpback whales within a population typically sing a single, shared song type that gradually changes over time (Payne and McVay, 1971; Payne & Payne, 1985; Guinee & Payne, 1988).

We can also consider the seasonality of the detected songs and compare it to the known behavior and distribution of the two species. As noted earlier, all the songs detected occurred in the fall and stopped abruptly in November, before sea ice began to form in the area. Previous studies show that humpback whale songs on North Atlantic feeding grounds occur primarily in autumn (Mattila et al., 1987; Clapham, 1996; McSweeney et al., 1989), while bowhead whale songs are more common in winter as they follow sea ice (Stafford et al., 2018; Stafford et al., 2012). Based on this, it could be assumed that the songs recorded in

October and November, before the onset of sea ice were likely produced by humpback whales.

x. Undetected Species

Despite reports from the Nunatsiavut community that minke whales are frequently observed year-round near the Torngat area of interest (Canadian Science Advisory Secretariat, 2024), no low-frequency minke whale vocalizations were detected in the data. This absence may suggest that minke whales did not pass near the hydrophone deployed in Saglek Bank. Alternatively, this could suggest that minke whales are not producing their characteristic low-frequency pulse trains, which are among one of the most common vocalizations below 300 Hz for this species (Risch et al., 2013; Winn & Perkins, 1976). Given their highly variable vocal repertoire, particularly in the mid-frequency range (Beamish and Mitchell 1973; Winn and Perkins 1976), it is possible that minke whales in this region are exclusively producing calls above 300 Hz if they are in Saglek Bank. Further research should focus on detecting mid-frequency minke whale vocalizations to confirm this. Additionally, more visual surveys would be valuable in verifying the presence of these whales in the area, even if they are not producing low-frequency calls.

Another species and its corresponding vocalization that was not included in the analysis is the North Atlantic right whale (NARW) upcall. As mentioned earlier, only calls identified with confidence were included in this study. Although upsweeps resembling North Atlantic right whale (NARW) upcalls were detected in summer and fall recordings, their variability and overlap with other species' vocalizations made confident identification challenging. NARW upcalls, ranging from 50 to 300 Hz, are produced by both sexes and all age classes, and are commonly used to detect the species across their range (Parks & Tyack, 2005; Durette-Morin et al., 2022). While NARW upcalls are typically sporadic, humpback whales also produce upsweeps within this frequency range, but theirs are more repetitive and are often associated with song (Kowarski et al., 2019; Davis et al., 2017). Most upsweeps in the data displayed these repetitive patterns around the time of song production and were attributed to humpbacks, but occasional sporadic signals could not be confidently classified, requiring further analysis to determine if they belong to NARWs. Future studies should focus on species-specific vocalization analyses to better identify baleen whale presence and acoustic behavior in this region. Expanding visual surveys would also help confirm whale presence, even when low-frequency calls are not detected. Additionally, incorporating acoustic monitoring above 300 Hz would improve detection, as many species produce vocalizations beyond the frequency range analyzed in this study.

xi. Call Parameter Measurement Tool Future Directions

The use of the call parameter measurement tool allowed us to extract precise measurements for fin and sei whale downsweeps, which manual detection alone could not achieve. By comparing the measurement outputs of the fin whale 20Hz downsweep and sei whale 90Hz downsweep, we can use their distinct averages to better understand the differences between the two calls. These differences have the potential for training an automated detection algorithm in the future. However, this process still required manually reviewing the year-long deployment to collect calls for input.

The resulting histograms shown above (Figure 8) illustrates the different slope distribution for each species' calls, highlighting distinct means and standard deviations. It is shown that the fin whale 20Hz downsweeps, derived from approximately 2,000 processed calls, displayed a consistent slope with a mean of -4.4 and minimal variation (±1.8). In contrast, sei whale 90Hz downsweeps exhibited greater variability (±6.2), with a distinct mean slope of -9.7. These findings reveal clear acoustic distinctions between the two species' vocalizations, demonstrating the potential of these parameter measurements to help in training and developing automated detection algorithms. RMS received level is also a valuable tool for both automated detection and whale localization. By measuring the strength of received signals, RMS levels can help train automated detection algorithms, improving their ability to distinguish whale vocalizations from background noise. Also, since sound intensity decreases with distance, RMS received levels can provide insights into how far a whale is from the hydrophone (Guazzo et al., 2017). This information can contribute to localization efforts, helping researchers estimate whale positions and movement patterns within a study area. Looking ahead, an automated detection algorithm capable of scanning novel long-term deployments and identifying multiple species calls autonomously could save researchers months of manual analysis.

CONCLUSION

i. Study Limitations

Autonomously recorded passive acoustic data is invaluable for filling knowledge gaps regarding baleen whale activity in remote regions during different and sometimes inaccessible times of the year. However, this method lacks the advantage of direct visual observation to confirm the animals producing the sounds. Species identification must, therefore, rely on previous acoustic descriptions from other regions and times, often with different analysis techniques. Baleen whales are known to produce a diverse range of vocalizations, which can vary greatly or overlap with those of other species. Unfortunately, few long-term, continuous acoustic datasets exist for these whales in high-latitude regions, particularly in the Eastern Canadian Arctic, limiting the ability to predict or compare findings to similar studies. A key challenge lies in determining species absence based solely on vocalization data. The absence of detected vocalizations does not necessarily mean the species is not present; it may simply be silent. Numerous factors may influence periods of reduced vocal activity, including a shift to a different call type, high ambient noise, sea ice conditions, diel behavior patterns, or predator presence. Call detection can also be influenced by factors such as source level, transmission loss, and local bathymetry. In ice-covered areas, increased scattering affects sound travel, reducing detection range and accuracy. Noise from ships, flow noise, and weather can also interfere with detecting vocalizations. Although calls were detected year-round, the changing Arctic soundscape poses challenges to detection accuracy and requires further study to understand its impact.

ii. Recommendations for Collaborators

To address these challenges, we suggest combining passive acoustic monitoring with visual and tagging surveys, especially during summer and fall when sea ice is minimal, and baleen whales are likely foraging in high latitudes. Also, during the quieter winter and spring months, as the absence of vocalizations should not be taken as evidence of species absence, making visual observation essential. Additionally, deploying more hydrophones in different locations around the site could improve coverage and help localize individual whales. Collaborative methods that integrate acoustic data with other approaches can enhance understanding of baleen whale seasonal distribution and behavior.

This study has also provided the special opportunity for our research to be informed by the local expertise of Inuit who have lived in this region for generations. Collaborating with partners at the Nunatsiavut Government who have conducted extensive surveys of Inuit knowledge on all types of wildlife in this region, presents an important next step in further gathering and integrating this knowledge to strengthen the conclusions of this work. Collaborative efforts that integrate acoustic data, visual observations, tagging data, and local knowledge will provide a more comprehensive understanding of the seasonal distribution and behavior of these species. Future studies could focus on refining methodologies to improve year-round monitoring of marine mammals in the Arctic, enhancing our ability to track their spatial and temporal patterns.

iii. Key Findings

This study provides the first ever year-round acoustic insights into the presence of multiple baleen whale species in the Torngat Area of Interest, including fin, sei, humpback, and bowhead whales. Passive acoustic monitoring (PAM) has proven to be a valuable method for tracking the seasonal and daily patterns of these species, particularly when visual surveys are limited by harsh weather, ice cover, and reduced daylight. While this study focused on acoustic presence, sea ice concentration, solar elevation angle, and flow noise over a single year, the findings indicate that baleen whale vocal activity increases during ice-free periods, especially in the fall. This pattern suggests that open-water conditions may support both seasonal foraging and breeding activity, though analyzing multiple consecutive years of data would help confirm these relationships. Additionally, the acoustic data collected offers important insights into the vocal behavior of these species, including call characteristics and their connection to environmental factors like sea ice and solar elevation. Combining PAM with boat-based and aerial surveys during the open-water season, along with tagging efforts in winter when whales are more difficult to observe, would provide a more complete picture of their spatial and temporal distribution in the TAOI.

The Arctic is rapidly changing due to global warming, with shrinking sea ice and shifting ocean conditions potentially altering baleen whale distribution and behavior as they adapt to new habitats and resources. PAM will be a key tool in assessing how these shifts impact the distribution and behavior of baleen whales in the region. Year-round monitoring that integrates acoustic, visual, and environmental data with Inuit knowledge is essential for understanding these changes. Expanding efforts now are critical to protecting these species, understanding the long-term ecological impacts on our oceans, and supporting Inuit communities dependent on marine life.

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