

Knock Knock, Who's There? Using Passive Acoustic Monitoring to Investigate the Vocal Presence of Arctic Marine Mammals and the Effects of Shipping on Walrus Vocal Activity in Foxe Basin, Nunavut.

by
Marine May Li Cailleau

A Thesis submitted to the Faculty of Graduate and Postdoctoral Studies of The University of
Manitoba

In partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Department of Environment and Geography,
Centre for Earth Observation Science (CEOS),
University of Manitoba
Winnipeg

August 2026

Copyright © 2026 by Marine Cailleau

Abstract

Sound is an important parameter in the marine environment. Foxe Basin, Nunavut, sustains a diverse community of Arctic marine mammals, including the Atlantic walrus (*Odobenus rosmarus rosmarus*), bowhead whale (*Balaena mysticetus*), beluga whale (*Delphinapterus leucas*), bearded seal (*Erignathus barbatus*), and ringed seal (*Pusa hispida*), all of which vocalize. Passive acoustic monitoring can be used to better understand these species and their relationship to their environment. The Atlantic walrus, in particular, holds significant cultural and ecological importance in Foxe Basin. As shipping is expected to increase in the region, its potential vulnerability to vessel disturbance remains largely undocumented. In the first data chapter, two hydrophones were deployed at two sites in Foxe Basin over a full year (2023-2024) to characterize daily vocal presence of multiple marine mammal species and evaluate the influence of environmental covariates. Walrus and bearded seal vocalizations were detected year-round, with peaks during the breeding season, whereas bowhead and beluga whale vocalizations were seasonal, reflecting summer migration and winter occurrence, respectively. Ringed seal vocal presence was less frequent. Overall, sea ice concentration emerged as the dominant environmental driver of marine mammal acoustic presence, with species-specific responses reflecting differences in ecological dependence on ice. In the second data chapter, recordings from a single hydrophone were combined with Automatic Identification System (AIS) vessel data during the 2023 shipping season (August-October) to assess the influence of vessel activity on walrus vocal behaviour. Walrus vocalized throughout the monitoring period, but hourly knock detections were 50% lower during the shipping season compared with the period before vessel arrival. Reduced vocal activity was associated with higher vessel speeds and closer vessel proximity, whereas the presence of two or more vessels was associated with increased vocal activity. This could potentially reflect a Lombard effect in walrus in response to elevated ambient noise levels. Together, the results of both data chapters highlight passive acoustic monitoring as a powerful tool to document marine mammal vocal presence, their relationship to the environment, and to identify acoustic response to vessel disturbance. As shipping activity increases, sustained acoustic monitoring will be essential to safeguarding species like the Atlantic walrus.

Dedication

This work is dedicated to my family and friends, who have always supported and encouraged me, even from across the ocean and different time zones. I have been very fortunate to be surrounded by such caring and loving people, and for that, I am deeply grateful.

Plus particulièrement, merci infiniment à mes parents, qui n'ont jamais cessé de croire en moi et sans qui je n'aurais jamais pu partir aussi loin, ni accomplir tout ce chemin dans mes études. Vous êtes la raison pour laquelle je persévère.

Acknowledgements

I would like to thank my supervisors, Dr. M. Marcoux and Dr. W. Bernauer, for their guidance and encouragement throughout this project. A special thank you Dr. C. Matthews for always encouraging his students to be their best, and for his trust and support since the beginning of my master's degree. I would like to thank Dr. J. Iacozza for serving on my committee and contributing to this thesis.

I would also like to thank WWF Canada for their generous financial support and the trust they placed in this project, without which this research would not have been possible.

Thank you to Claire Hornby, Bryanna Sherbo, and Maha Ghazal for their valuable help in the field and for their contributions to our lab. Thank you to Fanny Dupont for her precious assistance with biostatistics and to Veronica Coppolaro for sharing her expertise in walrus acoustics.

Thank you to my fellow students, friends (and roommate): Sarah, Abigail, and Madi. To all three of you, thank you for making these two years so special.

Lastly, I would like to thank Travis Qaunaq, Todd-King Ammaa, and the Igloodik and Sanirajak HTAs for the valuable work you do and for your inspiring commitment to preserving the land and waters.

Table of contents

Abstract.....	ii
Dedication.....	iii
Acknowledgements.....	iii
List of Tables.....	vi
List of Figures.....	vii
Chapter 1 General Introduction	1
1.1 Marine soundscape and passive acoustic monitoring.....	1
1.2 Impact of climate change and increasing vessel traffic.....	2
1.3 Study species: the Atlantic walrus (<i>Odobenus rosmarus rosmarus</i>)	3
1.3.1 General overview	3
1.3.2 Ecology	4
1.3.3 Vocalizations	5
1.3.4 Knowledge Gaps.....	6
1.4 Study area: Northern Foxe Basin	7
1.4.1 Overview.....	7
1.4.2 Significance for Indigenous Communities.....	7
1.4.3 Industrial development	8
1.5 Thesis objectives and structure.....	9
1.6 Literature cited	12
Chapter 2 Year-round passive acoustic monitoring reveals seasonal occurrence, migration timing, and environmental drivers of five Arctic marine mammal species in Foxe Basin, Nunavut.....	22
2.1 Abstract.....	22
2.2 Introduction	23
2.3 Methods	25
2.3.1 Study area.....	25
2.3.2 Acoustic data collection.....	26
2.3.3 Acoustic data analysis.....	28
2.3.4 Environmental covariates	30
2.3.5 Statistical analysis.....	31
2.4 Results.....	32
2.4.1 Study area.....	32
2.4.2 Overall vocal detections across sites.....	32
2.4.3 Influence of environmental parameters on vocal presence.....	37

2.5	Discussion	40
2.5.1	Year-round temporal and spatial acoustic occurrence of five marine mammal species	40
2.5.2	Potential interspecific interactions	47
2.5.3	Limitations.....	49
2.6	Conclusion	50
2.7	Literature cited	51
2.8	Supplementary materials	63
Chapter 3 Impact of vessel traffic and proximity on walrus vocal behaviour in northwest Foxe Basin		68
3.1	Abstract.....	68
3.2	Introduction	69
3.3	Methods.....	73
3.3.1	Study area.....	73
3.3.2	Acoustic data collection.....	76
3.3.3	Acoustic data analysis.....	76
3.3.4	AIS data analysis	77
3.3.5	Statistical analysis.....	79
3.4	Results.....	80
3.4.1	Walrus vocal activity in the study area.....	80
3.4.2	Effect of vessel exposure on walrus vocal activity	82
3.4.3	Effect of vessel characteristics on walrus vocal activity	83
3.5	Discussion	86
3.5.1	Limitations.....	90
3.5.2	Conservation and management implications	91
3.6	Conclusion	93
3.7	Literature cited	94
3.8	Supplementary materials	102
Chapter 4 General Conclusion		112
4.1	Summary	112
4.2	Limitations.....	113
4.3	Directions for future research	114
4.4	Literature cited	116

List of Tables

Table 2.1. Deployment name, coordinates, recording duration, and depth of two hydrophone moorings deployed in Foxe Basin from 2023 to 2024.....	28
Table 2.2 Summary of species-typical call types for five species. Parameters based on previously published literature.....	30
Table 2.3 Number of days with detected vocal presence and associated percentages (%) per species at each site and at both sites combined (i.e. total).....	33
Table 2.4. Parameter estimates from the best-supported model for each species. AR1 refers to the first-order autoregressive correlation structure; ϕ = AR1 correlation parameter. SE = standard error, z = Wald z-statistic. Bold p-values indicate statistical significance of the predictor ($p < 0.05$).....	38
Table S2.1. Model selection results for five species based on AICc. For each species, the five best-supported models are listed. SIC = sea ice concentration; Wind = wind speed; SST = sea surface temperature; x = predictor retained; Δ AICc = difference in AICc from best-supported model; w = Akaike weight. Walrus and bearded seal models include a fixed AR(1) autocorrelation structure across all models tested.....	63
Table 3.1. Summary of vessel transits retained as the closest vessel to the hydrophone FB-IGL1-23 per hour, August-October 2023.....	85
Table 3.2. Parameter estimates from the final negative binomial GLMM for walrus knock counts. SE = standard error, z = Wald z statistic.....	86
Table S3.1 Summary of all ship IDs and transits recorded within the 100 km buffer zone around the hydrophone FB-IGL1-23, Foxe Basin, August-October 2023.....	102
Table S3.2 AIS positions that were interpolated for vessels transiting within 100 km around FB-IGL1-23 during August-October 2023. For each gap between p_0 at time t_0 and p_1 at time t_1 , one position was interpolated per missing hour until the next p_1 was reached. This approach assumes constant linear movement between consecutive observed positions. The number of AIS points is the number of interpolated positions within the corresponding transit.....	103
Table S3.3 Model selection, ranked by AICc, with the ten first best-supported models. + = predictor retained. All models include (1 day) as a random effect.....	104

List of Figures

Figure 2.1. Map of Foxe Basin and the coastal communities, with the two hydrophone locations (FB-IGL1-23 and FB-IGL2-23) deployed during 2023-2024 in the northern part of the basin.....	27
Figure 2.2 Spectrograms showing different species' vocalizations from FB-IGL1-23 and FB-IGL2-23. (A) walrus knocks, (B) bowhead moans, (C) beluga whistles, (D,1) bearded trills, (D,2) ringed seal barks and yelps. Animal illustrations from NOAA Fisheries; available on https://www.fisheries.noaa.gov/findspecies	29
Figure 2.3 Daily acoustic presence of walrus, bowhead whale, beluga, bearded seal, and ringed seal at FB-IGL1-23, with sea ice concentration (blue shading), wind speed (blue line), and sea surface temperature (SST).....	35
Figure 2.4 Daily acoustic presence of walrus, bowhead whale, beluga, bearded seal, and ringed seal at FB-IGL2-23, with sea ice concentration (blue shading), wind speed (blue line), and sea surface temperature (SST).....	36
Figure 2.5 For each species, estimates from each best-supported model of acoustic presence with the retained predictors. Points represent model coefficients and horizontal lines indicate 95% confidence intervals. Open circles = non-significant effects ($p > 0.05$); filled circles = significant effects ($p \leq 0.05$). SIC: sea ice concentration; SST: sea surface temperature; Site: hydrophone site (FB-IGL2-23 vs. FB-IGL1-23).....	39
Figure S2.1 Map of the documented haul-outs (purple square) in Northern Foxe Basin, with the hydrophone location FB-IGL1-23 (blue star), and the communities of Igloodik and Sanirajak. In Inuktitut: Tangle Island is Nuvuklit and Tern Island is Siuraq. Haul-out coordinates were available on CAFF – Arctic Biodiversity Data Service (ABDS): https://geo.abds.is/geonetwork/srv/eng/catalog.search#/metadata/fcdc5e58-3318-4a02-a484-8ecb7cfb66e2	65
Figure S2.2 Diagram of a mooring equipped with a buoy, a hydrophone Soundtrap ST600HF, an acoustic release VEMCO VR2AR, and an anchor. Deployed at FB-IGL1-23 and FB-IGL2-23 between 2023-2024. Drawn on Procreate, version 5.3, Savage Interactive Pty Ltd.	66
Figure S2.3 For each species, the probability of presence in relation to significant environmental predictors. Grey points = individual observations. Lines represent fitted probabilities from the best-supported logistic regression model with 95% confidence intervals (shaded). For species with a significant interaction between two predictors, the curves correspond to low (mean - 1 SD) and high (mean + 1 SD) values of the variable, calculated from the dataset.	67
Figure 3.1 Map of Foxe Basin and the coastal communities, with the hydrophone mooring FB-IGL1-23 location.....	74
Figure 3.2. Ship tracks by vessel type (general cargo ship, chemical tanker, icebreaker, other activities, unknown), from August to October 2023 within a 100 km radius from the hydrophone FB-IGL1-23.....	75
Figure 3.3. Spectrogram of walrus knock from recordings at FB-IGL1-23.....	77

Figure 3.4 Hourly walrus knock detections and vessel presence at hydrophone FB-IGL1-23 deployed in Foxe Basin from August to October 2023. Each cell represents one hour; colour reflects knock count (yellow = low, dark red = high; grey = no detection). Black outlines indicate hours during which at least one vessel was present within 100 km around the hydrophone. Across all three months, outlined cells occurred at all hours of the day with no clear diel preference.....	80
Figure 3.5 Mean knock detections per recording prior shipping season (August 1st to August 23rd, 2023) and during shipping season (August 24th to October 31st, 2023) with 95% CIs from the GLMM. Exposure periods compared with a negative binomial GLMM ($p = 0.004$).....	82
Figure 3.6 Coefficient estimates from the best-supported model and the retained predictors for walrus knock counts. Points represent coefficient estimates on the log scale with 95% confidence intervals. Filled circles = $p < 0.05$; empty circles = $p \geq 0.05$	84
Figure S3.1 Map of the documented haul-outs (purple square) in Northern Foxe Basin, with the hydrophone location FB-IGL1-23 (blue star), and the communities of Igloolik and Sanirajak. In Inuktitut: Tangle Island is Nuvuklit and Tern Island is Siuraq. Haul-outs coordinates were available on CAFF – Arctic Biodiversity Data Service (ABDS): https://geo.abds.is/geonetwork/srv/eng/catalog.search#/metadata/fcdc5e58-3318-4a02-a484-8ecb7cfb66e2	106
Figure S3.2 Map of shipping tracks a 100km around the hydrophone FB-IGL1-23 in northern Foxe Basin during August-October 2023. The different colors represent different ship ID.....	107
Figure S3.3 Diagram of a mooring equipped with a buoy, a hydrophone Soundtrap ST600HF, an acoustic release VEMCO VR2AR, and an anchor. Deployed at FB-IGL1-23 between 2023 and 2024. Drawn on Procreate.....	108
Figure S3.4 Example of interpolated AIS positions (blue points) and three interpolated positions (orange points) for the transit 1 of the Icebreaker (ship ID: 439469789) in September 2023. The inset (top right) shows a close-up of the two interpolated positions nearest the hydrophone FB-IGL1-23 (cyan point). The dashed circle represents the 100 km buffer zone used in the study.....	109
Figure S3.5 Map of shipping tracks, after cleaning the AIS data and interpolating the AIS points, in northern Foxe Basin during (A) August, (B) September, and (C) October 2023. The different colors represent different transit.....	110
Figure S3.6 Predicted walrus knock counts with distance to hydrophone, vessel speed, and vessel category, derived from the negative binomial GLMM. (A) Predicted knock count in relation to distance between the vessel and the hydrophone (km). (B) Predicted knock count in relation to vessel speed (knots). (C) Predicted knock count by vessel category (single vessel vs. multiple vessels). (D) Predicted knock count in relation to vessel speed (knots) at three distances to the hydrophone (13 km, 42 km, and 70 km), chosen to represent the mean and $\pm$ one standard deviation of observed vessel distances to show how the effect of speed on knock counts changes with proximity to the hydrophone. Shaded areas and error bars represent 95% confidence intervals.....	111

Chapter 1 General Introduction

1.1 Marine soundscape and passive acoustic monitoring

Animals rely on sensory information for essential biological functions, such as foraging, mating, predator avoidance, orientation, and maintaining social bonds (Tyack, 2008). In the marine environment, light attenuates rapidly with depth, limiting visibility, whereas sound propagates faster and over greater distances than in air. This physical property has driven the evolution of advanced auditory and vocal adaptations in marine mammals (Duarte et al., 2021). Sound is therefore a fundamental component of their habitat, directly influencing their ability to communicate with conspecifics and interact with their environment (Tyack, 2008). The underwater soundscape is composed of three components: biophony, the sounds produced by living organisms; geophony, sounds originating from the environment such as wind, waves, and sea ice; and anthrophony, any sounds generated by human activities such as shipping (Farina, 2014). Within this soundscape, marine mammals produce a wide diversity of vocalizations, associated with specific behaviours, spanning from low- to high-frequency signals and short- to long-range calls (Richardson et al., 1995; Tyack, 2008; Erbe & Thomas, 2022). Vocalizations, therefore, serve as a reliable proxy for species presence and can provide information on behaviour, seasonal patterns, and habitat use without requiring direct observation (Mellinger et al., 2007; Nanaware et al., 2014). Passive Acoustic Monitoring (PAM) is based on the deployment of autonomous underwater hydrophones that capture the entire marine soundscape, offering a comprehensive picture of the biological, physical, and anthropogenic roles in shaping the marine environment (Cato et al., 2006; Cominelli et al., 2024; Gibb et al., 2019; Mellinger et al., 2007). As a non-invasive tool capable of long-term deployment, PAM is particularly well-suited to Arctic environments, where sea ice, prolonged darkness, and harsh weather restrict access and observational effort outside summer months (Cato et al., 2006; Cominelli et al., 2024; Gibb et al., 2019)

In the Arctic, PAM has been widely applied to monitor individual species, such as bowhead whales (Diogou et al., 2023; Wams et al., 2025), belugas (Castellote et al., 2020; Scharffenberg et al., 2025), walruses (Coppolaro et al., 2024; Mouy et al., 2012), and bearded seals (Frouin-Mouy et al., 2016; MacIntyre et al., 2013). PAM has also been used for multi-species acoustic monitoring (Chou et al., 2020; Coppolaro et al., 2024; De Vreese et al., 2018; Halliday et al., 2017a; Marcoux et al., 2017; Mattmüller et al., 2022). As highly specialized species, Arctic marine mammals are closely tied to their physical environment; therefore, long-term acoustic monitoring datasets are particularly valuable for examining how environmental variables shape marine mammal acoustic presence across time and space, as investigated in this thesis for Foxe Basin.

1.2 Impact of climate change and increasing vessel traffic

Arctic marine environments and the marine mammals that rely on them are increasingly affected by climate change and increasing industrial and commercial shipping (Hauser et al., 2018; Laidre et al., 2008). Over the past decade, Arctic sea ice has reached record-low levels, transitioning from perennial to seasonal ice cover with longer open-water seasons (Chou et al., 2020; Stroeve & Notz, 2018), leading to the spatiotemporal expansion of shipping routes across previously remote areas (Chou et al., 2020; Llobet et al., 2023; Taylor et al., 2023). Vessel traffic can cause ship strikes, drive displacement of animals from habitat, and lead to physiological stress and mortality (Bejder et al., 2006; Ferrari et al., 2026; Jansen et al., 2010; Laist et al., 2001; Lemos et al., 2022; Nichol et al., 2017). Marine vessels generate underwater noise primarily through propeller cavitation, machinery, and flow, producing broadband low-frequency sounds that can propagate over large distances (Aktas, 2016; Smith & Rigby, 2022). Underwater noise can overlap with the hearing and vocalization range of many marine mammals (Erbe, 2012; Khopkar et al., 2026). Shipping corridors also overlap with species' habitats (Halliday et al., 2017b), suggesting broader effects on migration paths and timing, breeding grounds, and foraging grounds. Prolonged exposure to vessel noise, especially at low frequency, can cause temporary or permanent shifts in hearing thresholds in marine mammals (Hildebrand, 2005; Southall et al., 2019). Increasing

underwater noise levels can interfere with marine mammal communication through acoustic masking (Brewer et al., 2023; Erbe, 2012; PAME, 2021), reducing communication range (Putland et al., 2017), altering signal structure (Holt et al., 2009, 2012; Maciel et al., 2026; Rolland et al., 2012), and driving changes in calling rates (Arranz et al., 2021; Hastie et al., 2021; Pirotta et al., 2012; Romano et al., 2011).

In cetaceans, elevated shipping noise has been associated with reduced communication ranges in beluga whales in the St. Lawrence Estuary (Gervaise et al., 2012), increased vocalization amplitude in North Atlantic right whales in response to rising ambient noise levels (Parks et al., 2011), and decreased vocal presence in narwhals with vessel proximity (Ewing et al., 2025). Pinnipeds show similar responses, including reduced vocalization amplitude in harp seals in the presence of vessels (Terhune et al., 1979) and altered dive behaviour in harbour and grey seals exposed to vessel noise (Mikkelsen et al., 2019). These numerous impacts underscore the need for continued acoustic monitoring in regions facing increasing industrial pressure, especially for species sensitive to disturbance.

1.3 Study species: the Atlantic walrus (*Odobenus rosmarus rosmarus*)

1.3.1 General overview

The walrus, known as *aivik* in Inuktitut, is a large pinniped and the only extant member of the family Odobenidae. The species is recognizable by its pair of elongated upper canine teeth into tusks (Berta et al., 2018). Two subspecies are recognized: the Pacific walrus (*Odobenus rosmarus divergens*) and the Atlantic walrus (*Odobenus rosmarus rosmarus*) (Linnaeus, 1758). The Atlantic walrus was listed as a species of “*Special Concern*” in 2006 and 2017 by the Committee on the Status of Endangered Wildlife in Canada for both the High Arctic/Baffin Bay and Central/Low Arctic populations (COSEWIC, 2006, 2017).

The Atlantic walrus has a discontinuous distribution across the Arctic and sub-Arctic (Higdon et al., 2022). In Canada, its total abundance has been estimated at 21,400, although it is believed to be underestimated due to a lack of survey coverage (COSEWIC, 2017). Based on genetics and tissue stable isotope composition, the Atlantic walrus in Canada is divided into two populations: the High Arctic Canada/Baffin Bay and the Central/Low Arctic Canada (DFO, 2002, 2019; Garde and Hansen, 2021). Each of these populations is divided into three management units (stocks). The High Arctic population comprises the Baffin Bay (BB), West Jones Sound (WJS) and Penny Strait-Lancaster Sound (PS-LS) stocks. The Central Arctic comprises the Foxe Basin (FB) and Hudson Bay-Davis Strait (HB-DS), and south and east Hudson Bay stocks (Stewart, 2008). The FB walrus stock is one of Canada's largest, with an abundance estimated at 13,452 (Stewart et al., 2013)

1.3.2 Ecology

Walruses are highly gregarious and can form large aggregations of thousands at haul-out sites (*uglit* in Inuktitut) (Stewart et al., 2016), where they rest, moult, nurse, breed, and have access to foraging grounds (Mansfield, 1958; Born and Acquarone, 2007; Hamilton et al., 2015). Although haul-out behaviour is central to walrus ecology, individuals spend substantial time at sea: in Svalbard, walruses spent approximately 83% of their time in the water (Gjertz et al., 2001), and in Greenland, 50-65% of their time was spent actively diving (Born et al., 2005). Walruses typically inhabit shallow, productive continental shelves, where they can dive to forage in waters less than 100 meters deep. Individuals use their vibrissae to detect and feed on benthic invertebrates including *Mya truncata* and *Macoma calcaria* (Mansfield, 1958; Fisher, 1989; Born et al., 1995; Fisher and Stewart, 1997). Due to its specialized benthic diet, the walrus occupies a narrow ecological niche. Although walruses are primarily benthic feeders, occasional predation on ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*) has been reported (Lowry & Fay, 1984; Seymour et al., 2014). Beyond foraging, the marine environment is also used for social interactions and reproduction; during the winter mating season, males vocalize extensively and

engage in competitive displays underwater to establish dominance and gain access to female groups (Sjare et al., 2003; Sjare & Stirling, 1996). Most walrus studies have focused on behaviour at haul-out sites, leaving underwater behaviour comparatively under-documented, a gap that PAM can address.

1.3.3 Vocalizations

On land, *grunts* and *roars* are associated with agonistic behaviour, *barks* are indicative of submission in adult individuals, distress in juveniles or mother-pup contact calls (Verboom et al., 1995; Charrier, 2021; Charrier et al., 2010, 2011; Miksis-Olds et al., 2016; Miller and Kochnev, 2021). Although walruses of both sexes and all ages are known to emit airborne vocalizations, only males have been reported, other than captive individuals (Schusterman and Reichmuth, 2008), to produce underwater calls, including *knocks* (low-frequency pulses, 0.5-15 repetitions per second, 0.2-8.0 kHz), *bell sounds* (metallic tonal sound, marking the beginning or the end of a song, lasting 1-2 seconds, 40-1200 Hz), *whistles* (tonal sound, emitted at the surface of water by blowing air while breathing), and *grunts* (low-frequency, < 1kHz) (Ray and Watkins, 1975; Sjare and Stirling, 1996; Sjare et al., 2003; Miksis-Olds et al., 2016; Larsen and Reichmuth, 2021; Panova et al., 2026). Other underwater calls in Pacific walrus have been described as *snorts*, *tones*, *rasps*, *moans*, and *chuffs*, although their function is not yet well understood (Schusterman and Reichmuth, 2008; Charrier, 2021).

Knock calls are produced by the lower jaw striking the upper jaw repeatedly (Larsen and Reichmuth, 2021; Miller and Kochnev, 2021). Knocks are impulsive vocalizations, meaning short duration sounds with a broad frequency range (Stirling et al., 1987; Rideout et al., 2013). The high amplitude of knocks enables sound propagation over several kilometres (Stirling et al., 1983; Sjare et al., 2003). A stereotypical series of repeated knocks punctuated by a bell sound and/or whistle is emitted by the dominant males, used to monopolize access to a female herd (Sjare et al., 2003). During the mating season in winter, from February to April, polygynous males engage in intense

competition for reproduction, establishing dominance, underwater territory and attracting females through these calls (Sjare and Stirling, 1996; Kovacs, 2015; COSEWIC, 2017). Recent studies using PAM have recorded knock calls outside of the breeding period and throughout the year (Mouy et al., 2012; Hannay et al., 2013; Coppolaro et al., 2024; Panova et al., 2026), suggesting that walruses are acoustically active year-round.

1.3.4 Knowledge Gaps

The International Union for Conservation of Nature (IUCN) classified the walrus as “*Near threatened*” (Kovacs, 2016). Significant knowledge gaps remain regarding walrus ecology, especially in acoustic behaviour, key areas for mating and foraging, and the potential impacts of increasing anthropogenic noise. To date, most of the acoustic studies have focused on the Pacific walrus (Fay, 1982, 1984, 1985; Verboom et al., 1995; Kastelein et al., 2002; Schusterman and Reichmuth, 2008; Mouy et al., 2012; Rideout et al., 2013; Chou et al., 2020; Reichmuth et al., 2020; Larsen and Reichmuth, 2021). Detailed descriptions of walrus vocal repertoire have relied on captive individuals (Charrier et al., 2011; Denes, 2014; McCord et al., 2016). Although PAM has been used in several recent studies of Atlantic walruses in the Canadian Arctic (Marcoux et al., 2017; Chou et al., 2020; Coppolaro et al., 2024; Folz, 2024), most of the studies have reviewed the vocal behaviour during the breeding season (Fay et al., 1984; Stirling et al., 1987; Sjare and Stirling, 1996; Sjare et al., 2003). Acoustic datasets outside of this period remain scarce, limiting our understanding of year-round vocal behaviour and habitat use. While the effects of shipping noise on walruses have been investigated using telemetry approaches (Taylor et al., 2023), only one study, to our knowledge, has examined these impacts using acoustic methods (Coppolaro et al., 2025). As a result, the influence of increasing vessel traffic on walrus communication and behaviour remains poorly understood.

1.4 Study area: Northern Foxe Basin

1.4.1 Overview

Foxe Basin is a shallow oceanic basin bordered by Baffin Island, the Melville Peninsula, and Southampton Island, Nunavut. It connects northward to the Arctic Ocean via the Gulf of Boothia and Fury and Hecla Strait, and southward to the Labrador Sea through Foxe Channel and Hudson Strait (Drinkwater, 1986). Sea ice dominates Foxe Basin from November to June. Freeze-up typically begins in mid- to late October, while break-up occurs in July or August (Babb et al., 2026; Hochheim & Barber, 2014).

The northwest portion of the basin contains persistent and seasonal polynyas that enhance local productivity and provide critical habitat for a diverse marine mammal community (Ford et al., 2009; Gough, 2025). The area is a year-round habitat for walrus, bearded seals, and ringed seals, which rely on the productive benthic and sympagic communities of the region. It also serves as a seasonal habitat and nursing ground for bowhead whales and falls within the seasonal range of beluga whales (Paulic et al., 2014).

1.4.2 Significance for Indigenous Communities

Along the shores of Foxe Basin, the communities of Igloodik (Iglulik, ᐃᓄᓗᓕᓴᓴ) and Sanirajak (ᓴᓄᓴᓴ) have long relied on the marine environment for subsistence and cultural continuity. The rich diversity of marine mammals and fishes allows Inuit to harvest bowhead whales, belugas, narwhals, walruses, bearded and ringed seals, and Arctic char (Ford et al., 2009). The marine environment and its wildlife remain to this day fundamental to these coastal communities, through the consumption of traditional foods such as *maktaaq* and *iqunaq*. Among these species, the Atlantic walrus holds a specific cultural and historical significance. Archaeological evidence indicates that walruses have been harvested since the Thule culture (ca. AD 1200 to 1500 in the Foxe Basin region), the direct ancestor of modern Inuit (Bennett and Rowley, 2004; Desjardins, 2013). Foxe Basin was a major walrus hunting area, but overexploitation by European sealers and

whalers increasingly targeted walrus as bowhead whale populations declined (Bennett and Rowley, 2004; Martini and Morrison, 2014; Garde and Hansen, 2021). This shift led to substantial population declines, with an estimated 41,300 walrus harvested over 200 years in the eastern Canadian Arctic (Stewart et al., 2014). Consequently, commercial walrus hunting was banned in Canada in 1928 by the Walrus Protection Regulations, restricting hunting to Inuit communities (Born et al., 1995; Wiig et al., 2014). Today, walrus harvesting remains an important cultural, nutritional, and economic activity for Inuit across Nunavut, with walrus harvested by 21 communities. Limited sport hunting also occurs, mainly in Coral Harbour (Salliᑦ, ᓴᓴᓴᓴ). In Igloodik, sport hunting and walrus tourism activity were suspended temporarily between 2008 and 2010, following observations of disturbance and displacement of walrus associated with these activities (Higdon et al., 2022). Sanirajak and Igloodik had the highest harvest rates (sport and traditional hunts combined) across Nunavut from 1997 to 2017, with an average of 69 and 83 catches per year, respectively, of which the majority were subsistence harvests (Matthews et al., 2018). Despite a decline in country food consumption, walrus products (like *igunaq*) remain culturally significant for many (Martinez-Levasseur et al., 2020). Climate change and increasing anthropogenic activities may directly or indirectly impact walrus populations, hunting success, and food security (Krupnik and Ray, 2007). Understanding walrus ecology and behaviour near the communities of Igloodik and Sanirajak is essential for supporting Indigenous livelihoods and sustaining culturally important practices.

1.4.3 Industrial development

Although vessel traffic in Foxe Basin is currently limited, industrial development in the eastern Canadian Arctic is expected to increase shipping activity in the region. The Mary River iron ore mine, operated by Baffinland Iron Mines Corporation (“Baffinland”), currently exports approximately 4.5 million tonnes (MT) of iron ore annually from Milne Inlet during the July-October shipping season (Baffinland, 2026). The proposed expansion of the mine (“Mary River Project”)

would increase exports to up to 18 MT of iron ore per year. This expansion would involve the construction of a railway leading to a new port at Steensby Inlet, resulting in year-round vessel traffic and icebreaking activities over a planned operational period of approximately 21 years (BIMC, NIRB, 2012; Martini and Morrison, 2014). The environmental assessment was accepted by the federal government in 2012 (BIMC, 2012). Potential effects include soil and air quality degradation, habitat disturbance, and cumulative impacts on both terrestrial and marine wildlife (DFO, 2012). Particular concerns have been raised regarding the effects of increased vessel traffic on marine mammals. As one elder expressed: “I am mostly concerned about the marine mammal. They are going to be greatly disturbed from the sound, from the noise, because I’m talking, speaking from my own knowledge, what I have seen” (NIRB, 2012a, p. 1926). These concerns have gained further support as a study has documented changes in narwhal surface movement and dive behaviour in response to vessel encounters in Eclipse Sound following the onset of Baffinland operations (Golder Associates Ltd., 2020). Changes in narwhal acoustic presence in response to vessel activity have also been reported in Eclipse Sound (Ewing et al., 2025). The proposed expansion has intensified concerns and controversy among communities regarding potential environmental and social impacts, particularly on the marine environment and the wildlife that supports Inuit livelihoods (Bernauer, 2025; Rodon & Bouchard, 2024). The Mary River Project illustrates a global trend of industrial expansion across the Arctic. Documenting the effects of vessel traffic on species such as the walrus has direct implications for the communities that depend on them for traditional harvesting, food security, and Inuit knowledge transmission.

1.5 Thesis objectives and structure

The overall objective of this thesis is to improve the understanding of marine mammal ecology and habitat use in Foxe Basin, especially for walrus, using passive acoustic monitoring. This research aims to (1) characterize the year-round acoustic presence and seasonal patterns of five marine mammals in Foxe Basin, (2) examine how environmental variables influence their acoustic presence, (3) compare walrus vocal activity before and during the shipping season, and

(4) assess whether vessel characteristics (e.g., vessel type, speed, and distance) influence walrus vocal activity.

This thesis is organized into two data chapter. The first one (Chapter 2) is a year-round acoustic monitoring dataset of Foxe Basin. This chapter documents the acoustic presence and seasonal patterns of five marine mammal species: walrus, bowhead whale, beluga, bearded and ringed seals. It also investigates how environmental variables, including sea ice concentration, sea surface temperature, and wind speed, influence the acoustic presence of these species. Walrus and bearded seal vocalizations dominated the acoustic recordings, with peak vocal presence during the breeding season, whereas bowhead and beluga whale vocalizations were seasonal, reflecting summer migration and winter occurrence. Ringed seal vocalizations were sporadic. Sea ice concentration emerged as the dominant environmental driver for multiple species, with contrasting effects reflecting each species' ecological dependence on ice.

The following data chapter (Chapter 3) focuses on the potential influence of vessel traffic on walrus vocal behaviour in northwest Foxe Basin. The chapter quantifies vessel activity within a key walrus habitat and assesses whether vessel exposure and vessel characteristics (e.g., vessel type, size, speed, and proximity) can influence walrus vocal activity. By examining the relationship between shipping and walrus vocal behaviour, this chapter provides new insights into how increasing vessel traffic may influence walrus acoustic behaviour in the region. Walrus vocal activity was significantly reduced during the shipping season compared to the period preceding the first vessel arrival. During the shipping season, lower vocal activity was associated with higher vessel speeds and closer vessel proximity to the hydrophone, while the presence of multiple vessels was associated with increased vocal activity.

These findings address knowledge gaps by documenting the acoustic diversity of Foxe Basin and demonstrating the effects of vessel activity on walrus acoustic behaviour. Furthermore, this study contributes valuable knowledge to inform the conservation of species that are both

important to the ecosystem and Inuit communities. The thesis also supports the development of proactive conservation measures for Atlantic walruses, including shipping regulations and mitigation strategies that allow Inuit to balance their conservation and development priorities, as vessel activity increases in Foxe Basin.

1.6 Literature cited

- Aktas, B. (2016). *A Systematic Experimental Approach to Cavitation Noise prediction of marine mammals*. Newcastle University.
- Arranz, P., Glarou, M., & Sprogis, K. R. (2021). Decreased resting and nursing in short-finned pilot whales when exposed to louder petrol engine noise of a hybrid whale-watch vessel. *Scientific Reports* 2021 11:1, 11(1), 21195-. <https://doi.org/10.1038/s41598-021-00487-0>
- Babb, D., Kirillov, S., Galley, R., & Ehn, J. (2026). Sea Ice Dynamics in Foxe Basin: Formation of a Thick Dirty Seasonal Ice Cover along a Proposed Year-Round Shipping Route. *Arctic Science*. <https://doi.org/10.1139/AS-2026-0008>
- Baffinland. (2026). *Baffinland Iron Mines 2025 Annual Report to the Nunavut Impact Review Board*. https://baffinland.com/_resources/document_portal/2025-NIRB-Annual-Report.pdf
- Bejder, L., Samuels, A., Whitehead, H., Gales, N., Mann, J., Connor, R., Heithaus, M., Watson-Capps, J., Flaherty, C., & Krützen, M. (2006). Decline in relative abundance of bottlenose dolphins exposed to long-term disturbance. *Conservation Biology*, 20(6), 1791–1798. <https://doi.org/10.1111/J.1523-1739.2006.00540.X>
- Bennett, J. R., & Rowley, S. (2004). *Uqalurait: An oral history of Nunavut* (Vol. 36). McGill-Queen's Press-MQUP.
- Bernauer, W. (2025). Against Fast-Tracking: Critical Minerals and Indigenous Rights in Nunavut. *Northern Review*, 57(57), 23–49–23–49. <https://doi.org/10.22584/NR57.2025.006>
- Berta, A., Churchill, M., & Boessenecker, R. W. (2018). The Origin and Evolutionary Biology of Pinnipeds: Seals, Sea Lions, and Walruses. *Annual Review of Earth and Planetary Sciences*, 46(Volume 46, 2018), 203–228. <https://doi.org/10.1146/annurev-earth-082517-010009>
- BIMC (Baffinland Iron Mines Corporation). (2012). *Mary River Project final environmental impact statement*. NIRB File No.: 08MN053.
- Born, E. W., & Acquarone, M. (2007). An estimation of walrus (*Odobenus rosmarus*) predation on bivalves in the Young Sound area (NE Greenland). In: Rysgaard, S. & Glud, R. N. (Eds.), Carbon cycling in Arctic marine ecosystems: Case study Young Sound. Meddr. Grønland, Bioscience 58: 176-191. In *Bioscience* (Vol. 58).
- Born, E. W., Acquarone, M., Knutsen, L. Ø., & Toudal, L. (2005). Homing Behaviour in an Atlantic Walrus (*Odobenus rosmarus rosmarus*). *Aquatic Mammals*, 31(1), 23–33. <https://doi.org/10.1578/am.31.1.2005.23>
- Born, E. W., Gjertz, I., & Reeves, R. R. (1995). *Population assessment of Atlantic walrus (Odobenus rosmarus rosmarus L.)*.
- Brewer, A. M., Castellote, M., Van Cise, A. M., Gage, T., & Berdahl, A. M. (2023). Communication in Cook Inlet beluga whales: Describing the vocal repertoire and masking of calls by commercial ship noise. *The Journal of the Acoustical Society of America*, 154(5), 3487–3505. <https://doi.org/10.1121/10.0022516>
- Castellote, M., Small, R. J., Lammers, M. O., Jenniges, J., Mondragon, J., Garner, C. D., Atkinson, S., Delevaux, J. M. S., Graham, R., & Westerholt, D. (2020). Seasonal distribution and

- foraging occurrence of Cook Inlet beluga whales based on passive acoustic monitoring. *Endangered Species Research*, 41, 225–243. <https://doi.org/10.3354/ESR01023>
- Cato, D., Mccauley, R., Rogers, T., & Noad, M. (2006). Passive acoustics for monitoring marine animals-progress and challenges. *Proceedings of ACOUSTICS*.
- Charrier, I. (2021). Vocal communication in otariids and odobenids. In *Ethology and behavioral ecology of otariids and the odobenid* (pp. 265–289). Cham: Springer International Publishing.
- Charrier, I., Aubin, T., & Mathevon, N. (2010). Mother-calf vocal communication in Atlantic walrus: A worst experimental study. *Animal Cognition*, 13(3), 471–482. <https://doi.org/10.1007/s10071-009-0298-9>
- Charrier, I., Burlet, A., & Aubin, T. (2011). Social vocal communication in captive Pacific walruses *Odobenus rosmarus divergens*. *Mammalian Biology*, 76(5), 622–627. <https://doi.org/10.1016/j.mambio.2010.10.006>
- Chou, E., Antunes, R., Sardelis, S., Stafford, K. M., West, L., Spagnoli, C., Southall, B. L., Robards, M., & Rosenbaum, H. C. (2020a). Seasonal variation in Arctic marine mammal acoustic detection in the northern Bering Sea. *Marine Mammal Science*, 36(2), 522–547. <https://doi.org/10.1111/mms.12658>
- Cominelli, S., Bellin, N., Brown, C. D., Rossi, V., & Lawson, J. (2024). Acoustic features as a tool to visualize and explore marine soundscapes: Applications illustrated using marine mammal passive acoustic monitoring datasets. *Ecology and Evolution*, 14(2). <https://doi.org/10.1002/ece3.10951>
- Coppolaro, V. L. M., Ausen, E. L., Loseto, L. L., & Marcoux, M. (2025). Vessel traffic disrupts walrus vocal behavior in a proposed marine protected area. *Frontiers in Marine Science*, 12. <https://doi.org/10.3389/fmars.2025.1658328>
- Coppolaro, V. L. M., Gupta, K., Loseto, L., Mundy, C. J., & Marcoux, M. (2024). Seasonal and diurnal marine mammal presence in the proposed marine protected area of Southampton Island, Hudson Bay, Nunavut as revealed by passive acoustic monitoring. *Arctic Science*, 10(3), 520–544.
- COSEWIC. (2006). *COSEWIC assessment and update status report on the Atlantic walrus, Odobenus rosmarus rosmarus, in Canada*. Committee on the Status of Endangered Wildlife in Canada.
- COSEWIC. (2017). *COSEWIC Assessment and Status Report Atlantic Walrus Odobenus rosmarus rosmarus High Arctic population Central-Low Arctic population Nova Scotia-Newfoundland-Gulf of St. Lawrence population in Canada High Arctic population-SPECIAL CONCERN Central-Low Arctic population-SPECIAL CONCERN Nova Scotia-Newfoundland-Gulf of St. Lawrence population-EXTINCT 2017*. www.sararegistry.gc.ca/status/status_e.cfm
- De Vreese, S., van der Schaar, M., Weissenberger, J., Erbs, F., Kosecka, M., Solé, M., & André, M. (2018). Marine mammal acoustic detections in the Greenland and Barents Sea, 2013 – 2014 seasons. *Scientific Reports* 2018 8:1, 8(1), 16882-. <https://doi.org/10.1038/s41598-018-34624-z>

- Denes, S. L. (2014). *Ocean environmental effects on walrus communication*. The Pennsylvania State University.
- Desjardins, S. P. A. (2013). Evidence for intensive walrus hunting by Thule Inuit, northwest Foxe Basin, Nunavut, Canada. *Anthropozoologica*, 48(1), 37–51. <https://doi.org/10.5252/az2013n1a2>
- DFO. (2002). *Atlantic Walrus. Stock Status Report. E5-17, 18, 19, 20.* https://www.researchgate.net/publication/315014053_Review_of_Atlantic_walrus_Odobenus_rossmarus_in_Canada
- DFO. (2012). *Technical Review of Baffinland's Mary River Project Draft Environmental Impact Statement (EIS)*.
- DFO. (2019). *Mitigation Buffer Zones for Atlantic Walrus (Odobenus rosmarus rosmarus) in the Nunavut Settlement Area*.
- Diogou, N., Halliday, W. D., Dosso, S. E., Mouy, X., Niemi, A., & Insley, S. J. (2023). Bowhead whale year-round acoustic presence and habitat associations in the Amundsen Gulf, Western Canadian Arctic, 2018–2019. *Progress in Oceanography*, 213. <https://doi.org/10.1016/j.pocean.2023.103004>
- Drinkwater, K. F. (1986). Physical oceanography of Hudson strait and Ungava Bay. In *Elsevier oceanography series* (Vol. 44, pp. 237–264). Elsevier.
- Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., & Harding, H. R. (2021). The soundscape of the Anthropocene ocean. *Science*, 371(6529), eaba4658.
- Erbe, C. (2012). Effects of underwater noise on marine mammals. *The Effects of Noise on Aquatic Life*, 17–22.
- Erbe, C., & Thomas, J. A. (2022). *Exploring Animal Behavior Through Sound: Volume 1* (Vol. 1).
- Ewing, J. P., Hidalgo-Pla, E., Solsona-Berga, A., Frasier, K. E., Ootoowak, A. J., Westdal, K. H., Wiggins, S. M., Hildebrand, J. A., & Jones, J. M. (2025). Narwhal acoustic presence in Eclipse Sound, Nunavut: relationships with sea ice and responses to ships. *Scientific Reports* 2025 15:1, 15(1), 23126-. <https://doi.org/10.1038/s41598-025-04032-1>
- Farina, A. (2014). *Soundscape Ecology Principles, Patterns, Methods and Applications*.
- Fay, F. H. (1982). Ecology and biology of the Pacific walrus, *Odobenus rosmarus divergens* Illiger. *North American Fauna*, (74), 1–279.
- Fay, F. H. (1985). *Odobenus rosmarus*. *Mammalian Species*, (238), 1–7. <https://doi.org/10.2307/3503810>
- Fay, F. H., Ray, G. C., & Kibal'chich, A. A. (1984). Time and location of mating and associated behavior of the Pacific walrus, *Odobenus rosmarus divergens* Illiger. *Soviet-American Cooperative Research on Marine Mammals*, 1, 89–99.

- Ferrari, V., Hague, E., Sciberras, M., Alexander, K. A., O'Hara, P. D., & McWhinnie, L. (2026). Exploring the evidence of direct threats to cetaceans from maritime vessels: A systematic map. *PLOS ONE*, 21(5), e0348502. <https://doi.org/10.1371/JOURNAL.PONE.0348502>
- Fisher, K. 1, & Stewart, R. E. A. (1997). *Summer foods of Atlantic walrus, Odobenus rosmarus rosmarus, in northern Foxe Basin, Northwest Territories*. www.nrcresearchpress.com
- Fisher, K. I. (1989). *Food habits and digestive efficiency in walrus, Odobenus rosmarus*. Thesis (M.Sc). University of Manitoba.
- Folz, N. M. (2024). *Tusâven aivik and utjuk? Observing bearded seal and walrus seasonal presence and underwater sounds from year-round ocean acoustic recordings in the Torngat Area of Interest, Nunatsiavut, Canada* [University of California San Diego]. <https://escholarship.org/uc/item/7tc8m1dn>
- Ford, J. D., Gough, W. A., Laidler, G. J., MacDonald, J., Irngaut, C., & Qrunnut, K. (2009). Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. *Climate Research*, 38(2), 137–154. <https://doi.org/10.3354/cr00777>
- Frouin-Mouy, H., Mouy, X., Martin, B., & Hannay, D. (2016). Underwater acoustic behavior of bearded seals (*Erignathus barbatus*) in the northeastern Chukchi Sea, 2007-2010. *Marine Mammal Science*, 32(1), 141–160. <https://doi.org/10.1111/mms.12246>
- Garde, E., & Hansen, R. G. (2021). Stocks, distribution and abundance. In *The Atlantic Walrus: Multidisciplinary Insights into Human-Animal Interactions* (pp. 77–95). Elsevier. <https://doi.org/10.1016/B978-0-12-817430-2.00011-X>
- Gervaise, C., Simard, Y., Roy, N., Kinda, B., & Ménard, N. (2012). Shipping noise in whale habitat: Characteristics, sources, budget, and impact on belugas in Saguenay–St. Lawrence Marine Park hub. *The Journal of the Acoustical Society of America*, 132(1), 76–89. <https://doi.org/10.1121/1.4728190>
- Gibb, R., Browning, E., Glover-Kapfer, P., & Jones, K. E. (2019). Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. In *Methods in Ecology and Evolution* (Vol. 10, Number 2, pp. 169–185). British Ecological Society. <https://doi.org/10.1111/2041-210X.13101>
- Gjertz, I., Griffiths, D., Krafft, B. A., Lydersen, C., & Wiig. (2001). Diving and haul-out patterns of walruses *Odobenus rosmarus* on Svalbard. *Polar Biology*, 24(5), 314–319. <https://doi.org/10.1007/s0030000000211>
- Golder Associates Ltd. (2020). *Mary River Project 2017–2018 Integrated Narwhal Tagging Study – Technical Data Report*. https://www.baffinland.com/_resources/document_portal/1663724-188-R-Rev0-12000-BIM-2017-2018-Integrated-Narwhal-Tagging-Study-14AUG-20.pdf
- Gough, W. A. (2025). A Marine Season Metric for Foxe Basin, Nunavut, Canada: Insights into the Evolving Nature of Sea-Ice Breakup and Freeze-Up. *Coasts*, 5(1). <https://doi.org/10.3390/coasts5010007>
- Halliday, W. D., Insley, S. J., de Jong, T., & Mouy, X. (2017a). Seasonal patterns in acoustic detections of marine mammals near Sachs Harbour, Northwest Territories. *Arctic Science*, 1–20. <https://doi.org/10.1139/as-2017-0021>

- Halliday, W. D., Insley, S. J., Hilliard, R. C., De Jong, T., & Pine, M. K. (2017b). Potential impacts of shipping noise on marine mammals in the western Canadian arctic. *Marine Pollution Bulletin*, 123(1–2), 73–82.
- Hamilton, C. D., Kovacs, K. M., & Lydersen, C. (2015). Year-round haul-out behaviour of male walrus *Odobenus rosmarus* in the Northern Barents Sea. *Marine Ecology Progress Series*, 519, 251–263. <https://doi.org/10.3354/meps11089>
- Hannay, D. E., Delarue, J., Mouy, X., Martin, B. S., Leary, D., Oswald, J. N., & Vallarta, J. (2013). Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011. *Continental Shelf Research*, 67(4), 127–146. <https://doi.org/10.1016/j.csr.2013.07.009>
- Hastie, G. D., Lepper, P., McKnight, J. C., Milne, R., Russell, D. J. F., & Thompson, D. (2021). Acoustic risk balancing by marine mammals: anthropogenic noise can influence the foraging decisions by seals. *Journal of Applied Ecology*, 58(9), 1854–1863. <https://doi.org/10.1111/1365-2664.13931>
- Hauser, D. D. W., Laidre, K. L., & Stern, H. L. (2018). Vulnerability of arctic marine mammals to vessel traffic in the increasingly ice-free northwest passage and Northern Sea Route. *Proceedings of the National Academy of Sciences of the United States of America*, 115(29), 7617–7622. <https://doi.org/10.1073/pnas.1803543115>
- Higdon, J. W., Stewart, D. B., & Stewart, R. E. A. (2022). *Atlantic walrus (Odobenus rosmarus rosmarus) in northern Hudson Bay-status, research needs, and monitoring opportunities Prepared for Oceans North under contract to Higdon Wildlife Consulting* (.).
- Hildebrand, J. A. (2005). Impact of anthropogenic sound. In Reynolds, J.E. et al. (ed.) *Marine mammal research: Conservation beyond crisis*. (pp. 101–124). The Johns Hopkins University Press, Baltimore, Maryland.
- Hochheim, K., & Barber, D. (2014). An update on the ice climatology of the Hudson Bay system. *Arctic, Antarctic, and Alpine Research*, 46(1), 66–83. <https://doi.org/10.1657/1938-4246-46.1.66>
- Holt, M. M., Noren, D. P., & Emmons, C. K. (2012). Does vessel noise affect the use of sound by foraging *Orcinus orca* (killer whales)? *Advances in Experimental Medicine and Biology*, 730, 327–330. https://doi.org/10.1007/978-1-4419-7311-5_73
- Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., & Veirs, S. (2009). Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America*, 125(1), EL27–EL32. <https://doi.org/10.1121/1.3040028>
- Jansen, J. K., Boveng, P. L., Dahle, S. P., & Bengtson, J. L. (2010). Reaction of Harbor Seals to Cruise Ships. *The Journal of Wildlife Management*, 74(6), 1186–1194. <https://doi.org/10.1111/J.1937-2817.2010.TB01239.X>
- Kastelein, R. A., Mosterd, P., van Santen, B., Hagedoorn, M., & de Haan, D. (2002). Underwater audiogram of a Pacific walrus (*Odobenus rosmarus divergens*) measured with narrow-band frequency-modulated signals. *The Journal of the Acoustical Society of America*, 112(5), 2173–2182. <https://doi.org/10.1121/1.1508783>

- Khopkar, S., Yeo, M., Seo, H., & Sul La, H. (2026). Underwater Noise, Marine Mammal Impacts, and Monitoring strategies in the Arctic ocean. *Ocean Science Journal*, 61:18, 16.
- Kovacs, K. M. (2016). *Odobenus rosmarus ssp. rosmarus*. *The IUCN red list of threatened species 2016*.
- Kovacs, K. M., Lemons, P., MacCracken, J. G., & Lydersen, C. (2015). Walruses in a time of climate change. *Arctic Report Card*, 66–74.
- Krupnik, I., & Ray, G. C. (2007). Pacific walruses, indigenous hunters, and climate change: Bridging scientific and indigenous knowledge. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 54(23–26), 2946–2957. <https://doi.org/10.1016/j.dsr2.2007.08.011>
- Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, Ø., Heide-Jørgensen, M. P., & Ferguson, S. H. (2008). Quantifying the sensitivity of arctic marine mammals to climate-induced habitat change. In *Ecological Applications* (Vol. 18, Number SUPPL.2). <https://doi.org/10.1890/06-0546.1>
- Laist, D. W., Knowlton, A. R., Mead, J. G., Collet, A. S., & Podesta, M. (2001). Collisions between ships and whales. *Marine Mammal Science*, 17(1), 35–75. <https://doi.org/10.1111/J.1748-7692.2001.TB00980.X;CTYPE:STRING:JOURNAL>
- Larsen, O. N., & Reichmuth, C. (2021). Walruses produce intense impulse sounds by clap-induced cavitation during breeding displays. *Royal Society Open Science*, 8(6). <https://doi.org/10.1098/rsos.210197>
- Lemos, L. S., Haxel, J. H., Olsen, A., Burnett, J. D., Smith, A., Chandler, T. E., Nieukirk, S. L., Larson, S. E., Hunt, K. E., & Torres, L. G. (2022). Effects of vessel traffic and ocean noise on gray whale stress hormones. *Scientific Reports 2022 12:1*, 12(1), 18580-. <https://doi.org/10.1038/s41598-022-14510-5>
- Llobet, S. M., Ahonen, H., Lydersen, C., & Kovacs, K. M. (2023). The Arctic and the future Arctic? Soundscapes and marine mammal communities on the east and west sides of Svalbard characterized through acoustic data. *Frontiers in Marine Science*, 10. <https://doi.org/10.3389/fmars.2023.1208049>
- Lowry, L. F., & Fay, F. H. (1984). Seal eating by walruses in the Bering and Chukchi Seas. *Polar Biology*, 3(1), 11–18.
- Maciel, I., Tardin, R., Moreira, S. C., Melo-Santos, G., Maricato, G., & Alves, M. A. S. (2026). Cetaceans Change Their Acoustic Behavior During the Airgun Noise of Seismic surveys (Humpback whale and Pantropical spotted dolphin in Brazil). *Journal of Marine Science and Engineering*, 14, 181.
- MacIntyre, K. Q., Stafford, K. M., Berchok, C. L., & Boveng, P. L. (2013). Year-round acoustic detection of bearded seals (*Erignathus barbatus*) in the Beaufort Sea relative to changing environmental conditions, 2008–2010. *Polar Biology 2013 36:8*, 36(8), 1161–1173. <https://doi.org/10.1007/S00300-013-1337-1>
- Mansfield, A. W. (1958). *The biology of the Atlantic walrus Odobenus rosmarus rosmarus (Linnaeus) in the eastern Canadian Arctic*. Fisheries Research Board of Canada Manuscript Report.

- Marcoux, M., Ferguson, S. H., Roy, N., Bedard, J. M., & Simard, Y. (2017). Seasonal marine mammal occurrence detected from passive acoustic monitoring in Scott Inlet, Nunavut, Canada. *Polar Biology*, 40(5), 1127–1138. <https://doi.org/10.1007/s00300-016-2040-9>
- Martinez-Levasseur, L. M., Simard, M., Furgal, C. M., Burness, G., Bertrand, P., Suppa, S., Avar, E., & Lemire, M. (2020). Towards a better understanding of the benefits and risks of country food consumption using the case of walrus in Nunavik (Northern Quebec, Canada). *Science of the Total Environment*, 719, 137307.
- Martini, I. P., & Morrison, R. I. G. (2014). Coasts of foxe basin, arctic Canada. *Geological Society Special Publication*, 388(1), 165–198. <https://doi.org/10.1144/SP388.14>
- Matthews, C. J. D., Hammill, M. O. , & Young, J. (2018). *Hunt statistics for walrus (Odobenus rosmarus rosmarus) in Canada from 1994-2017*.
- Mattmüller, R. M., Thomisch, K., Van Opzeeland, I., Laidre, K. L., & Simon, M. (2022). Passive acoustic monitoring reveals year-round marine mammal community composition off Tasiilaq, Southeast Greenland. *The Journal of the Acoustical Society of America*, 151(2), 1380–1392. <https://doi.org/10.1121/10.0009429>
- McCord, J. M., Frick, E. E., Cameron, D., & Kuczaj, S. A. (2016). Mating Behaviors Exhibited by a Captive Male Pacific Walrus (*Odobenus rosmarus divergens*). *International Journal of Comparative Psychology*, 29, 1–16. <https://doi.org/10.46867/IJCP.2016.29.00.18>
- Mellinger, D. K., Stafford, K. M., Moore, S. E., Dziak, R. P., & Matsumoto, H. (2007). An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography*, 20(4), 36–45.
- Mikkelsen, L., Johnson, M., Wisniewska, D. M., van Neer, A., Siebert, U., Madsen, P. T., & Teilmann, J. (2019). Long-term sound and movement recording tags to study natural behavior and reaction to ship noise of seals. *Ecology and Evolution*, 9(5), 2588–2601. <https://doi.org/10.1002/ece3.4923>
- Miksis-Olds, J. L., Van Opzeeland, I. C., Van Parijs, S. M., & Jones, J. (2016). Pinniped sounds in the polar oceans. *Listening in the Ocean*, 257–308.
- Miller, E. H., & Kochnev, A. A. (2021). *Ethology and Behavioral Ecology of the Walrus (Odobenus rosmarus), with Emphasis on Communication and Social Behavior* (pp. 437–488). https://doi.org/10.1007/978-3-030-59184-7_22
- Mouy, X., Hannay, D., Zykov, M., & Martin, B. (2012). Tracking of Pacific walrus in the Chukchi Sea using a single hydrophone. *The Journal of the Acoustical Society of America*, 131(2), 1349–1358. <https://doi.org/10.1121/1.3675008>
- Nanaware, S., Shastri, R., Joshi, Y., & Das, A. (2014). Passive acoustic detection and classification of marine mammal vocalizations. *2014 International Conference on Communication and Signal Processing*, 493–497. <https://doi.org/10.1109/ICCSP.2014.6949891>
- Nichol, L. M., Wright, B. M., O'Hara, P., & Ford, J. K. B. (2017). Risk of lethal vessel strikes to humpback and fin whales off the west coast of Vancouver Island, Canada. *Endangered Species Research*, 32(1), 373–390. <https://doi.org/10.3354/ESR00813>

- NIRB (Nunavut Impact Review Board). (2012a). *NIRB's final hearing in Igloolik regarding Baffinland's Mary River project proposal (Hearing Days 6–8)*. <https://www.nirb.ca/project/123910>
- NIRB (Nunavut Impact Review Board). (2012b). *NIRB Project Certificate [No.: 005]. NIRB File No. 08MN053*.
- PAME. (2021). *Protection of the Arctic Marine Environment Working Group - UNDERWATER NOISE POLLUTION FROM SHIPPING IN THE ARCTIC*.
- Panova, E. M., Tolstoy, M. L., Belikov, R. A., & Bogomolova, I. M. (2026). Summer underwater vocalizations of male Atlantic walrus *Odobenus rosmarus rosmarus* near their terrestrial haul-out site. *Behavioural Processes*, 237, 105362. <https://doi.org/10.1016/j.beproc.2026.105362>
- Parks, S. E., Johnson, M., Nowacek, D., & Tyack, P. L. (2011). Individual right whales call louder in increased environmental noise. *Biology Letters*, 7(1), 33–35. <https://doi.org/10.1098/rsbl.2010.0451>
- Paulic, J. E., Cleator, H., Fisheries, K. A. M., & Canada, O. (2014). *Ecologically and biologically significant areas (EBSA) in northern Foxe Basin: identification and delineation*. <http://www.dfo-mpo.gc.ca/csas-sccs/>
- Pirotta, E., Milor, R., Quick, N., Moretti, D., Di Marzio, N., Tyack, P., Boyd, I., & Hastie, G. (2012). Vessel Noise Affects Beaked Whale Behavior: Results of a Dedicated Acoustic Response Study. *PLOS ONE*, 7(8), e42535. <https://doi.org/10.1371/JOURNAL.PONE.0042535>
- Putland, R. L., Merchant, N. D., Farcas, A., & Radford, C. A. (2017). Vessel noise cuts down communication space for vocalizing fish and marine mammals. *Global Change Biology*, 24(4), 1708–1721. <https://doi.org/10.1111/GCB.13996>
- Ray and Watkins. (1975). Social function of underwater sounds in walrus. *Rapp. P.-v. Réun. Cons. Int. Explor. Mer*, 169, 524–526.
- Reichmuth, C., Sills, J. M., Brewer, A., Triggs, L., Ferguson, R., Ashe, E., & Williams, R. (2020). Behavioral assessment of in-air hearing range for the Pacific walrus (*Odobenus rosmarus divergens*). *Polar Biology*, 43(6), 767–772. <https://doi.org/10.1007/s00300-020-02667-6>
- Richardson, W. J., Greene Jr C. R., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise*. Academic press.
- Rideout, B., Dosso, S. E., & Hannay, D. (2013). Underwater passive acoustic localization of pacific walrus in the northeastern chukchi sea. *Canadian Acoustics - Acoustique Canadienne*, 40(3), 44–45. <https://doi.org/10.1121/1.4816580>
- Rodon, T., & Bouchard, K. (2024). Between a rock and a hard place: the Social Acceptability of the Mary River mining project in Nunavut. *Mineral Economics* 2024 39:2, 39(2), 397–410. <https://doi.org/10.1007/S13563-024-00462-X>
- Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K., & Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences*, 279(1737), 2363–2368. <https://doi.org/10.1098/RSPB.2011.2429>

- Romano, T. A., Keogh, M. J., Kelly, C., Feng, P., Berk, L., Schlundt, C. E., Carder, D. A., & Finneran, J. J. (2011). Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. *https://doi.org/10.1139/F04-055*, 61(7), 1124–1134. <https://doi.org/10.1139/F04-055>
- Scharffenberg, K., Macphee, S. A., Mouy, X., Whalen, D., Wright, A. J., & Loseto, L. L. (2025). Identifying beluga distribution in the Tarium Niryutait Marine protected area using passive acoustic monitoring. *https://doi.org/10.1139/as-2024-0052*, 11. <https://doi.org/10.1139/AS-2024-0052>
- Schusterman, R. J., & Reichmuth, C. (2008). Novel sound production through contingency learning in the Pacific walrus (*Odobenus rosmarus divergens*). *Animal Cognition*, 11(2), 319–327. <https://doi.org/10.1007/s10071-007-0120-5>
- Seymour, J., Horstmann-Dehn, L., & Wooller, M. J. (2014). Proportion of higher trophic-level prey in the diet of Pacific walruses (*Odobenus rosmarus divergens*). *Polar Biology*, 37(7), 941–952. <https://doi.org/10.1007/s00300-014-1492-z>
- Sjare, B., & Stirling, I. (1996). The breeding behavior of Atlantic walruses, *Odobenus rosmarus rosmarus*, in the Canadian High Arctic. *Canadian Journal of Zoology*, 74(5), 897–911. <https://doi.org/10.1139/z96-103>
- Sjare, B., Stirling, I., & Spencer, C. (2003). Structural variation in the songs of Atlantic walruses breeding in the Canadian High Arctic. *Aquatic Mammals*, 29(2), 297–318.
- Smith, T. A., & Rigby, J. (2022). Underwater radiated noise from marine vessels: A review of noise reduction methods and technology. *Ocean Engineering*, 266, 112863. <https://doi.org/10.1016/J.OCEANENG.2022.112863>
- Southall, E. B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P., & Tyack, P. L. (2019). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals*, 45(2), 125–232. <https://doi.org/10.1578/AM.45.2.2019.125>
- Stewart, D. B., Higdon, J. W., Reeves, R. R., & Stewart, R. E. A. (2014). Catch history for Atlantic Walrus (*Odobenus rosmarus rosmarus*) in the eastern Canadian Arctic. *NAMMCO Scientific Publication*, 9, 219–313.
- Stewart, R. E. A. (2008). Redefining walrus stocks in Canada. *Arctic*, 61(3), 292–308.
- Stewart, R. E. A., Hamilton, J. W., & Dunn, J. B. (2013). *Results of Foxe Basin walrus (Odobenus rosmarus rosmarus) surveys: 2010-2011. (Erratum: February 2014) : iv*. <http://www.dfo-mpo.gc.ca/csas-sccs/>
- Stewart, R. E. A., Stewart, D. B., & Higdon, J. W. (2016). *Report of the 2016 Workshop to inform the DFO Five-year Research Plan for Atlantic Walruses in Canada*.
- Stirling, I., Calvert, W., Cleator, H., Stirling, I., & Cleator, H. (1983). Underwater Vocalizations as a Tool for Studying the Distribution and Relative Abundance of Wintering Pinnipeds in the High Arctic. In *Source: Arctic* (Vol. 36, Number 3).

- Stirling, I., Calvert, W., & Spencer, C. (1987). Evidence of stereotyped underwater vocalizations of male Atlantic walrus (*Odobenus rosmarus rosmarus*) . *Canadian Journal of Zoology*, 65(9), 2311–2321. <https://doi.org/10.1139/z87-348>
- Stroeve, J., & Notz, D. (2018). Changing state of Arctic sea ice across all seasons. In *Environmental Research Letters* (Vol. 13, Number 10). Institute of Physics Publishing. <https://doi.org/10.1088/1748-9326/aade56>
- Taylor, R. L., Jay, C. V., Beatty, W. S., Fischbach, A. S., Quakenbush, L. T., & Crawford, J. A. (2023). Exploring effects of vessels on walrus behaviors using telemetry, automatic identification system data and matching. *Ecosphere*, 14(3). <https://doi.org/10.1002/ecs2.4433>
- Terhune, J. M., Stewart, R. E. A., & Ronald, K. (1979). Influence of vessel noises on underwater vocal activity of harp seals. *https://Doi.Org/10.1139/Z79-170*, 57(6), 1337–1338. <https://doi.org/10.1139/z79-170>
- Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy*, 89(3), 549–558.
- Verboom, W., Kastelein, R., & Postma, R. (1995). *Airborne vocalizations of Pacific walrus pups (Odobenus rosmarus divergens)*.
- Wams, L., Kovacs, K. M., Lydersen, C., Lindstrøm, U., Tollefsen, D., & Ahonen, H. (2025). Singers of the high Arctic; Seasonal acoustic presence of bowhead whales (*Balaena mysticetus*) around Svalbard, Norway. *Scientific Reports*, 15(1). <https://doi.org/10.1038/s41598-025-98302-7>
- Wiig, Ø., Born, E. W., & Stewart, R. E. A. (2014). Management of Atlantic walrus (*Odobenus rosmarus rosmarus*) in the arctic Atlantic. *NAMMCO Scientific Publications*, 9, 315–341.

Chapter 2 Year-round passive acoustic monitoring reveals seasonal occurrence, migration timing, and environmental drivers of five Arctic marine mammal species in Foxe Basin, Nunavut.

2.1 Abstract

Foxe Basin (FB) is a key migration corridor and year-round habitat for multiple Arctic marine mammals, including the Atlantic walrus (*Odobenus rosmarus rosmarus*), bowhead whale (*Balaena mysticetus*), beluga whale (*Delphinapterus leucas*), bearded seal (*Erignathus barbatus*), and ringed seal (*Pusa hispida*). Two hydrophones were deployed for a full year in northern FB during 2023-2024. Based on manual analysis of recordings, the daily vocal presence was assessed for each species. The influence of environmental covariates (sea ice concentration, wind speed, and sea surface temperature) and site location on each species occurrence was then evaluated. Walrus vocalizations were the most detected species at both sites year-round (40.8% of recordings), with detections peaking during the breeding season and associated with higher sea ice concentration ($p < 0.001$). Bearded seal vocalizations were the second most detected (36.2%), with vocal presence peaking during the breeding season and declining under stronger wind conditions ($p = 0.038$). Bowhead whale vocalizations were detected during their summer migration to Foxe Basin and declined following freeze-up. Vocal detections had a strong negative relationship with sea ice concentration ($p < 0.001$) and were concentrated at one site (17.5% vs. 1.1% of recordings, $p < 0.001$). Beluga vocalizations were detected primarily during winter, indicating the presence of individuals outside typical migration periods, with vocal presence increasing under colder sea surface temperatures ($p = 0.004$) and varying between sites ($p = 0.016$). Ringed seal vocalizations were the least detected (4.1%), with sporadic vocal presence at both sites during the breeding season. Sea ice concentration emerged as the dominant environmental driver for multiple species, with contrasting effects reflecting each species' ecological dependence on ice. Year-round acoustic monitoring provides an essential window into when and where marine mammal species occur in Foxe Basin and how the environment shapes their vocal presence, complementing the local knowledge in the region.

2.2 Introduction

The Arctic marine ecosystem is highly dynamic and strongly influenced by seasonal environmental conditions. Sea ice cover, wind regimes, and sea surface temperature regulate key biological processes, such as primary productivity, directly shaping trophic dynamics and the seasonal distribution of Arctic marine mammals (Matthes et al., 2021; Miksis-Olds et al., 2013; Sakshaug, 2004). Among these drivers, sea ice plays a structuring role in Arctic marine food webs by determining the duration of productive open-water seasons and shaping habitat availability throughout the year (Kovacs et al., 2011; Laidre & Regehr, 2016; Popova et al., 2010; Sakshaug, 2004). Wind modulates nutrient mixing and underwater ambient noise conditions (Dahl et al., 2007; Nishino et al., 2015; Shajahan et al., 2024). Sea surface temperature influences prey distribution and the energetic costs of thermoregulation (Hind & Gurney, 1997; Popova et al., 2010). These dynamics are particularly pronounced in regions such as Foxe Basin, in the central Canadian Arctic, which has experienced trends toward earlier break-up and later freeze-up consistent with broader changes observed across the eastern Canadian Arctic (Laidler et al., 2008; Tivy et al., 2011; Hochheim and Barber, 2014; Parkinson, 2014; Andrews et al., 2018).

The behaviour and distribution of some Arctic marine mammals are tightly coupled to variation in environmental conditions, influencing habitat use, vocal activity, and migration (Hauser et al., 2017b; Kovacs et al., 2011; Laidre et al., 2015; Laidre & Regehr, 2016; Moore & Huntington, 2008). Migratory cetaceans such as the bowhead whale (*Balaena mysticetus*) and the beluga whale (*Delphinapterus leucas*) follow seasonal ice dynamics and prey availability between wintering and summering grounds (Ferguson et al., 2010; Heide-Jørgensen et al., 2010; Heide-Jørgensen, 2003; Citta et al., 2012; Barber et al., 2001; Hauser et al., 2017b; Hornby et al., 2017; Richard & Stewart, 2008). Ice-associated pinnipeds, including the Atlantic walrus (*Odobenus rosmarus rosmarus*), bearded seal (*Erignathus barbatus*), and ringed seal (*Pusa hispida*), depend on sea ice as a platform for hauling out, resting, nursing, and moulting, as well as for access to prey

(Breed et al., 2018; Harwood et al., 2015; Kastelein, 2009; Kingsley & Stirling, 1991; Lydersen, 2011; Sjare & Stirling, 1996; Stirling, 1983).

Passive acoustic monitoring (PAM) provides an effective and non-invasive approach for studying vocal activity of soniferous species in remote Arctic environments, where direct observations remain logistically challenging. Many Arctic species produce predictable vocalizations linked to different behaviours, allowing acoustic detections to serve as a proxy for presence in a region (Llobet et al., 2023). Walrus knocks and bell sounds are typically produced during the breeding season for mate attraction and male competition (Sjare, 1993; Sjare & Stirling, 1996). Bowhead whales produce calls throughout the year, including moans, whereas they produce songs only seasonally, which are believed to be associated with breeding displays (Stafford & et al., 2012; Stafford & Clark, 2021). Beluga whistles and pulsed calls are linked to social behaviour, including group cohesion and mother-calf communication, while echolocation clicks are associated with navigating and foraging behaviour (Cotillard et al., 2024; Garland et al., 2015). Bearded seal trills, moans and sweeps are produced during the breeding season to defend territories and for courtship (Cleator et al., 2011; Van Parijs et al., 2001), while ringed seal barks and yelps are described as breeding behaviour and male-male competition during the pupping and mating season (Mizuguchi et al., 2016; Stirling, 1973). PAM has been widely applied in the Canadian Arctic, where these typical vocalizations provide information on species presence, migration timing, and behaviour across seasons (Van Opzeeland et al., 2010; Van Parijs et al., 2003; Moore et al., 2011; Marcoux et al., 2017).

This study used year-round PAM to examine the occurrence of five marine mammal species in northern Foxe Basin: walrus, bowhead whale, beluga, bearded seal, and ringed seal. The objectives were to (1) characterize seasonal patterns of acoustic occurrence and (2) examine the influence of sea ice concentration, wind speed, and sea surface temperature on species presence. Vocal activity was predicted to peak during breeding periods for walrus, bearded seal, and ringed

seal, and during seasonal presence for bowhead and beluga whales. Sea ice concentration, wind speed, and sea surface temperature were expected to shape acoustic presence through species-specific habitat needs. Sea ice was predicted to positively influence pinniped and beluga presence, given their reliance on ice, but negatively influence bowhead whales, which migrate in association with ice retreat (Asselin et al., 2011; Boveng et al., 2025; Fay, 1982; Citta et al., 2015). Wind speed was expected to reduce call detection across all species through acoustic masking (Halliday et al., 2020; Insley et al., 2017; Shajahan et al., 2024). Sea surface temperature was expected to negatively influence ice-dependent species through reduced habitat availability (Laidre et al., 2008; Chambault et al., 2018; Bailleul et al., 2012). By providing a year-round multi-species acoustic dataset, this study contributes to understanding how these five marine mammals use northern Foxe Basin under varying environmental conditions.

2.3 Methods

2.3.1 Study area

Foxe Basin (FB), located in the central Canadian Arctic, is connected to Fury and Hecla Strait to the northwest and Hudson Strait to the southeast. Coastal Inuit communities along the basin include Igloolik (Iglulik, ᐃᓖᓕᓴᓴ) and Sanirajak (ᓴᓂᓴᓴ). The basin is characterized by a full seasonal sea ice cycle, with freeze-up typically occurring in November and break-up in July or August (Hochheim & Barber, 2014; Kowal et al., 2024). Pack ice dominates the basin most of the year, although persistent polynyas provide areas of low sea ice to open waters throughout the year (Babb et al., 2026). Polynyas are characteristic of the northwest basin and along Sanirajak. The formation of polynyas depends on sea ice and wind dynamics (Martini & Morrison, 2014). Waters remain relatively cold year-round, influenced by currents entering through Fury and Hecla Strait and northerly winds (Martini & Morrison, 2014).

2.3.2 Acoustic data collection

Underwater acoustic data were collected using two autonomous hydrophones (Soundtrap ST600HF; Oceans Instruments, NZ) from June 2023 to June 2024 (Table 2.1). Both were deployed in the northern part of FB, 46 km apart (Figure 2.1). FB-IGL1-23 was deployed north of Igloolik, at 6.6km from the nearest coast and at a depth of 59 m. FB-IGL2-23 was located 8.8 km from Tangle Island (Figure S2. 1), at a depth of 26 m, and closer to polynyas. Deployment sites were selected collaboratively with Inuit researchers from Igloolik and Sanirajak, based on local knowledge of areas used by resident and seasonal marine mammal species. Specifically, Inuit researchers identified areas of interest and potential hydrophone deployment locations on a map. The deployment and retrieval of hydrophone moorings were conducted collaboratively with Inuit researchers.

Each mooring consisted of an anchor, acoustic release (Vemco VR2AR, INNOVASEA), the hydrophone, and a buoy connected by a rope (Figure S2.2). The buoy was submerged at least 10 m below the surface, with the hydrophone 4 m below that, the acoustic release an additional meter below the hydrophone, and the anchor another 10 m below. FB-IGL1-23 and FB-IGL2-23 were retrieved using a deck box receiver (VR100-300, INNOVASEA) and a transponding hydrophone after approximately one year of recording. Hydrophones recorded continually with no set gain at a sample rate of 192 kHz, capturing sounds up to 96 kHz. This high sampling rate preserves the vocalization structure with higher frequency resolution in spectrograms, allowing for more detailed recordings. A duty cycle of 6 minutes on and 54 minutes off was set for each hydrophone to reduce power consumption and allow for year-long deployments.

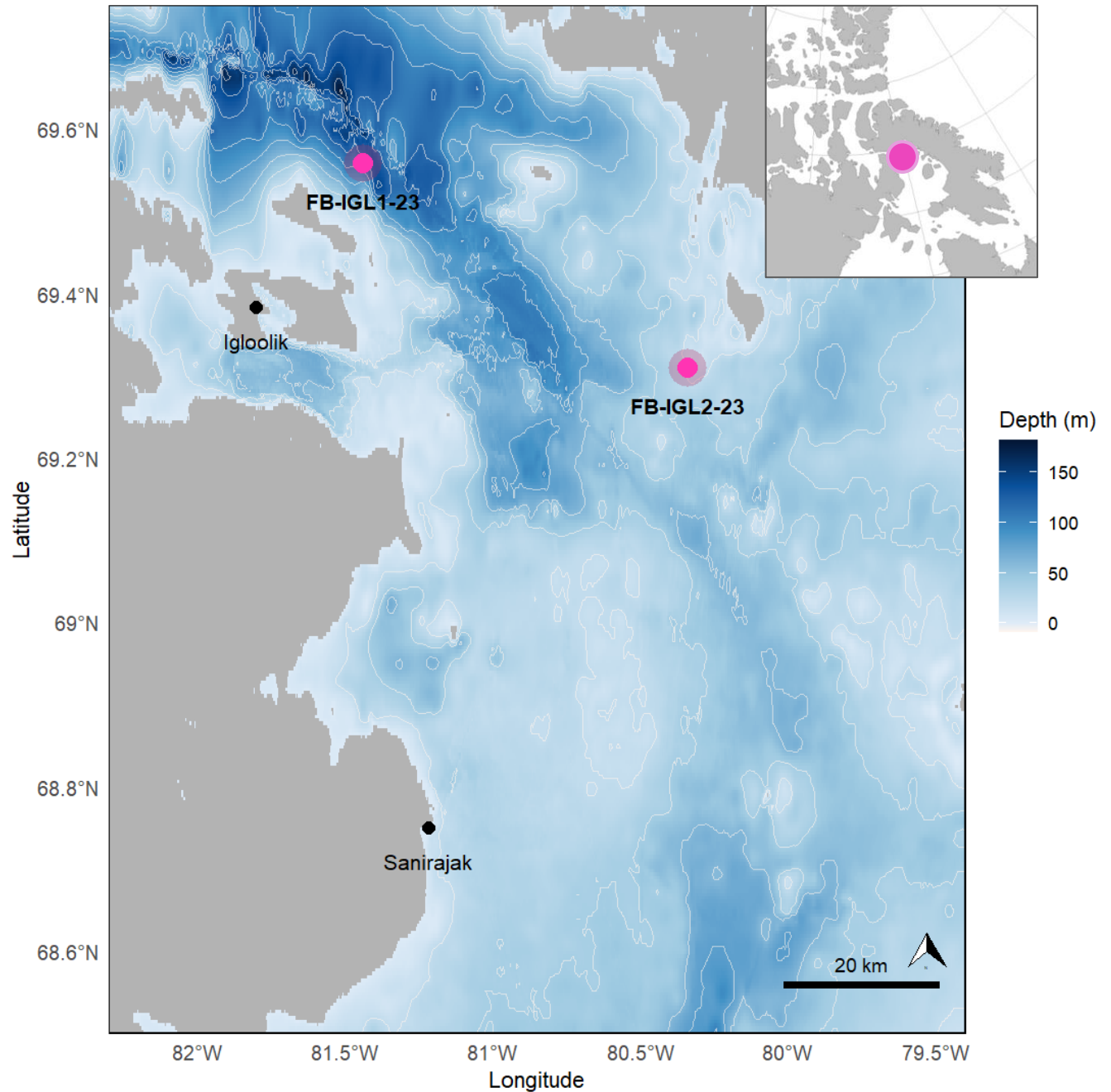


Figure 2.1 Map of Foxe Basin and the coastal communities of Igloolik and Sanirajak, with the two hydrophone locations (FB-IGL1-23 and FB-IGL2-23) deployed during 2023-2024 in the northern part of the basin.

Table 2.1. Deployment names, coordinates, recording duration, and depths of two hydrophone moorings deployed in Foxe Basin from 2023 to 2024.

Deployment name	Latitude (°N)	Longitude (°W)	Start date (YYYY-MM-DD)	End date (YYYY-MM-DD)	Recording duration (days)	Numbers of recordings	Water depth (m)
FB-IGL1-23	69.51913	81.36013	2023-06-27	2024-06-21	366	8808	59
FB-IGL2-23	69.31363	80.33806	2023-06-27	2024-06-25	364	8760	26

2.3.3 Acoustic data analysis

One recording per day was manually inspected to detect calls of walrus, bowhead whale, beluga, and bearded and ringed seal. To ensure even temporal coverage and minimize potential bias related to the time of day, the *hour* of the analyzed recording was shifted by one hour each day (e.g., 00:00 on Day 1, 01:00 on Day 2, and so on). In total, 731 files were manually analyzed from the two locations (4% of the total files).

For each recording (.wav format), a spectrogram was generated using the sound analysis software Raven Pro, version 1.6.5 (Raven Pro, 2024), with a Hanning window of 2,048 points and 50% overlap, and a frequency range of 0-30 kHz. Each spectrogram was systematically inspected visually and aurally for species-typical vocalizations: walrus knocks and bell sounds, bowhead whale moans and songs, beluga whistles, pulsed calls, and clicks, bearded seal trills, moans, and sweeps, and ringed seal barks and yelps (Figure 2.2), according to parameters based on previously published literature (Table 2.2).

A vocalization was retained only if (1) its start and end points were clearly distinguishable on the spectrogram and (2) its signal contour was well-defined. When these criteria were met, a presence (1) was assigned to the corresponding species. Absence (0) was assigned when no

vocalization was detected or when a signal could not be confidently attributed to a species due to poor signal quality or ambiguity. This resulted in a binary presence/absence (1/0) dataset for each species across all analyzed recordings.

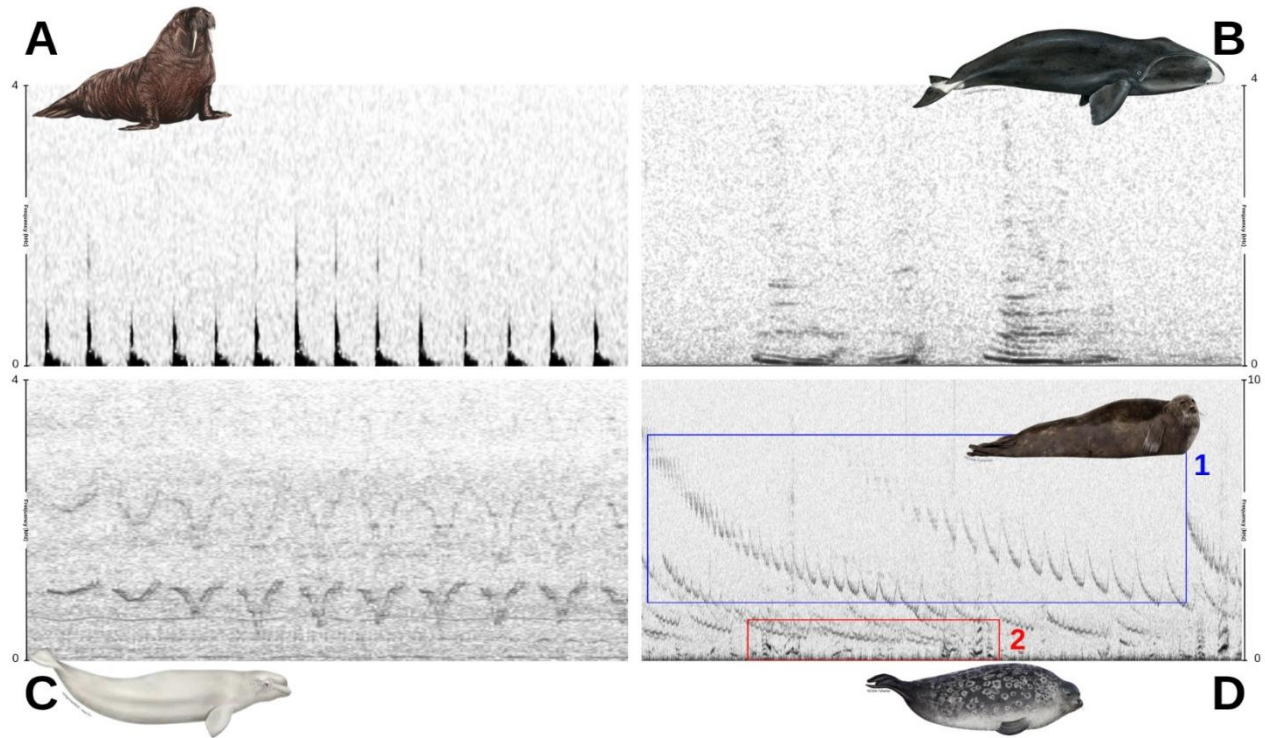


Figure 2.2 Spectrograms showing different species' vocalizations from FB-IGL1-23 and FB-IGL2-23. (A) walrus knocks, (B) bowhead moans, (C) beluga whistles, (D,1) bearded trills, (D,2) ringed seal barks and yelps. Animal illustrations from NOAA Fisheries; available at <https://www.fisheries.noaa.gov/find-species>

Table 2.2 Summary of species-typical call types for five species. Parameters based on previously published literature.

Species	Call type	Duration	Frequency range	References
Atlantic walrus (<i>Odobenus rosmarus rosmarus</i>)	Knocks, taps, and bell sounds	~10/s	200 Hz to 8 kHz	Stirling et al., 1987; Sjare and Stirling, 1996; Sjare et al., 2003
Bowhead whale (<i>Balaena mysticetus</i>)	Moans	0.5-5 s	<500 Hz	Stafford and Clark, 2021; Stafford, 2022
Beluga (<i>Delphinapterus leucas</i>)	Whistles, pulsed calls, and clicks	From 0.25 to 1.95 s	0.1-12 kHz; >60kHz	Sjare and Smith, 1986; O'Neill, 2015; Zahn et al., 2021
Bearded seal (<i>Erignathus barbatus</i>)	Trills, moans, ascents, and sweeps	From 2 s to 3 min	130 Hz to 6 kHz	Cleator et al., 2011; Heimrich et al., 2021
Ringed seal (<i>Pusa hispida</i>)	Bark and yelps	Short duration (<0.5 s)	400 Hz to 2 kHz	Stirling, 1973, 1983; Jones et al., 2014

2.3.4 Environmental covariates

Daily SIC was retrieved from the Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations (NRTSI; Meier et al., 2021; <https://nsidc.org/data/nsidc-0081/versions/2>), generated using the NASA Team algorithm. Data (NetCDF files) from the F18 sensor were obtained at a spatial resolution of 25 x 25 km. For each hydrophone location, the nearest grid cell to the deployment location was identified. Daily SIC was computed as the mean of nine cells (a 3 x 3 window, approximately 75 x 75 km) centered on the identified cell.

Daily wind speed and sea surface temperature were obtained from the NetCDF files of the ERA5 post-processed daily statistics on single levels (Copernicus Climate Change Service; Hersbach et al., 2023; <https://cds.climate.copernicus.eu/datasets/derived-era5-single-levels-daily-statistics>). Daily means were extracted with the maximum temporal frequency (computed from 6-hourly samples) and at a spatial resolution of $0.25^\circ \times 0.25^\circ$ (approximately 28×11 km at 69°N).

The 10-m wind speed was derived from the instantaneous zonal (u) and meridional (v) wind components at 10 m height using the equation:

$$\text{Wind speed} = \sqrt{u^2 + v^2}$$

SST was converted from Kelvin (K) to Celsius ($^\circ\text{C}$) by subtracting 273.15 from the values.

2.3.5 Statistical analysis

Generalized Linear Models (GLMs) with a binomial error distribution and logit link function were used to model species presence-absence. Species presence was coded as a daily binary variable (1 = presence, 0 = absence). Four candidate predictors were considered: sea ice concentration (proportion), wind speed ($\text{m}\cdot\text{s}^{-1}$), sea surface temperature ($^\circ\text{C}$), and site as a fixed categorical effect (FB-IGL1-23; FB-IGL2-23). All continuous predictors were standardized before model fitting. Candidate models were evaluated using the *dredge* function from the *MuMIn* package, and the best model was selected based on AICc (Table S2.1). Model fit was assessed using residual diagnostics implemented in the DHARMA package. All final models passed uniformity and dispersion tests ($p > 0.05$). Potential multicollinearity was assessed using the variance inflation factor (VIF).

To assess whether temporal autocorrelation required explicit modelling, preliminary GLMs including all candidate predictors were fitted for each species. Autocorrelation function (ACF) and partial autocorrelation function (PACF) plots of the Pearson residuals were inspected for each

species. *Walrus* and *bearded seal* showed significant lag-1 autocorrelation with gradual ACF decay, consistent with a first-order autoregressive (AR(1)) process. For the two species, models were therefore fitted using the *glmmTMB* package with an AR(1) correlation structure specified as *ar1(day_index + 0 | site)*, where *day_index* is the day number of the recording period, modelling temporal autocorrelation independently within each site. Post-hoc ACF and PACF plots of AR(1) model residuals were inspected, confirming that temporal autocorrelation was adequately removed for *walrus* and *bearded seal*. The AR(1) correlation structure was held fixed across all candidate models for *walrus* and *bearded seal*. For *ringed seal*, *bowhead whale*, and *beluga whale*, residuals showed no significant autocorrelation, and standard binomial GLMs were fitted using *glm()*. All analyses were conducted in R (v. 4.3.0; R Core Team 2023).

2.4 Results

2.4.1 Study area

FB-IGL1-23 and FB-IGL2-23 showed similar ice regimes, with slight differences in the timing of freeze-up and break up (Figures 2.3 and 2.4). Open-water conditions (<25% SIC) occurred from late July until freeze-up in November at both locations. Consolidated ice persisted until early June at FB-IGL1-23, while ice concentrations decreased slightly earlier at FB-IGL2-23 during break-up. Across both sites, wind speeds ranged from 0.34 to 14.79 m s⁻¹, with high-wind events (>10 m·s⁻¹) occurring more frequently during autumn and winter. SST followed a seasonal pattern associated with sea ice dynamics, ranging from -1.69 to 3.92°C. Spring warming began in May, with higher temperatures observed at FB-IGL2-23 relative to FB-IGL1-23, consistent with a lower SIC in July at the second site (Figures 2.3 and 2.4).

2.4.2 Overall vocal detections across sites

Across both sites, walrus vocalizations were the most frequently detected, recorded on 298 of 730 monitoring days (40.8%), followed by bearded seals (264 days; 36.2%), bowhead

whales (68 days; 9.3%), beluga whales (31 days; 4.2%), and ringed seals (30 days; 4.1%) (Table 2.3).

Table 2.3 Number of days with detected vocal presence and associated percentages (%) per species at each site and at both sites combined (i.e. total).

Species	FB-IGL1-23 (days, %)	FB-IGL2-23 (days, %)	Total (days, %)
Walrus	179 (48.9%)	119 (32.7%)	298 (40.8%)
Bowhead whale	64 (17.5%)	4 (1.1%)	68 (9.3%)
Beluga whale	22 (6.0%)	9 (2.5%)	31 (4.2%)
Bearded seal	161 (44.0%)	103 (28.4%)	264 (36.2%)
Ringed seal	17 (4.6%)	13 (3.6%)	30 (4.1%)

At FB-IGL1-23, walrus detections were almost daily from December 2023 to June 2024, with earlier peaks from July to October 2023 and no vocal detections from October to December 2023 (Figure 2.3). At FB-IGL2-23, detections were more evenly distributed throughout the year, with a peak from January to June 2024 (Figure 2.4). Bowhead whale detections were recorded from July 2023 to January 2024, with peak vocal activity in late July at FB-IGL1-23. At FB-IGL2-23, detections were sporadic, occurring only in September, October, and December 2023, and February 2024 (Figure 2.4). Beluga calls were detected at FB-IGL1-23 from October 2023 to March 2024, and at FB-IGL2-23 from December 2023 to March 2024, with fewer vocal detections at the latter site (9 days; 2.5%) (Table 2.3). Bearded seal vocal presence was seasonal. At FB-IGL1-23, vocal activity was restricted to December 2023 through July 2024, gradually increasing from December to a consistent detection from late March onward (Figure 2.3). A similar pattern was observed at FB-IGL2-23, where vocal activity increased gradually. Occasional detections occurred in September and October 2023 (Figure 2.4). At both sites, walrus and bearded seals co-occurred from January to May 2024. Ringed seal vocal detections were the least frequent

overall. Presence was recorded at FB-IGL1 -23 from March to July 2024, and at FB-IGL2-23 from September 2023 to February 2024 (Figures 2.3 and 2.4). Vocal detections peaked in June 2024 at FB-IGL1-23, coinciding with bearded seal presence. At FB-IGL1-23, December 2023 was the only month in which walrus, bearded seal, and bowhead whale vocalizations were detected concurrently.

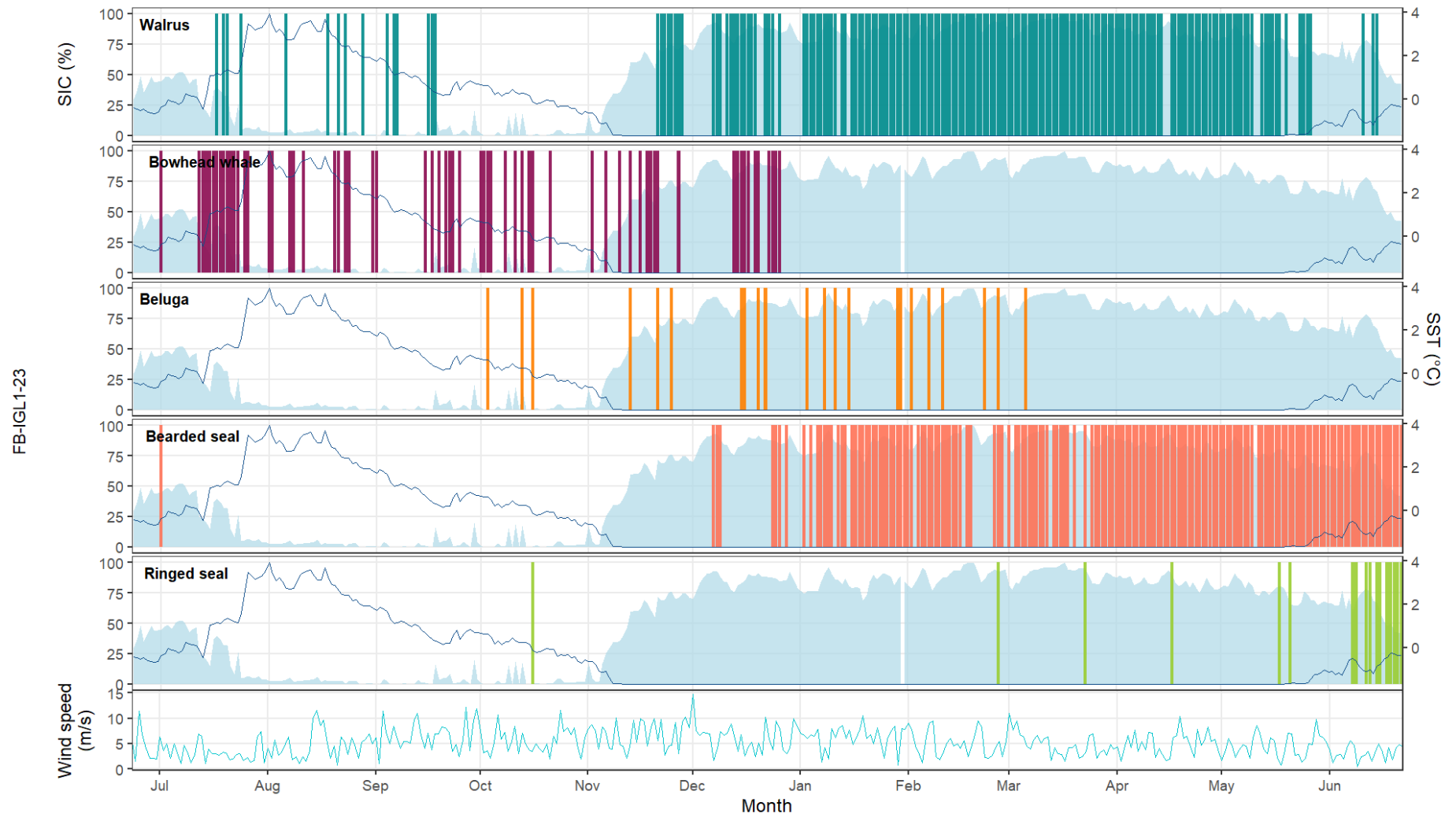


Figure 2.3. Daily acoustic presence of walrus, bowhead whale, beluga, bearded seal, and ringed seal at FB-IGL1-23, with sea ice concentration (blue shading), wind speed (blue line), and sea surface temperature (SST).

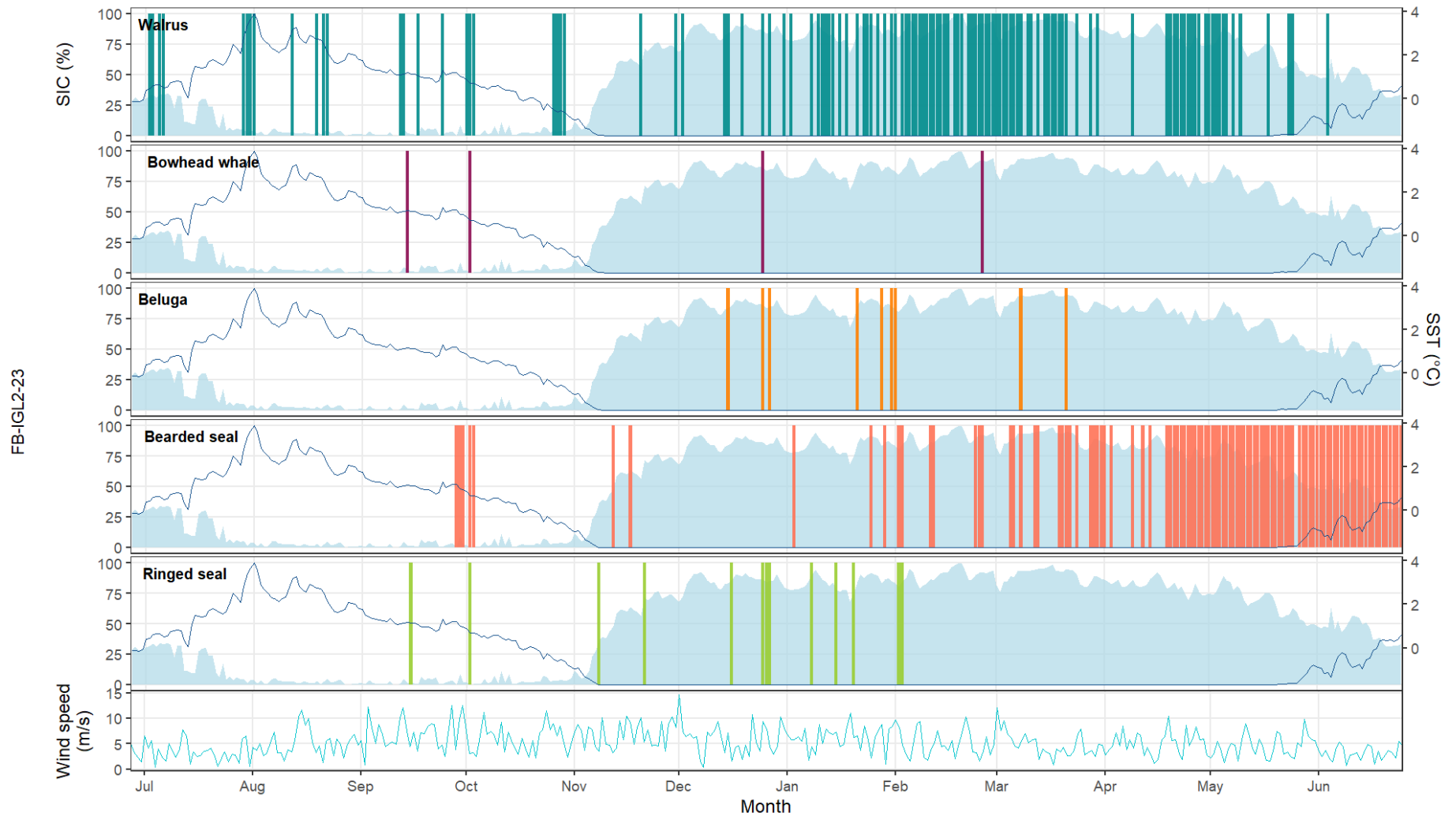


Figure 2.4. Daily acoustic presence of walrus, bowhead whale, beluga, bearded seal, and ringed seal at FB-IGL2-23, with sea ice concentration (blue shading), wind speed (blue line), and sea surface temperature (SST).

2.4.3 Influence of environmental parameters on vocal presence

All results are summarized in Table 2.4 and represented in Figure 2.5 and Figure S2.3. Multicollinearity among predictors was assessed using the variance inflation factor (VIF). All VIF values were below the threshold of 4, and no predictors were removed before model selection.

The best-supported model ($AICc = 621.8$) for the detection of walrus calls retained SIC as the sole predictor. SIC had a significant positive effect ($\beta = 2.096$, $p < 0.001$), with the probability of vocal presence showing a sharp increase when SIC ranged between 50% and 100% (Figure S2.3). The AR(1) parameter ($\phi = 0.92$) indicated strong temporal persistence from one day to another.

The best-supported model ($AICc = 355.8$) for the detection of bowhead whale calls retained three predictors. First, SIC had a significant negative effect ($\beta = -0.780$, $p < 0.001$), with a probability of vocal presence reaching 50% under open water conditions, consistent with summer vocal detections (Figure S2.3). Site had a strong negative effect ($\beta = -3.104$, $p < 0.001$), with higher vocal presence at FB-IGL1-23 compared to FB-IGL2-23 (Figure S2.3). Wind speed was retained in the model but did not have a significant effect ($\beta = -0.223$, $p = 0.118$).

The best-supported model ($AICc = 243.7$) for the detection of beluga whale calls retained two predictors. SST had a significant negative effect ($\beta = -1.441$, $p = 0.004$), with predicted vocal presence increasing under colder temperatures, consistent with their winter occurrence in the study area (Figure S2.3). Site had a significant negative effect ($\beta = -0.969$, $p = 0.016$), with lower vocal presence at FB-IGL2-23 than at FB-IGL1-23 (2.5% versus 6.0% of monitoring days).

The best-supported model ($AICc = 382.4$) for the detection of bearded seal calls retained wind speed as the sole predictor ($\beta = -0.391$, $p = 0.038$), indicating reduced detection probability under stronger wind conditions, although uncertainty around the predicted relationship remained high (Figure S2.3). The AR(1) parameter ($\phi = 0.99$) indicated a strong temporal autocorrelation accounting for most of the explained variance.

The best-supported model (AICc = 249.8) for the detection of ringed seal calls retained SST ($\beta = -0.447$, $p = 0.069$) and wind speed ($\beta = -0.355$, $p = 0.090$). Although neither predictor reached significance, both showed negative trends, suggesting reduced vocal presence under warmer SST and stronger winds.

Table 2.4. Parameter estimates from the best-supported model for each species. AR1 refers to the first-order autoregressive correlation structure; ϕ = AR1 correlation parameter. SE = standard error, z = Wald z -statistic. Bold p -values indicate statistical significance of the predictor ($p < 0.05$).

Species	Model	Predictor	Estimate	SE	z	p
Walrus	GLMM + AR1, $\phi = 0.92$	SIC	2.096	0.527	3.977	< 0.001
Bowhead whale	GLM	SIC	-0.780	0.140	-5.559	< 0.001
		Site (IGL2 vs IGL1)	-3.104	0.527	-5.894	< 0.001
		Wind speed	-0.223	0.143	-1.562	0.118
Beluga	GLM	Site (IGL2 vs IGL1)	-0.969	0.404	-2.400	0.016
		SST	-1.441	0.502	-2.870	0.004
Bearded seal	GLMM + AR1, $\phi = 0.99$	Wind speed	-0.391	0.188	-2.077	0.038
Ringed seal	GLM	SST	-0.447	0.245	-1.822	0.069
		Wind speed	-0.355	0.209	-1.697	0.090

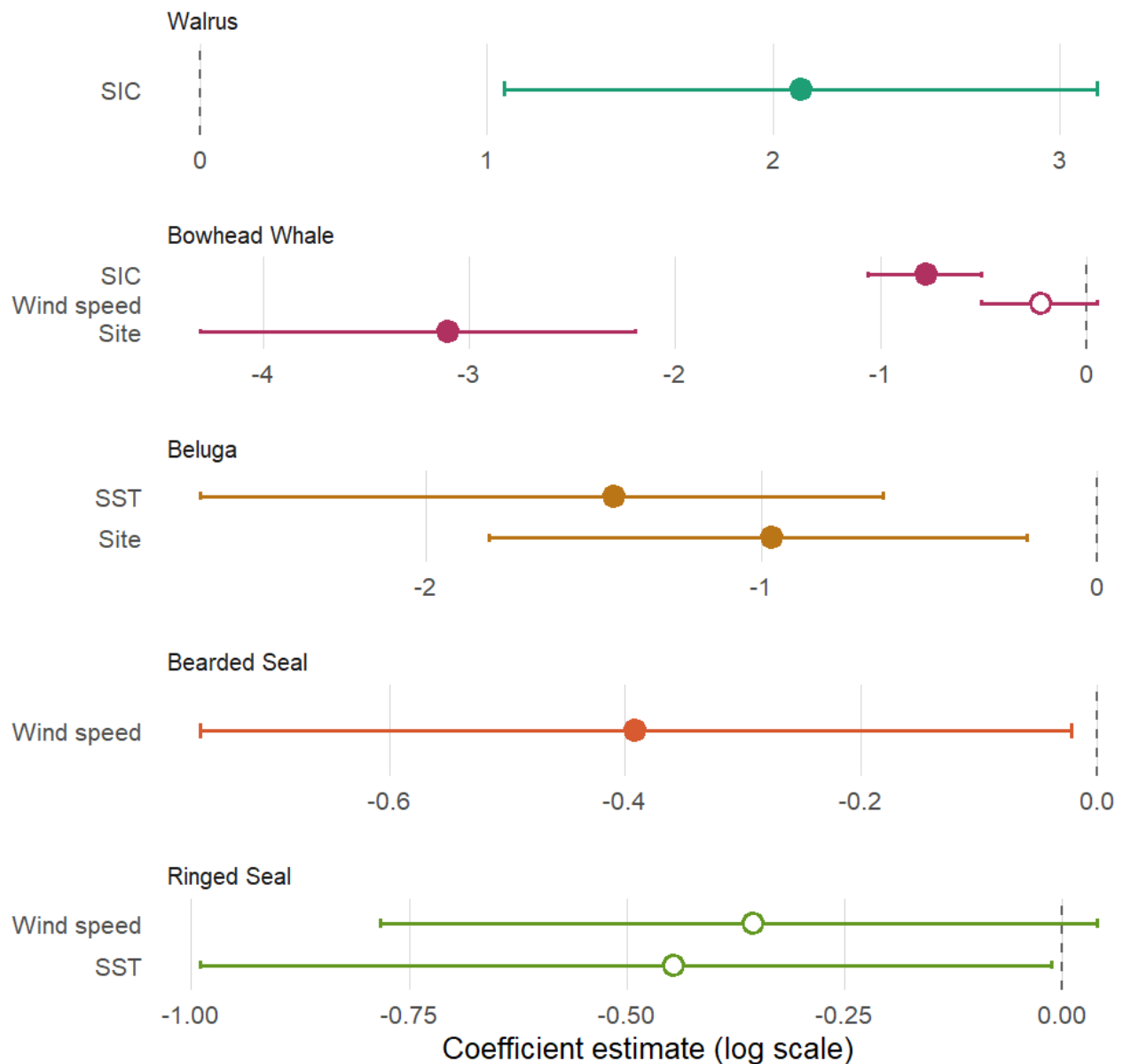


Figure 2.5. For each species, estimates from each best-supported model of acoustic presence with the retained predictors. Points represent model coefficients and horizontal lines indicate 95% confidence intervals. Open circles = non-significant effects ($p > 0.05$); filled circles = significant effects ($p \leq 0.05$). SIC: sea ice concentration; SST: sea surface temperature; Site: hydrophone site (FB-IGL2-23 vs. FB-IGL1-23).

2.5 Discussion

2.5.1 Year-round temporal and spatial acoustic occurrence of five marine mammal species

Walrus

Walrus vocalizations were the most frequently detected among all species, consistent with the high abundance of Atlantic walruses in FB (Hammill et al., 2016). Walruses are present year-round in the region and are typically associated with polynyas and coastal areas (Higdon et al., 2022). Seasonal movements occur within FB, generally oriented southward in winter and northward in summer, following sea ice dynamics and access to benthic foraging grounds (Fay, 1982; Freitas et al., 2009). Continuous vocal presence was recorded throughout the year at both recording locations. Telemetry data collected from walruses tagged in Igloodik and Sanirajak across multiple years (2021-2025) indicate that seasonal movements can remain relatively localized within northern and central FB (DFO, unpublished data), which also supports the acoustic results of a year-round presence. The persistent detections observed at both sites are likely supported by high benthic productivity and, therefore, prey availability in the region. As exclusive benthic feeders, walruses are strongly associated with shallow, productive habitats that support abundant bivalve communities (Born et al., 2003; Fay, 1982; Fisher, 1989; Fisher & Stewart, 1997; Freitas et al., 2009). Walruses forage typically at a depth of less than 80 m (Fay, 1982), which corresponds to both depths of 59 m at FB-IGL1-23 and 26 m at FB-IGL2-23. Adult males can consume between 23 and 50 kg of biomass daily, making prey availability an important driver of habitat selection, particularly during summer (Born et al., 2003; Garde et al., 2018; Gebruk et al., 2021; Skern-Mauritzen et al., 2022). The high temporal autocorrelation observed in the model (AR(1): $\phi = 0.86$) further suggests repeated use of these habitats throughout the year.

Walrus presence was inferred using knocks, taps, and bell-sounds, which are calls typically associated with breeding behaviour (Larsen & Reichmuth, 2021; Sjare, 1993; Sjare & Stirling, 1996). At FB-IGL2-23, detections were distributed throughout the year, with a peak from January

to June 2024, which overlaps with the breeding season. From February to April, male walrus vocalize almost continuously underwater to establish dominance among males and advertise their reproductive fitness to females (Larsen & Reichmuth, 2021; Nowicki et al., 1997; Sjare et al., 2003; Sjare, 1993; Sjare & Stirling, 1996; Stirling et al., 1987). Daily detections during this period were consistent across both sites. Although the broader December to June window of intense vocal activity, associated with earlier vocal detection in the year, suggests it is not limited to breeding behaviour alone and may serve broader social or ecological functions. Mouy et al. (2012) suggested that knocks could be emitted in association with travelling behaviour or with foraging behaviour, such as exploration of the seafloor for prey. Panova et al. (2026) suggested that knocks outside of the breeding season may represent vocal practice by young males in preparation for future mating seasons. Males compete intensively for feeding and resting grounds (Solovyova et al., 2024), and might engage in aggressive underwater interactions (Kastelein, 2009). The ecological significance of knocks outside of the reproductive context remains poorly understood and needs further investigation.

Walrus rely heavily on sea ice for resting, moulting, nursing, accessing foraging grounds and avoiding predation (Fay, 1982; Kastelein, 2009; Moore & Huntington, 2008), which is consistent with SIC being the sole predictor and with the strong positive relationship between this variable and vocal presence. Seasonal movements of walrus are triggered by sea ice availability (Mansfield, 1958), where summering areas are known to be around the islands in the northern part of FB and wintering areas around the floe edge close to Rowley Island (Orr et al., 1986; Stewart, 2008; Figure S2.1). Lower number of detections between July and October 2023 may reflect reduced sea ice availability during this period, which could trigger walrus to haul out on terrestrial sites (Freitas et al., 2009; Mikkelsen et al., 2024; Solovyova et al., 2024) farther from FB-IGL1-23, reducing the vocal presence near that site. Based on the Atlantic walrus haul-out site database published by Cubaynes et al. (2026), the closest terrestrial haul-out to FB-IGL2-23 is on

Tangle Island (69.397°N, 80.198°W; Figure S2.1), approximately 11 km away, whereas the closest haul-out site to FB-IGL1-23 is on Tern Island (69.551°N, 80.843°W; Figure S2.1), approximately 26 km away. This difference in proximity to terrestrial haul-out habitat may explain the more even temporal distribution of detections observed at FB-IGL2-23 relative to FB-IGL1-23, given that walrus vocalizations can propagate up to 10 km underwater (Sjare et al., 2003; Sjare & Stirling, 1996). High vocal detections at FB-IGL1-23 and FB-IGL2-23 during winter could indicate the use of the area during this period for some individuals, with summer migrations towards terrestrial haul outs closer to FB-IGL2-23.

Bowhead whale

Bowhead whale acoustic detections at FB-IGL1-23 followed a seasonal pattern consistent with the migratory cycle of the Eastern Canada-West Greenland Arctic (EC-WG) population (Biddlecombe et al., 2023; Cosens & Blouw, 2003; Ferguson et al., 2010). During their summer aggregation in northern Foxe Basin, bowheads feed extensively (Cosens & Blouw, 2003; Diogou et al., 2023; Ferguson et al., 2010; George et al., 2015) to accumulate enough energy reserves required for their migration toward northern Hudson Bay and Hudson Strait (Fortune, 2018). The presence of polynyas north of Igloolik and the shallow productive waters at FB-IGL1-23 (Babb et al., 2026), likely create favourable foraging conditions for the EC-WG bowhead whale population. The peak in vocal activity observed at FB-IGL1-23 during summer aligns with this productive period in northern FB. The area has also been identified as a nursery ground (Hay et al., 2000; Heide-Jørgensen et al., 2010) with juveniles and calves representing 79-97% of individuals observed during aerial surveys (Cosens & Blouw, 2003). Nursing females communicate with calves through underwater vocalizations that maintain cohesion and coordination within groups (Würsig & Clark, 1993), which may contribute to the elevated detections observed during this period. Detections after freeze-up at FB-IGL1-23 may reflect delayed fall migration toward wintering areas. This could result from favourable prey availability or predator avoidance,

particularly from killer whales, as shallow waters may provide refuge from predation (Moore et al., 2021). The absence of detections after late December likely marks the departure southwards of bowheads from the area.

Bowhead whales are known to track the floe edge, moving northward as sea ice retreats in summer and southward with advancing pack ice in autumn (Ferguson et al., 2010). This aligns with the negative relationship between SIC and vocal presence observed in this study and previously reported in Amundsen Gulf (Diogou et al., 2023). Although SIC was a significant predictor of bowhead whale vocal presence, both locations experienced similar SIC conditions during summer (i.e., the ice-free period). Therefore, the higher vocal presence of bowhead whales at FB-IGL1-23 may instead reflect habitat preferences between sites. The spatial differences may be driven by factors not considered in the study, such as prey availability associated with differences in depth. Habitat features may also play an important role by providing suitable calving areas and reducing exposure to predators such as killer whales (Ferguson et al., 2010, 2012; Moore et al., 2000)

Beluga

Beluga call detections indicated vocal presence throughout the winter period. This contrasts with our initial hypothesis that detections would peak during migration periods, as beluga vocal activity was recorded outside the main migration periods typically described for the region. FB lies within the seasonal extent of the Eastern High Arctic-Baffin Bay population, when belugas migrate from their summering areas in Somerset Islands towards North Water or West Greenland (COSEWIC, 2020; Ferguson & Hansen, 2018). In FB, sightings of belugas are typically during summer and early fall before freeze-up (Paulic et al., 2014). The acoustic detections from October to March suggest that some individuals may continue to use northern Foxe Basin after freeze-up and throughout the winter period.

As belugas feed on ice-associated prey like Arctic cod, foraging behaviour could be facilitated by lower SST. Although vocalizations were not quantified by call type in this study, the presence of whistles, pulsed calls, and echolocation clicks at both sites suggests that belugas were not only transiting through the area but were also engaging in social and foraging behaviours (O'Neill, 2015; Sjare & Smith, 1986; Zahn et al., 2021). Local knowledge has also reported beluga engaging in feeding behaviour in the area (Stewart et al., 1995). The difference in vocal detections between sites may therefore reflect spatial variation in prey availability or proximity to productive areas such as polynyas. Additionally, sex segregation in winter habitat use may also contribute to the observed pattern. Females generally prefer coastal and estuarine habitats with lighter ice conditions, whereas males are more commonly associated with heavier pack ice (Barber et al., 2001; Hauser et al., 2017b). Therefore, winter vocal detections in FB may reflect male individuals, when SIC was approximately 75% or higher during this period.

Bearded seal

Bearded seal is a year-round resident species, present in high densities in northern FB (Fuirst et al., 2023), although limited information is available. Daily detections during April to July coincided with the breeding season, a period with increased vocal activity of males, in which trills are used to advertise reproductive fitness to females, and to defend territories (Cleator et al., 2011; Frouin-Mouy et al., 2016; Heimrich et al., 2021; Jones et al., 2014; Risch et al., 2007; Van Parijs et al., 2003). Almost no detections were recorded for FB-IGL1-23 between June and December. Similar seasonal declines in bearded seal vocal activity during open-water periods have been documented in other regions (Chou et al., 2020; Folz, 2024; Marcoux et al., 2017) and could be associated with transiting behaviour for juveniles (Breed et al., 2018), or may reflect seasonal migrations towards other areas (Melnikov, 2017).

Bearded seal trills are long-range vocalizations that can propagate over distances of 30-45 km under calm conditions (Cleator et al., 2011; Stirling, Calvert, & Cleator, 1983). Elevated

wind speeds could mask the vocalizations through an increase in underwater ambient noise (Dahl et al., 2007). However, wind speed may also reflect broader sea state conditions, as strong wind events are often associated with storm activity that could motivate bearded seals to seek refuge in sheltered areas or reduce vocal activity due to lower detectability (Llobet et al., 2023). The negative relationship between wind speed and vocal presence may reflect acoustic masking or behavioural response to harsh sea conditions, though these mechanisms cannot be distinguished using only passive acoustic monitoring.

Bearded seal vocal activity was highly seasonal at both sites, with detections occurring from December through July, and progressively increasing after the freeze-up to late March. Increases in vocal activity following freeze-up are consistent with previous studies showing that bearded seal vocalizations intensify as pack ice forms in winter (Breed et al., 2018; MacIntyre et al., 2013, 2015; Van Parijs et al., 2001). Stable sea ice conditions are essential for pupping, nursing, and moulting, especially over shallow waters close to benthic foraging areas (Kovacs, 2018). SIC has been identified as a strong predictor of ribbon and bearded seal vocal activity in the Bering Sea (Miksis-Olds & Madden, 2014), and bearded seal sightings were associated with 75-85% SIC in the Hudson Bay (Chambellant et al., 2012; Lunn et al., 2011). However, SIC did not explain enough variance in the dataset and was not retained as the best-supported model.

Habitat selection in bearded seals may also be driven by parameters not analyzed in this study, such as benthic prey availability (Gryba et al., 2019; Hamilton et al., 2018; Hjelset et al., 1999), as bearded seals have been found to spend 70% of their time foraging on benthos (McClintock et al., 2017). The high temporal autocorrelation in the model (AR(1): $\phi = 0.99$) indicates repeated use of both sites throughout the year, and both deployment sites appear to be suitable habitats for bearded seals in northern FB. Whether the bearded seal seasonal vocal pattern reflects annual site fidelity, as documented for breeding males returning to the same

grounds every year (Van Parijs et al., 2001; Van Parijs & Clark, 2006), would require multi-year acoustic monitoring.

Ringed seal

Ringed seals are found along the northwestern coastline in FB (NCRI, 2008), although they occur at lower densities compared to other areas (Paulic et al., 2014). Ringed seals also showed the lowest vocal detections among the five species, despite their wide circumpolar distribution (Smith, 1987), which may reflect habitat preferences or prey availability. Ringed seals also have a low call amplitude (Stirling, 1973), which likely reduces their detectability by PAM. Despite overall low detections, seasonal differences in occurrence were observed between sites. At FB-IGL2-23, ringed seals were detected from September to February, corresponding to freeze-up and early ice formation. In contrast, detections at FB-IGL1-23 occurred from March to July, with a peak in June. This complementary temporal pattern may indicate seasonal redistribution between sites. At freeze-up, ringed seals typically establish territories in landfast or pack ice, where stable ice is needed for breeding (Cleator et al., 2011; Kelly, 2022; Lydersen & Ryg, 1991; Smith & Hammill, 2011). Ringed seals breed from March to May (Lydersen & Ryg, 1991; Smith & Hammill, 2011), with increased vocal activity documented during this period (Mizuguchi et al., 2016; Stirling et al., 1983; Young et al., 2025). The peak in June at FB-IGL1-23 could reflect a later local breeding season, although further PAM effort would be needed to determine whether northern FB is used as a breeding ground.

Sea ice conditions are essential for ringed seals for moulting, reproduction, and pup-rearing, as they provide stable platforms and access to breathing holes (Reeves, 1998; Smith, 1987; Smith & Hammill, 2011). However, in this study, ringed seal vocal presence was best explained by SST and wind speed, while sea ice concentration was not retained as a predictor in the final model. These patterns may reflect the association of ringed seals with colder, more stable environmental conditions. During summer, as temperatures increase, ringed seals become less

vocal and more widely distributed, reducing their acoustic presence (Gjertz et al., 2000; Martinez-Bakker et al., 2013). However, the lack of significant environmental predictors suggests that other factors not examined in this study may also influence ringed seal vocal presence.

Ongoing environmental change may affect Arctic marine mammals differently in FB. Walrus and bearded seals are strongly dependent on sea ice for breeding, resting, and access to foraging habitat (Kovacs et al., 2011; Moore & Huntington, 2008), and shorter ice-covered seasons are expected to reduce the availability and duration of suitable habitat for these species. Whereas bowhead whales may benefit from increased open-water productivity and longer foraging seasons associated with sea ice decline (George et al., 2015), though increased killer whale access may offset these gains. Ringed seals and belugas have already shown shifts in distribution, migration timing, or habitat use in response to changing ice conditions elsewhere in the Arctic (Breed et al., 2018; Ferguson et al., 2005, 2017; Hauser et al., 2017a; Kovacs et al., 2011; O’Corry-Crowe et al., 2016; Reimer et al., 2019; Young & Ferguson, 2014).

2.5.2 Potential interspecific interactions

FB-IGL1-23 had more days with detected vocal presence for all species compared with FB-IGL2-23, indicating greater overall vocal activity at this site throughout the year. The co-occurrence of multiple species in northern FB and the overlap of vocal activity provide an opportunity to explore potential interactions between species. Walruses and bearded seals were both detected between January and May at both sites. Walruses can occasionally prey on seals, including bearded seals (COSEWIC, 2017; Fay et al., 1990; Lowry & Fay, 1984), which may influence bearded seal spatial behaviour in the study area. However, the absence of a significant site effect and the consistent detections of both species across locations suggest that predation pressure did not result in detectable acoustic displacement of bearded seals in northern FB. High acoustic detections of walrus may also be associated with reduced ringed seal occurrence, as walrus presence has been linked to local displacement of ringed seals in some regions, potentially

due to predation pressure (Reeves, 1998). Such predator-prey interactions may become increasingly important as declining Arctic sea ice is facilitating the northward expansion of killer whale range (Ferguson et al., 2025; Higdon & Ferguson, 2009; Kimber et al., 2025). Predation events on bowhead whales have increased with sea ice loss, particularly during calving season (Kimber et al., 2025; Willoughby et al., 2020), and belugas and bowheads may shift habitat use in response to killer whale presence (Ferguson et al., 2012, 2025; Higdon & Ferguson, 2009; Matthews et al., 2025). Although killer whale vocalizations were not assessed here, continued passive acoustic monitoring will be important for tracking future shifts in marine mammal occurrence.

Beyond predation, the co-occurrence of walruses and bearded seals also raises the possibility of resource competition. Both species are associated with shallow and productive benthic habitats and share several benthic prey resources, including bivalves (Dehn et al., 2006; Hjelset et al., 1999; Lowry et al., 1980). However, bearded seals also consume demersal and pelagic fishes, indicating a broader dietary niche compared to walruses, which rely predominantly on benthic bivalves (Finley & Evans, 1983). This partial overlap in diet implies some degree of resource partitioning, which may reduce direct competition and facilitate co-occurrence in northern FB. If benthic prey availability decreases in the future, interspecific competition could disproportionately affect walruses due to their restricted diet (Lowry et al., 1980). Further investigations, including compound-specific stable isotope analyses, could provide additional insight into prey partitioning and trophic interactions between both species in northern FB, as demonstrated in previous studies from the Bering Sea (Oxtoby et al., 2017). Interspecific interactions can also shape the underwater soundscape; ecoacoustics describes how species partition acoustic space through time and frequency within ecological communities (Sueur & Farina, 2015). Periods of high bowhead whale acoustic activity were associated with lower walrus detections, suggesting a potential temporal partitioning of the soundscape between the two

species. Similar patterns have previously been reported by Llobet et al. (2023), where walrus vocal activity decreased during periods of intense bowhead singing. Although this pattern could also reflect reduced walrus presence or acoustic masking.

2.5.3 Limitations

Passive acoustic monitoring presents inherent limitations that should be considered when interpreting the results of this study. Acoustic detections represent presence rather than abundance, and acoustic absence does not necessarily indicate true absence, as species may be present but not vocalizing.

Species detectability may vary according to vocal behaviour, ambient noise, and hydrophone location. Furthermore, the hydrophones operated on a duty cycle with a 54-minute off period, potentially missing vocalization detections. This limitation likely affected species differently depending on their vocal behaviour: species that vocalize for extended periods, such as walrus, bowhead whales, and bearded seals during peak activity, were less likely to be missed. In contrast, species that produce brief calls, such as ringed seals, may be more difficult to detect under this duty cycle, which could explain their low vocal presence at both sites (Michel et al., 2025; Rand et al., 2022). The analyses were also based on a single year of passive acoustic monitoring, limiting the ability to assess interannual variability in species occurrence and identify environmental drivers.

The systematic selection of recording hours for analysis was not aligned with the tidal cycle and therefore did not account for potential effects of tides on animal behaviour or acoustic detectability. Tides are predictable events that can influence underwater sound propagation through tidal currents, tidal phases, and turbidity (Mawer et al., 2026). However, tidal amplitudes in northwestern Foxe Basin are relatively small (1-4 m; Campbell & Collin, 2011), which may limit their influence. Future studies should consider including tidal phase or tidal current as a covariate.

2.6 Conclusion

This study demonstrates that Foxe Basin supports a diverse and seasonally dynamic marine mammal community throughout the year. Passive acoustic monitoring documented the presence of walrus, bowhead whale, beluga, bearded seal, and ringed seal, with species occurrence strongly influenced by seasonal environmental conditions, particularly sea ice dynamics. Sea ice concentration emerged as the primary environmental driver for several species, although the contrasting effects reflect how sea ice plays different ecological roles for each animal. Differences in detection patterns between species and recording sites highlight the ecological importance of northern Foxe Basin. Particular attention for management and conservation will be needed around FB-IGL1-23, as it supported a greater overall vocal activity.

Although this study could not resolve abundance, movement, or behavioural interactions, it provides valuable information on the seasonal and year-round use of Foxe Basin by five marine mammals. As sea ice declines and vessel traffic increases across the Arctic, multi-year passive acoustic monitoring will be essential for informing conservation in Foxe Basin. While extensive marine mammal research has been conducted in Hudson Bay, Foxe Basin remains comparatively understudied, and the results of this study underscore the need for further research in the region.

2.7 Literature cited

- Andrews, J., Babb, D., & Barber, D. G. (2018). Climate change and sea ice: Shipping in Hudson Bay, Hudson Strait, and Foxe Basin (1980–2016). *Elementa*, 6. <https://doi.org/10.1525/elementa.281>
- Asselin, N. C., Barber, D. G., Stirling, I., Ferguson, S. H., & Richard, P. R. (2011). Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biology* 2011 34:12, 34(12), 1973–1988. <https://doi.org/10.1007/S00300-011-0990-5>
- Babb, D., Kirillov, S., Galley, R., & Ehn, J. (2026). Sea Ice Dynamics in Foxe Basin: Formation of a Thick Dirty Seasonal Ice Cover along a Proposed Year-Round Shipping Route. *Arctic Science*. <https://doi.org/10.1139/AS-2026-0008>
- Bailleul, F., Lesage, V., Power, M., Doidge, D. W., & Hammill, M. O. (2012). Migration phenology of beluga whales in a changing Arctic. *Climate Research*, 53, 169–178. <https://www.jstor.org/stable/24875031>
- Barber, D. G., Saczuk, E., & Richard, P. R. (2001). Examination of Beluga-habitat Relationships through the Use of Telemetry and a Geographic Information System. *ARCTIC*, 54(3), 305–316. <https://doi.org/10.14430/ARCTIC790>
- Biddlecombe, B. A., Ferguson, S. H., Heide-Jørgensen, M. P., Gillis, D. M., & Watt, C. A. (2023). Estimating abundance of Eastern Canada-West Greenland bowhead whales using genetic mark-recapture analyses. *Global Ecology and Conservation*, 45. <https://doi.org/10.1016/j.gecco.2023.e02524>
- Born, E. W., Rysgaard, S., Ehlme, G., Sejr, M., Acquarone, M., & Levermann, N. (2003). Underwater observations of foraging free-living Atlantic walrus (*Odobenus rosmarus rosmarus*) and estimates of their food consumption. *Polar Biology*, 26(5), 348–357. <https://doi.org/10.1007/s00300-003-0486-z>
- Boveng, P. L., Chernook, V. I., Moreland, E. E., Conn, P. B., Trukhanova, I. S., Cameron, M. F., Christman, C. L., Crawford, J. A., Glazov, D. M., Harwood, L., Hou, B. X., Koslovsky, S. M., Lindsay, J. M., Litovka, D. I., London, J. M., McClintock, B. T., Platonov, N., Quakenbush, L., Richmond, E. L., ... Willoughby, A. (2025). Abundance and distribution of ringed and bearded seals in the Chukchi Sea: a reference for future trends. <https://doi.org/10.1139/as-2024-0068>, 11. <https://doi.org/10.1139/AS-2024-0068>
- Breed, G. A., Cameron, M. F., Ver Hoef, J. M., Boveng, P. L., Whiting, A., & Frost, K. J. (2018). Seasonal sea ice dynamics drive movement and migration of juvenile bearded seals *Erignathus barbatus*. *Marine Ecology Progress Series*, 600, 223–237. <https://doi.org/10.3354/meps12659>
- Campbell, N. J., & Collin, A. E. (2011). The Discoloration of Foxe Basin Ice. <https://doi.org/10.1139/F58-062>, 15(6), 1175–1188. <https://doi.org/10.1139/F58-062>
- Chambault, P., Albertsen, C. M., Patterson, T. A., Hansen, R. G., Tervo, O., Laidre, K. L., & Heide-Jørgensen, M. P. (2018). Sea surface temperature predicts the movements of an Arctic cetacean: the bowhead whale. *Scientific Reports* 2018 8:1, 8(1), 9658-. <https://doi.org/10.1038/s41598-018-27966-1>

- Chambellant, M., Lunn, N. J., & Ferguson, S. H. (2012). Temporal variation in distribution and density of ice-obligated seals in western Hudson Bay, Canada. *Polar Biology* 2012 35:7, 35(7), 1105–1117. <https://doi.org/10.1007/S00300-012-1159-6>
- Chou, E., Antunes, R., Sardelis, S., Stafford, K. M., West, L., Spagnoli, C., Southall, B. L., Robards, M., & Rosenbaum, H. C. (2020). Seasonal variation in Arctic marine mammal acoustic detection in the northern Bering Sea. *Marine Mammal Science*, 36(2), 522–547. <https://doi.org/10.1111/mms.12658>
- Citta, J. J., Quakenbush, L. T., Okkonen, S. R., Druckenmiller, M. L., Maslowski, W., Clement-Kinney, J., George, J. C., Brower, H., Small, R. J., Ashjian, C. J., Harwood, L. A., & Heide-Jørgensen, M. P. (2015). Ecological characteristics of core-use areas used by Bering–Chukchi–Beaufort (BCB) bowhead whales, 2006–2012. *Progress in Oceanography*, 136, 201–222. <https://doi.org/10.1016/J.POCEAN.2014.08.012>
- Citta, J. J., Quakenbush, L. T., George, J. C., Small, R. J., Heide-Jørgensen, M. P., Brower, H., Adams, B. & Brower, L. (2012). Winter movements of bowhead whales (*Balaena mysticetus*) in the Bering Sea. *Arctic*, 13-34.
- Cleator, H. J., Stirling, I., & Smith, T. G. (2011). Underwater vocalizations of the bearded seal (*Erignathus barbatus*). <https://doi.org/10.1139/Z89-272>, 67(8), 1900–1910. <https://doi.org/10.1139/z89-272>
- Cosens, S. E., & Blouw, A. (2003). Size- and age-class segregation of bowhead whales summering in northern Foxe Basin: A photogrammetric analysis. *Marine Mammal Science*, 19(2), 284–296. <https://doi.org/10.1111/J.1748-7692.2003.TB01109.X>;REQUESTEDJOURNAL:JOURNAL:17487692;WGROU:STRING: PUBLICATION
- COSEWIC. (2017). *COSEWIC Assessment and Status Report Atlantic Walrus *Odobenus rosmarus rosmarus* High Arctic population Central-Low Arctic population Nova Scotia-Newfoundland-Gulf of St. Lawrence population in Canada High Arctic population-SPECIAL CONCERN Central-Low Arctic population-SPECIAL CONCERN Nova Scotia-Newfoundland-Gulf of St. Lawrence population-EXTINCT 2017*. www.sararegistry.gc.ca/status/status_e.cfm
- COSEWIC. (2020). *COSEWIC assessment and status report on the Beluga Whale *Delphinapterus leucas*, Eastern High Arctic - Baffin Bay population, Cumberland Sound population, Ungava Bay population, Western Hudson Bay population, Eastern Hudson Bay population and James Bay population in Canada*.
- Cotillard, T., Sécheresse, X., Aubin, J., Mikus, M.-A., Vergara, V., Gambs, S., Michaud, R., Martins, C. C. A., Turgeon, S., Chion, C., & Roca, I. (2024). Automatic detection and classification of beluga whale calls in the St. Lawrence estuary. *The Journal of the Acoustical Society of America*, 156(6), 3723–3740. <https://doi.org/10.1121/10.0030472>
- Cubaynes, H. C., Matthews, C. J. D., Garde, E., Gavrillo, M., Heide-Jørgensen, M. P., Higdon, J. W., Kovacs, K. M., Leskova, M., Lydersen, C., Solovyev, B., Vergara-Pena, A., & Fretwell, P. T. (2026). A distribution-wide dataset of Atlantic walrus terrestrial haul-out sites. *Scientific Data* 2026 13:1, 13(1), 808-. <https://doi.org/10.1038/s41597-026-07210-6>

- Dahl, P. H., Miller, J. H., Cato, D. H., & Andrew, R. K. (2007). Underwater ambient noise. *Acoustics Today*, 23–33.
- Dehn, L. A., Sheffield, G. G., Follmann, E. H., Duffy, L. K., Thomas, D. L., & O'Hara, T. M. (2006). Feeding ecology of phocid seals and some walrus in the Alaskan and Canadian Arctic as determined by stomach contents and stable isotope analysis. *Polar Biology* 2006 30:2, 30(2), 167–181. <https://doi.org/10.1007/S00300-006-0171-0>
- Diogou, N., Halliday, W. D., Dosso, S. E., Mouy, X., Niemi, A., & Insley, S. J. (2023). Bowhead whale year-round acoustic presence and habitat associations in the Amundsen Gulf, Western Canadian Arctic, 2018–2019. *Progress in Oceanography*, 213. <https://doi.org/10.1016/j.pocean.2023.103004>
- Fay, F. H. (1982). Ecology and biology of the Pacific walrus, *Odobenus rosmarus divergens* Illiger. *North American Fauna*, (74), 1–279.
- Fay, F. H., Sease, J. L., & Merrick, R. L. (1990). Predation on a ringed seal *phoca hispida* and a black guillemot *cepheus grylle* by a pacific walrus *odobenus rosmarus divergens*. *Marine Mammal Science*, 6(4), 348–350. <https://doi.org/10.1111/J.1748-7692.1990.TB00364.X>
- Ferguson, S. H., Biddlecombe, B. A., Westdal, K., Petersen, S. D., Watt, C., Matthews, C. J. D., & Higdon, J. W. (2025). Killer whale range expansion and extended seasonal presence in the eastern Canadian Arctic, 2002–2023. *Frontiers in Marine Science*, 12, 1595960. <https://doi.org/10.3389/FMARS.2025.1595960/TEXT>
- Ferguson, S. H., Dueck, L., Loseto, L. L., & Luque, S. Á. P. (2010). Bowhead whale *Balaena mysticetus* seasonal selection of sea ice. *Marine Ecology Progress Series*, 411, 285–297. <https://doi.org/10.3354/MEPS08652>
- Ferguson, S. H., Kingsley, M. C. S., & Higdon, J. W. (2012). Killer whale (*Orcinus orca*) predation in a multi-prey system. *Population Ecology* 2011 54:1, 54(1), 31–41. <https://doi.org/10.1007/S10144-011-0284-3>
- Ferguson, S. H., Stirling, I., & McLoughlin, P. (2005). Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay. *Marine Mammal Science*, 21(1), 121–135. <https://doi.org/10.1111/J.17487692.2005>
- Ferguson, S. H., Young, B. G., Yurkowski, D. J., Anderson, R., Willing, C., & Nielsen, O. (2017). Demographic, ecological, and physiological responses of ringed seals to an abrupt decline in sea ice availability. *PeerJ*, 2017(2), e2957. <https://doi.org/10.7717/PEERJ.2957/SUPP-5>
- Ferguson, S., & Hansen, R. G. (2018). Annex 10: Eastern High Arctic – Baffin Bay and West Greenland beluga whale stock. In *NAMMCO (2018)*.
- Finley, K. J., & Evans, C. R. (1983). Summer Diet of the Bearded Seal (*Erignathus barbatus*) in the Canadian High Arctic. *ARCTIC*, 36(1), 82–89. <https://doi.org/10.14430/ARCTIC2246>
- Fisher, K. I. (1989). *Food habits and digestive efficiency in walrus, Odobenus rosmarus*. Thesis (M.Sc.) . University of Manitoba.
- Fisher, K. I., & R.E.A. Stewart. (1997). Summer foods of Atlantic walrus, *Odobenus rosmarus rosmarus*, in northern Foxe Basin, Northwest Territories. *Canadian Journal of Zoology*, 75(7), 1166–1175.

- Folz, N. M. (2024). *Tusâven aivik and utjuk? Observing bearded seal and walrus seasonal presence and underwater sounds from year-round ocean acoustic recordings in the Torngat Area of Interest, Nunatsiavut, Canada* [University of California San Diego]. <https://escholarship.org/uc/item/7tc8m1dn>
- Fortune, S. M. E. (2018). *Diet, feeding behaviour and habitat-use patterns of bowhead whales in the Eastern Canadian Arctic*. PhD Thesis. University of British Columbia. <https://doi.org/10.14288/1.0375660>
- Freitas, C., Kovacs, K. M., Ims, R. A., Fedak, M. A., & Lydersen, C. (2009). Deep into the ice: Over-wintering and habitat selection in male Atlantic walruses. *Marine Ecology Progress Series*, 375, 247–261. <https://doi.org/10.3354/meps07725>
- Frouin-Mouy, H., Mouy, X., Martin, B., & Hannay, D. (2016). Underwater acoustic behavior of bearded seals (*Erignathus barbatus*) in the northeastern Chukchi Sea, 2007-2010. *Marine Mammal Science*, 32(1), 141–160. <https://doi.org/10.1111/mms.12246>
- Fuirst, M., Ferguson, S. H., Higdon, J. W., Young, B. G., Lea, E. V., Koski, W. R., & Yurkowski, D. J. (2023). A review of aerial survey density estimates of bearded seals (*Erignathus barbatus*) in the Canadian Arctic highlights important knowledge gaps and research needs. *Polar Biology* 2023 46:12, 46(12), 1251–1263. <https://doi.org/10.1007/S00300-023-03200-1>
- Garde, E., Jung-Madsen, S., Ditlevsen, S., Hansen, R. G., Zinglensen, K. B., & Heide-Jørgensen, M. P. (2018). Diving behavior of the Atlantic walrus in high Arctic Greenland and Canada. *Journal of Experimental Marine Biology and Ecology*, 500, 89–99. <https://doi.org/10.1016/J.JEMBE.2017.12.009>
- Garland, E. C., Castellote, M., & Berchok, C. L. (2015). Beluga whale (*Delphinapterus leucas*) vocalizations and call classification from the eastern Beaufort Sea population . *The Journal of the Acoustical Society of America*, 137(6), 3054–3067. <https://doi.org/10.1121/1.4919338>
- Gebruk, A., Mikhaylyukova, P., Mardashova, M., Semenova, V., Henry, L. A., Shabalin, N., Narayanaswamy, B. E., & Mokievsky, V. (2021). Integrated study of benthic foraging resources for Atlantic walrus (*Odobenus rosmarus rosmarus*) in the Pechora Sea, south-eastern Barents Sea. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31(1), 112–125. <https://doi.org/10.1002/AQC.3418>
- George, J. C., Druckenmiller, M. L., Laidre, K. L., Suydam, R., & Person, B. (2015). Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. *Progress in Oceanography*, 136(8), 250–262. <https://doi.org/10.1016/j.pocean.2015.05.001>
- Gjertz, I., Kovacs, K. M., Lydersen, C., & Wiig, Å. (2000). Movements and diving of adult ringed seals (*Phoca hispida*) in Svalbard. *Polar Biology*, 23(9), 651–656. <https://doi.org/10.1007/S0030000000143/METRICS>
- Gryba, R. D., Wiese, F. K., Kelly, B. P., Von Duyke, A. L., Pickart, R. S., & Stockwell, D. A. (2019). Inferring foraging locations and water masses preferred by spotted seals *Phoca largha* and bearded seals *Erignathus barbatus*. *Marine Ecology Progress Series*, 631, 209–224. <https://doi.org/10.3354/MEPS13145>

- Halliday, W. D., Pine, M. K., & Insley, S. J. (2020). Underwater noise and Arctic marine mammals: review and policy recommendations. *https://doi.org/10.1139/Er-2019-0033*, 28(4), 438–448. <https://doi.org/10.1139/ER-2019-0033>
- Hamilton, C. D., Kovacs, K. M., & Lydersen, C. (2018). Individual variability in diving, movement and activity patterns of adult bearded seals in Svalbard, Norway. *Scientific Reports* 2018 8:1, 8(1), 16988-. <https://doi.org/10.1038/s41598-018-35306-6>
- Hammill, M. O., Mosnier, A., Gosselin, J.-F., Higdon, J. W., Stewart, D. B., Doniol-Valcroze, T., Ferguson, S. H., & Dunn, J. B. (2016). *Estimating abundance and total allowable removals for walrus in the Hudson Bay-Davis Strait and south and east Hudson Bay stocks during September 2014*. <http://www.dfo-mpo.gc.ca/csas-sccs/>
- Harwood, L. A., Smith, T. G., Auld, J. C., Melling, H., & Yurkowski, D. J. (2015). Seasonal movements and diving of ringed seals, *pusa hispida*, in the western canadian arctic, 1999–2001 and 2010–11. *Arctic*, 68(2), 193–209. <https://doi.org/10.14430/arctic4479>
- Hauser, D. D. W., Laidre, K. L., Stafford, K. M., Stern, H. L., Suydam, R. S., & Richard, P. R. (2017). Decadal shifts in autumn migration timing by Pacific Arctic beluga whales are related to delayed annual sea ice formation. *Global Change Biology*, 23(6), 2206–2217. <https://doi.org/10.1111/gcb.13564>
- Hauser, D. D. W., Laidre, K. L., Stern, H. L., Moore, S. E., Suydam, R. S., & Richard, P. R. (2017). Habitat selection by two beluga whale populations in the Chukchi and Beaufort seas. *PLOS ONE*, 12(2), e0172755. <https://doi.org/10.1371/JOURNAL.PONE.0172755>
- Hay, K., Aglukark, D., Igutsaq, D., Ikkidluak, J., & Mike, M. (2000). *Final Report of the Inuit Bowhead Knowledge Study, Nunavut, Canada*. <https://doi.org/10.25607/OBP-1675>
- Heide-Jørgensen, M., Laidre, K., Wiig, Ø., Postma, L., Dueck, L., & Bachmann, L. (2010). Large-scale sexual segregation of bowhead whales. *Endangered Species Research*, 13(1), 73–78. <https://doi.org/10.3354/esr00315>
- Heide-Jørgensen MP, L. K. W. Ø. J. M. and others. (2003). From Greenland to Canada in Ten Days: Tracks of Bowhead Whales, *Balaena mysticetus*, across Baffin Bay. *Arctic*, 56, 21. <https://www.jstor.org/stable/40512155>
- Heimrich, A. F., Halliday, W. D., Frouin-Mouy, H., Pine, M. K., Juanes, F., & Insley, S. J. (2021). Vocalizations of bearded seals (*Erignathus barbatus*) and their influence on the soundscape of the western Canadian Arctic. *Marine Mammal Science*, 37(1), 173–192. <https://doi.org/10.1111/mms.12732>
- Hersbach, H., Comyn-Platt, E., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N., Cagnazzo, C., & Cucchi, M. (2023). *ERA5 post-processed daily-statistics on pressure levels from 1940 to present*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).
- Higdon, J. W., & Ferguson, S. H. (2009). Loss of Arctic sea ice causing punctuated change in sightings of killer whales (*Orcinus orca*) over the past century. *Ecological Applications*, 19(5), 1365–1375. <https://doi.org/10.1890/07-1941.1;PAGE:STRING:ARTICLE/CHAPTER>

- Higdon, J. W., Stewart, D. B., & Stewart, R. E. A. (2022). *Atlantic walrus (Odobenus rosmarus rosmarus) in northern Hudson Bay-status, research needs, and monitoring opportunities Prepared for Oceans North under contract to Higdon Wildlife Consulting.*
- Hind, A. T., & Gurney, W. S. C. (1997). The Metabolic Cost Of Swimming In Marine Homeotherms. *Journal of Experimental Biology*, 200(3), 531–542. <https://doi.org/10.1242/JEB.200.3.531>
- Hjelset, A. M., Andersen, M., Gjertz, I., Lydersen, C., & Gulliksen, B. (1999). Feeding habits of bearded seals (*Erignathus barbatus*) from the Svalbard area, Norway. *Polar Biology*, 21(3), 186–193. <https://doi.org/10.1007/S003000050351/METRICS>
- Hochheim, K., & Barber, D. (2014). An update on the ice climatology of the Hudson Bay system. *Arctic, Antarctic, and Alpine Research*, 46(1), 66–83. <https://doi.org/10.1657/1938-4246-46.1.66>
- Insley, S. J., Halliday, W. D., & de Jong, T. (2017). Seasonal Patterns in Ocean Ambient Noise near Sachs Harbour, Northwest Territories. *Arctic*, 70(3), 239–248. <https://www.jstor.org/stable/26379737>
- Jones, J. M., Thayre, B. J., Roth, E. H., Mahoney, M., Sia, I., Mercuri, K., Jackson, C., Zeller, C., Clare, M., Bacon, A., Weaver, S., Gentes, Z., Small, R. J., Stirling, I., Wiggins, S. M., & Hildebrand, J. A. (2014). Ringed, bearded, and ribbon seal vocalizations north of Barrow, Alaska: Seasonal presence and relationship with sea ice. *Arctic*, 67(2), 203–222. <https://doi.org/10.14430/arctic4388>
- Kastelein, R. A. (2009). Walrus: *Odobenus rosmarus*. In *Encyclopedia of marine mammals* (pp. 1212–1217). Elsevier.
- Kathleen M. Stafford, & et al. (2012). Spitsbergen's endangered bowhead whales sing through the polar night. *Endangered Species Research*, 18, 95–103. <https://www.int-res.com/articles/feature/n018p095.pdf>
- Kelly, B. P. (2022). *The Ringed Seal: Behavioral Adaptations to Seasonal Ice and Snow Cover*. 553–597. https://doi.org/10.1007/978-3-030-88923-4_15
- Kimber, B. M., Braen, E. K., Wright, D. L., Harlacher, J. M., Crance, J. L., & Berchok, C. L. (2025). Less ice, more predators: passive acoustic monitoring shows variation in killer whale (*Orcinus orca*) presence in the U.S. Arctic with declining sea ice. *Polar Biology*, 48(1). <https://doi.org/10.1007/s00300-024-03332-y>
- Kingsley, M. C. S., & Stirling, I. (1991). Haul-out behaviour of ringed and bearded seals in relation to defence against surface predators. <https://doi.org/10.1139/Z91-257>, 69(7), 1857–1861. <https://doi.org/10.1139/z91-257>
- Kovacs, K. M. (2018). Bearded Seal: *Erignathus barbatus*. *Encyclopedia of Marine Mammals, Third Edition*, 83–86. <https://doi.org/10.1016/B978-0-12-804327-1.00063-7>
- Kovacs, K. M., Lydersen, C., Overland, J. E., & Moore, S. E. (2011). Impacts of changing sea-ice conditions on Arctic marine mammals. *Marine Biodiversity* 2011 41:1, 41(1), 181–194. <https://doi.org/10.1007/s12526-010-0061-0>

- Kowal, S., Gough, W. A., & Butler, K. (2024). Seasonal sea ice of Foxe Basin, Canada: Spatial and temporal evolution, 1971–2018. *Elementa*, 12(1). <https://doi.org/10.1525/elementa.2024.00033>
- Laidler, G. J., Ford, J. D., Gough, W. A., Ikummaq, T., Gagnon, A. S., Kowal, S., Qrunnut, K., & Irngaut, C. (2008). Travelling and hunting in a changing Arctic: assessing Inuit vulnerability to sea ice change in Igloodik, Nunavut. *Climatic Change* 2008 94:3, 94(3), 363–397. <https://doi.org/10.1007/s10584-008-9512-z>
- Laidre, K. L., & Regehr, E. V. (2016). Arctic marine mammals and sea ice. *Sea Ice: Third Edition*, 516–533. <https://doi.org/10.1002/9781118778371.ch21>
- Laidre, K. L., Stern, H., Kovacs, K. M., Lowry, L., Moore, S. E., Regehr, E. V., Ferguson, S. H., Wiig, Ø., Boveng, P., Angliss, R. P., Born, E. W., Litovka, D., Quakenbush, L., Lydersen, C., Vongraven, D., & Ugarte, F. (2015). Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conservation Biology*, 29(3), 724–737. <https://doi.org/10.1111/cobi.12474>
- Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, Ø., Heide-Jørgensen, M. P., & Ferguson, S. H. (2008). Quantifying the sensitivity of arctic marine mammals to climate-induced habitat change. In *Ecological Applications* (Vol. 18, Number SUPPL.2). <https://doi.org/10.1890/06-0546.1>
- Larsen, O. N., & Reichmuth, C. (2021). Walruses produce intense impulse sounds by clap-induced cavitation during breeding displays. *Royal Society Open Science*, 8(6). <https://doi.org/10.1098/rsos.210197>
- Llobet, S. M., Ahonen, H., Lydersen, C., & Kovacs, K. M. (2023). The Arctic and the future Arctic? Soundscapes and marine mammal communities on the east and west sides of Svalbard characterized through acoustic data. *Frontiers in Marine Science*, 10. <https://doi.org/10.3389/fmars.2023.1208049>
- Lowry, L. F., & Fay, F. H. (1984). Seal eating by walruses in the Bering and Chukchi Seas. *Polar Biology*, 3(1), 11–18.
- Lowry, L. F., Frost, K. J., & Burns, J. J. (1980). Feeding of Bearded Seals in the Bering and Chukchi Seas and Trophic Interaction with Pacific Walruses on JSTOR. *Arctic*, 33, 330–342.
- Lunn, N. J., Stirling, I., & Nowicki, S. N. (2011). Distribution and abundance of ringed (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) in western Hudson Bay. 54(4), 914–921. <https://doi.org/10.1139/F96-346>
- Lydersen, C. (2011). Monitoring ringed seal (*Phoca hispida*) activity by means of acoustic telemetry, 69(5), 1178–1182. <https://doi.org/10.1139/Z91-167>
- Lydersen, C., & Ryg, M. (1991). Evaluating breeding habitat and populations of ringed seals *Phoca hispida* in Svalbard fjords. *Polar Record*, 27(162), 223–228. <https://doi.org/10.1017/S0032247400012614>
- MacIntyre, K. Q., Stafford, K. M., Berchok, C. L., & Boveng, P. L. (2013). Year-round acoustic detection of bearded seals (*Erignathus barbatus*) in the Beaufort Sea relative to changing environmental conditions, 2008–2010. *Polar Biology* 2013 36:8, 36(8), 1161–1173. <https://doi.org/10.1007/S00300-013-1337-1>

- MacIntyre, K. Q., Stafford, K. M., Conn, P. B., Laidre, K. L., & Boveng, P. L. (2015). The relationship between sea ice concentration and the spatio-temporal distribution of vocalizing bearded seals (*Erignathus barbatus*) in the Bering, Chukchi, and Beaufort Seas from 2008 to 2011. *Progress in Oceanography*, 136, 241–249. <https://doi.org/10.1016/J.POCEAN.2015.05.008>
- Mansfield, A. W. (1958). The biology of the Atlantic walrus *Odobenus rosmarus rosmarus* (Linnaeus) in the eastern Canadian Arctic. *Fisheries Research Board of Canada Manuscript Report*.
- Marcoux, M., Ferguson, S. H., Roy, N., Bedard, J. M., & Simard, Y. (2017). Seasonal marine mammal occurrence detected from passive acoustic monitoring in Scott Inlet, Nunavut, Canada. *Polar Biology*, 40(5), 1127–1138. <https://doi.org/10.1007/s00300-016-2040-9>
- Martinez-Bakker, M. E., Sell, S. K., Swanson, B. J., Kelly, B. P., & Tallmon, D. A. (2013). Combined Genetic and Telemetry Data Reveal High Rates of Gene Flow, Migration, and Long-Distance Dispersal Potential in Arctic Ringed Seals (*Pusa hispida*). *PLOS ONE*, 8(10), e77125. <https://doi.org/10.1371/JOURNAL.PONE.0077125>
- Martini, I. P., & Morrison, R. I. G. (2014). Coasts of foxe basin, arctic Canada. *Geological Society Special Publication*, 388(1), 165–198. <https://doi.org/10.1144/SP388.14>
- Matthes, L. C., Ehn, J. K., Dalman, L. A., Babb, D. G., Peeken, I., Harasyn, M., Kirillov, S., Lee, J., Bélanger, S., Tremblay, J., Barber, D. G., & Mundy, C. J. (2021). Environmental drivers of spring primary production in Hudson Bay. *Elementa*, 9(1). <https://doi.org/10.1525/elementa.2020.00160>
- Matthews, C. J. D., Breed, G. A., Leblanc, B., Ferguson, S. H., & Estes, J. A. (2025). *Killer whale presence drives bowhead whale selection for sea ice in Arctic seascapes of fear*. <https://doi.org/10.1073/pnas.1911761117/-/DCSupplemental>
- Mawer, R., Franconi, N., Linley-Adams, T., Blow, G., Duke, O., Jones, A., Rees, C., Breckels, M., Gregory, S., Maxwell, D., Velterop, R., & Clarke, D. (2026). Going with the flow: tidal and tag influences upon the performance of acoustic telemetry systems. *Animal Biotelemetry* 2026 14:1, 14(1), 14-. <https://doi.org/10.1186/S40317-026-00453-5>
- McClintock, B. T., London, J. M., Cameron, M. F., & Boveng, P. L. (2017). Bridging the gaps in animal movement: Hidden behaviors and ecological relationships revealed by integrated data streams. *Ecosphere*, 8(3), e01751. <https://doi.org/10.1002/ECS2.1751>;WEBSITE:WEBSITE:ESAJOURNALS;ISSUE:ISSUE:DOI
- Meier, W., Stewart, J., Wilcox, H., Hardman, M., & Scott, D. (2021). *Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations, Version 2. [F16 sensor]*. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: <https://doi.org/10.5067/YTTHO2FJQ97K>. [03:09:2025].
- Melnikov, V. V. (2017). Seasonal Movements and Relative Abundance of Bearded Seals (*Erignathus barbatus*) in the Coastal Waters of the Chukotka Peninsula. *ARCTIC*, 70(4), 403–413. <https://doi.org/10.14430/ARCTIC4682>

- Michel, M., Béseau, J., Torterotot, M., Todd, N., & Samaran, F. (2025). Effects of duty cycle on passive acoustic monitoring metrics: The case of odontocete vocalizations. *The Journal of the Acoustical Society of America*, 158(6), 5033–5046. <https://doi.org/10.1121/10.0039925>
- Miksis-Olds, J. L., & Madden, L. E. (2014). Environmental Predictors of Ice Seal Presence in the Bering Sea. *PLOS ONE*, 9(9), e106998. <https://doi.org/10.1371/journal.pone.0106998>
- Miksis-Olds, J. L., Stabeno, P. J., Napp, J. M., Pinchuk, A. I., Nystuen, J. A., Warren, J. D., & Denes, S. L. (2013). Ecosystem response to a temporary sea ice retreat in the Bering Sea: Winter 2009. *Progress in Oceanography*, 111, 38–51. <https://doi.org/10.1016/j.pocean.2012.10.010>
- Mizuguchi, D., Tsunokawa, M., Kawamoto, M., Kohshima, S., Mizuguchi, Daisuke, Tsunokawa, Masatoshi, Kawamoto, Mamoru, Kohshima, & Shiro. (2016). Underwater vocalizations and associated behavior in captive ringed seals (*Pusa hispida*). *PoBio*, 39(4), 659–669. <https://doi.org/10.1007/S00300-015-1821-X>
- Moore, S. E., deMaster, D. P., & Dayton, P. K. (2000). Cetacean Habitat Selection in the Alaskan Arctic during Summer and Autumn. *Arctic*, 53(4), 432–447. <https://www.jstor.org/stable/40512256>
- Moore, S. E., George, J. C., & Reeves, R. R. (2021). Bowhead whale ecology in changing high-latitude ecosystems. *The Bowhead Whale: Balaena Mysticetus: Biology and Human Interactions*, 417–427. <https://doi.org/10.1016/B978-0-12-818969-6.00027-3>
- Moore, S. E., & Huntington, H. P. (2008). Arctic marine mammals and climate change: Impacts and resilience. In *Ecological Applications* (Vol. 18, Number SUPPL.2). <https://doi.org/10.1890/06-0571.1>
- Mouy, X., Hannay, D., Zykov, M., & Martin, B. (2012). Tracking of Pacific walruses in the Chukchi Sea using a single hydrophone. *The Journal of the Acoustical Society of America*, 131(2), 1349–1358. <https://doi.org/10.1121/1.3675008>
- NCRI. (2008). *Iglulik Pilot Project*.
- Nishino, S., Kawaguchi, Y., Inoue, J., Hirawake, T., Fujiwara, A., Futsuki, R., Onodera, J., & Aoyama, M. (2015). Nutrient supply and biological response to wind-induced mixing, inertial motion, internal waves, and currents in the northern Chukchi Sea. *Journal of Geophysical Research: Oceans*, 120(3), 1975–1992. <https://doi.org/10.1002/2014JC010407>;PAGEGROUP:STRING:PUBLICATION
- Nowicki, S. N., Stirling, I., & Sjare, B. (1997). Duration of stereotyped underwater vocal displays by male Atlantic walruses in relation to aerobic dive limit. *Marine Mammal Science*, 13(4), 566–575. <https://doi.org/10.1111/j.1748-7692.1997.tb00084.x>
- O’Corry-Crowe, G., Mahoney, A. R., Suydam, R., Quakenbush, L., Whiting, A., Lowry, L., & Harwood, L. (2016). Genetic profiling links changing sea-ice to shifting beluga whale migration patterns. *Biology Letters*, 12(11). <https://doi.org/10.1098/rsbl.2016.0404>
- O’Neill, C. (2015). Marine Mammal Vocalisations in the High Arctic: Resolute Bay, Nunavut. *Canadian Acoustics*, 43(3).

- Orr, J. R., Renooy, B., & Dhalke, L. (1986). *Information from hunts and surveys of walrus (Odobenus rosmarus) in northern Foxe Basin, Northwest Territories, 1982-1984.*
- Oxtoby, L. E., Horstmann, L., Budge, S. E., O'Brien, D. M., Wang, S. W., Schollmeier, T., & Wooller, M. J. (2017). *Resource partitioning between Pacific walruses and bearded seals in the alaska arctic and sub-arctic.*
- Panova, E. M., Tolstoy, M. L., Belikov, R. A., & Bogomolova, I. M. (2026). Summer underwater vocalizations of male Atlantic walruses *Odobenus rosmarus rosmarus* near their terrestrial haul-out site. *Behavioural Processes*, 237, 105362. <https://doi.org/10.1016/j.beproc.2026.105362>
- Parkinson, C. L. (2014). Spatially mapped reductions in the length of the Arctic sea ice season. *Geophysical Research Letters*, 41(12), 4316–4322. <https://doi.org/10.1002/2014GL060434>
- Paulic, J. E., Cleator, H., Fisheries, K. A. M., & Canada, O. (2014). *Ecologically and biologically significant areas (EBSA) in northern Foxe Basin: identification and delineation.* <http://www.dfo-mpo.gc.ca/csas-sccs/>
- Popova, E. E., Yool, A., Coward, A. C., Aksenov, Y. K., Alderson, S. G., De Cuevas, B. A., & Anderson, T. R. (2010). Control of primary production in the Arctic by nutrients and light: Insights from a high resolution ocean general circulation model. *Biogeosciences*, 7(11), 3569–3591. <https://doi.org/10.5194/BG-7-3569-2010>
- Rand, Z. R., Wood, J. D., & Oswald, J. N. (2022). Effects of duty cycles on passive acoustic monitoring of southern resident killer whale (*Orcinus orca*) occurrence and behavior. *The Journal of the Acoustical Society of America*, 151(3), 1651–1660. <https://doi.org/10.1121/10.0009752>
- Reeves, R. R. (1998). Distribution, abundance and biology of ringed seals (*Phoca hispida*): an overview. *NAMMCO Scientific Publications*, 1, 9–45. <https://doi.org/10.7557/3.2979>
- Reimer, J. R., Caswell, H., Derocher, A. E., & Lewis, M. A. (2019). Ringed seal demography in a changing climate. *Ecological Applications*, 29(3), e01855. <https://doi.org/10.1002/EAP.1855>;PAGEGROUP:STRING:PUBLICATION
- Risch, D., Clark, C. W., Corkeron, P. J., Elepfandt, A., Kovacs, K. M., Lydersen, C., Stirling, I., & Van Parijs, S. M. (2007). Vocalizations of male bearded seals, *Erignathus barbatus*: classification and geographical variation. *Animal Behaviour*, 73(5), 747–762. <https://doi.org/10.1016/j.anbehav.2006.06.012>
- Sakshaug, E. (2004). Primary and Secondary Production in the Arctic Seas. *The Organic Carbon Cycle in the Arctic Ocean*, 57–81. https://doi.org/10.1007/978-3-642-18912-8_3
- Shajahan, N., Halliday, W. D., & Insley, S. (2024). Under-ice ambient noise and its masking effect on marine mammals in the Arctic. *The Journal of the Acoustical Society of America*, 156(4_Supplement), A112–A112. <https://doi.org/10.1121/10.0035288>
- Sjare, B. L. (1993). *Vocalizations and breeding behavior of Atlantic walruses in the Canadian High Arctic.*

- Sjare, B. L., & Smith, T. G. (1986). The vocal repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. *https://doi.org/10.1139/Z86-063*, 64(2), 407–415. <https://doi.org/10.1139/z86-063>
- Sjare, B., & Stirling, I. (1996). The breeding behavior of Atlantic walruses, *Odobenus rosmarus rosmarus*, in the Canadian High Arctic. *Canadian Journal of Zoology*, 74(5), 897–911. <https://doi.org/10.1139/z96-103>
- Sjare, B., Stirling, I., & Spencer, C. (2003). Structural variation in the songs of Atlantic walruses breeding in the Canadian High Arctic. *Aquatic Mammals*, 29(2), 297–318.
- Skern-Mauritzen, M., Lindstrøm, U., Biuw, M., Elvarsson, B., Gunnlaugsson, T., Haug, T., Kovacs, K. M., Lydersen, C., McBride, M. M., Mikkelsen, B., Øien, N., & Víkingsson, G. (2022). Marine mammal consumption and fisheries removals in the Nordic and Barents Seas. *ICES Journal of Marine Science*, 79(5), 1583–1603. <https://doi.org/10.1093/ICESJMS/FSAC096>
- Smith, T. G. (1987). The ringed seal, *Phoca hispida*, of the Canadian western Arctic. *Department of Fisheries and Oceans*, 216.
- Smith, T. G., & Hammill, M. O. (2011). Ecology of the ringed seal, *Phoca hispida*, in its fast ice breeding habitat. *https://doi.org/10.1139/Z81-135*, 59(6), 966–981. <https://doi.org/10.1139/Z81-135>
- Solovyova, M., Gebruk, A., Artemyeva, S., Rozhnov, V. V., Isachenko, A., Lazareva, R., Chukmasov, P., Glazov, D., Ermilova, Y., Kokorin, A., Mardashova, M., & Shabalin, N. (2024). The movement patterns and foraging resources of Atlantic walruses (*Odobenus rosmarus rosmarus*) in Franz Josef Land archipelago and connectivity with the Kara – Barents Sea population. *Mar Mamm Sci*, 40(3). <https://doi.org/10.1111/mms.13103>
- Stafford, K. M. (2022). Singing Behavior in the Bowhead Whale. In *Ethology and behavioral ecology of mysticetes* (pp. 277–295). Springer, Cham. https://doi.org/10.1007/978-3-030-98449-6_12
- Stafford, K. M., & Clark, C. W. (2021). Acoustic behavior. *The Bowhead Whale: Balaena Mysticetus: Biology and Human Interactions*, 323–338. <https://doi.org/10.1016/B978-0-12-818969-6.00022-4>
- Stewart, by D., Akeeqok, A., Arnarualik, R., Panipakutsuk, S., & Taqtu, A. (1995). *Local knowledge of beluga and narwhal from four communities in arctic canada*.
- Stewart, R. E. A. (2008). Redefining walrus stocks in Canada. *Arctic*, 61(3), 292–308.
- Stirling, I. (1973). Vocalization in the ringed seal (*Phoca hispida*). *J. Fish. Res. Board. Can.* 30 1592-1594.
- Stirling, I. (1983). The evolution of mating systems in pinnipeds. In *Advances in the study of mammalian behavior* (Vol. 7, pp. 489–527).
- Stirling, I., Calvert, W., & Cleator, H. (1983). Underwater vocalizations as a tool for studying the distribution and relative abundance of wintering pinnipeds in the High Arctic. *Arctic*, 262–274.

- Stirling, I., Calvert, W., & Spencer, C. (1987). Evidence of stereotyped underwater vocalizations of male Atlantic walrus (*Odobenus rosmarus rosmarus*). *Canadian Journal of Zoology*, 65(9), 2311–2321. <https://doi.org/10.1139/z87-348>
- Sueur, & Farina. (2015). *Ecoacoustics the Ecological Investigation Interpretation of environmental sound*.
- Tivy, A., Howell, S. E. L., Alt, B., McCourt, S., Chagnon, R., Crocker, G., Carrieres, T., & Yackel, J. J. (2011). Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service Digital Archive, 1960–2008 and 1968–2008. *Journal of Geophysical Research: Oceans*, 116(3), 3007. <https://doi.org/10.1029/2009JC005855>
- Van Opzeeland, I., Van Parijs, S., Bornemann, H., Frickenhaus, S., Kindermann, L., Klinck, H., Plötz, J., & Boebel, O. (2010). Acoustic ecology of antarctic pinnipeds. *Marine Ecology Progress Series*, 414, 267–291. <https://doi.org/10.3354/meps08683>
- Van Parijs, S. M., & Clark, C. W. (2006). Long-term mating tactics in an aquatic-mating pinniped, the bearded seal, *Erignathus barbatus*. *Animal Behaviour*, 72(6), 1269–1277. <https://doi.org/10.1016/J.ANBEHAV.2006.03.026>
- Van Parijs, S. M., Kovacs, K. M., & Lydersen, C. (2001). Spatial and temporal distribution of vocalising male bearded seals: implications for male mating strategies. *Behaviour*, 905–922.
- Van Parijs, S. M., Lydersen, C., & Kovacs, K. M. (2003). Vocalizations and movements suggest alternative mating tactics in male bearded seals. *Animal Behaviour*, 65(2), 273–283. <https://doi.org/10.1006/anbe.2003.2048>
- Willoughby, A. L., Ferguson, M. C., Stimmelmayer, R., Clarke, J. T., & Brower, A. A. (2020). Bowhead whale (*Balaena mysticetus*) and killer whale (*Orcinus orca*) co-occurrence in the U.S. Pacific Arctic, 2009–2018: evidence from bowhead whale carcasses. *Polar Biology* 2020 43:11, 43(11), 1669–1679. <https://doi.org/10.1007/S00300-020-02734-Y>
- Würsig, B., & Clark, C. (1993). The Bowhead Whale: Behavior. In *The bowhead whale* (pp. 157–199). Society for Marine Mammalogy.
- Young, B. G., & Ferguson, S. H. (2014). Using stable isotopes to understand changes in ringed seal foraging ecology as a response to a warming environment. *Marine Mammal Science*, 30(2), 706–725. <https://doi.org/10.1111/MMS.12075>;PAGE:STRING:ARTICLE/CHAPTER
- Young, M., Nykänen, M., Niemi, M., Kurkilahti, M., & Kunnasranta, M. (2025). Aquatic vocalization activity indicates the timing of the mating season of Saimaa ringed seals. *Marine Mammal Science*, 41(3), e13225. <https://doi.org/10.1111/MMS.13225>
- Zahn, M. J., Rankin, S., McCullough, J. L. K., Koblitz, J. C., Archer, F., Rasmussen, M. H., & Laidre, K. L. (2021). Acoustic differentiation and classification of wild belugas and narwhals using echolocation clicks. *Scientific Reports* 2021 11:1, 11(1), 22141-. <https://doi.org/10.1038/s41598-021-01441-w>

2.8 Supplementary materials

Table S2.1. Model selection results for five species based on AICc. For each species, the five best-supported models are listed. SIC = sea ice concentration; Wind = wind speed; SST = sea surface temperature; x = predictor retained; ΔAICc = difference in AICc from best-supported model; w = Akaike weight. Walrus and bearded seal models include a fixed AR(1) autocorrelation structure across all models tested

	Predictors				df	Model fit			
	SIC	Wind	SST	Site		AICc	ΔAICc	Log Likelihood	w
<i>Walrus</i>									
1	x				4	621.87	0.00	-306.91	0.209
2	x			x	5	622.53	0.67	-306.22	0.150
3	x	x			5	622.67	0.80	-306.29	0.140
4	x		x		5	622.67	0.81	-306.30	0.140
5	x		x	x	6	623.15	1.29	-305.52	0.110
<i>Bowhead Whale</i>									
1	x	x		x	4	355.80	0.00	-173.87	0.409
2	x			x	3	356.30	0.50	-175.14	0.319
3	x	x	x	x	5	357.80	2.00	-173.86	0.151
4	x		x	x	4	358.28	2.48	-175.11	0.118
5			x	x	3	366.69	10.89	-180.33	0.002
<i>Beluga Whale</i>									
1			x	x	3	243.76	0.00	-118.86	0.204
2	x	x		x	4	243.85	0.08	-117.90	0.196
3		x	x	x	4	244.14	0.38	-118.04	0.169
4	x	x	x	x	5	244.92	1.16	-117.42	0.114
5	x			x	3	245.11	1.35	-119.54	0.104
<i>Bearded Seal</i>									
1		x			4	382.43	0.00	-187.19	0.211
2	x	x			5	383.01	0.58	-186.46	0.158
3		x	x		5	383.76	1.33	-186.84	0.108
4		x		x	5	384.37	1.94	-187.14	0.080
5	x				4	384.51	2.08	-188.23	0.074

Ringed Seal

1		x	x		3	249.84	0.00	-121.90	0.180
2			x		2	250.91	1.07	-123.45	0.106
3	x	x			3	251.07	1.23	-122.52	0.097
4		x	x	x	4	251.41	1.57	-121.68	0.082
5	x				2	251.42	1.58	-123.70	0.082

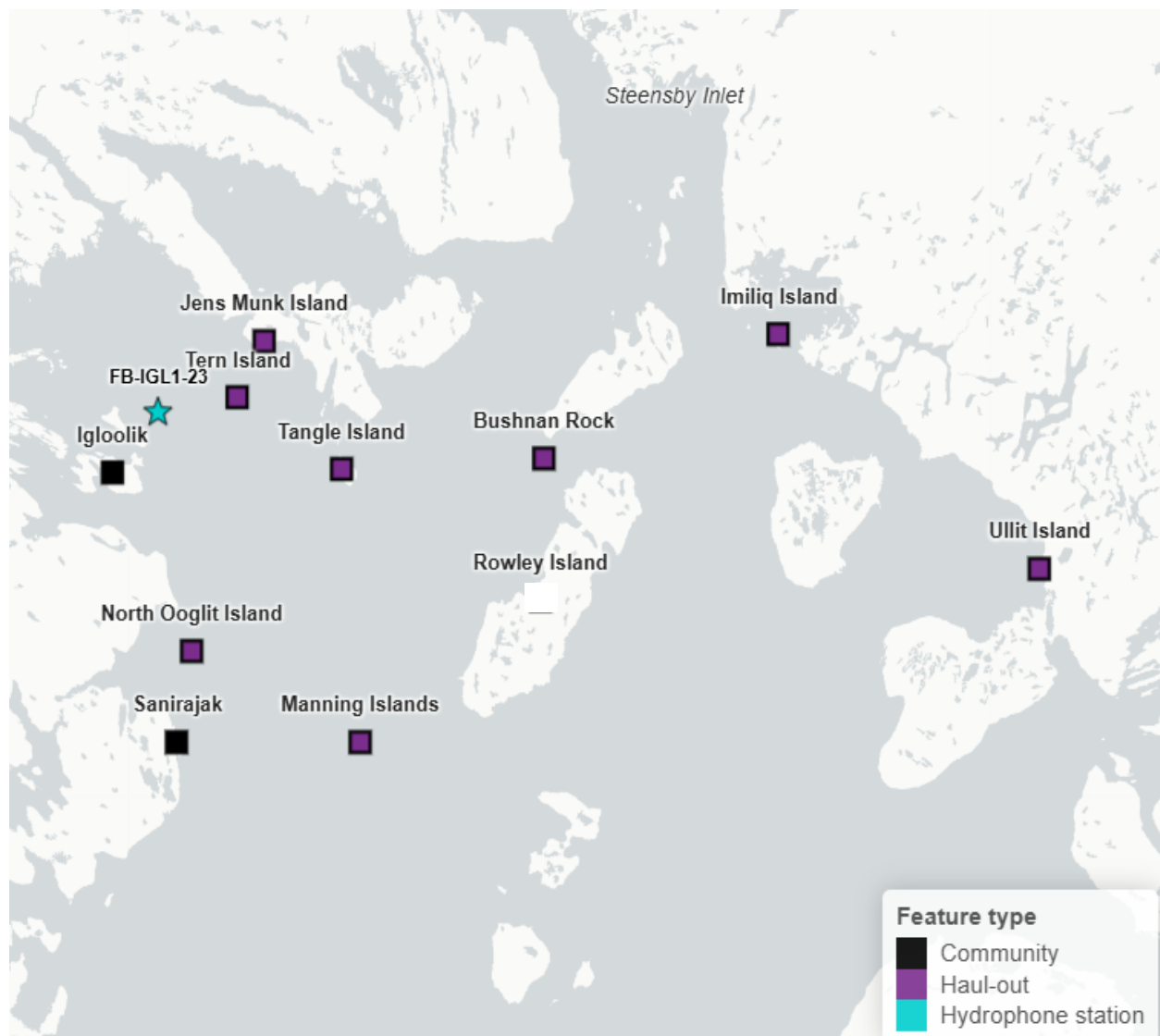


Figure S2.1 Map of the documented haul-outs (purple square) in Northern Foxe Basin, with the hydrophone location FB-IGL1-23 (blue star), and the communities of Igloolik and Sanirajak. In Inuktitut: Tangle Island is Nuvuklit and Tern Island is Siuraq. Haul-out coordinates were available on CAFF – Arctic Biodiversity Data Service (ABDS): <https://geo.abds.is/geonetwork/srv/eng/catalog.search#/metadata/fcdc5e58-3318-4a02-a484-8ecb7cfb66e2>.

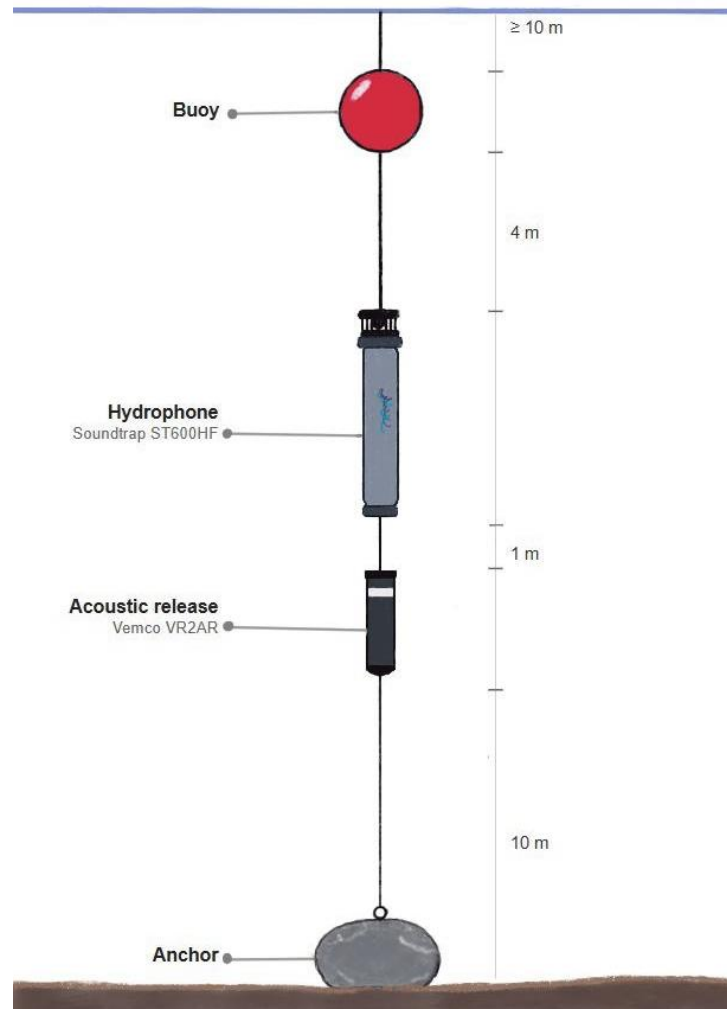


Figure S2.2 Diagram of a mooring equipped with a buoy, a hydrophone Soundtrap ST600HF, an acoustic release VEMCO VR2AR, and an anchor. Deployed at FB-IGL1-23 and FB-IGL2-23 between 2023-2024. Drawn on Procreate, version 5.3, Savage Interactive Pty Ltd.

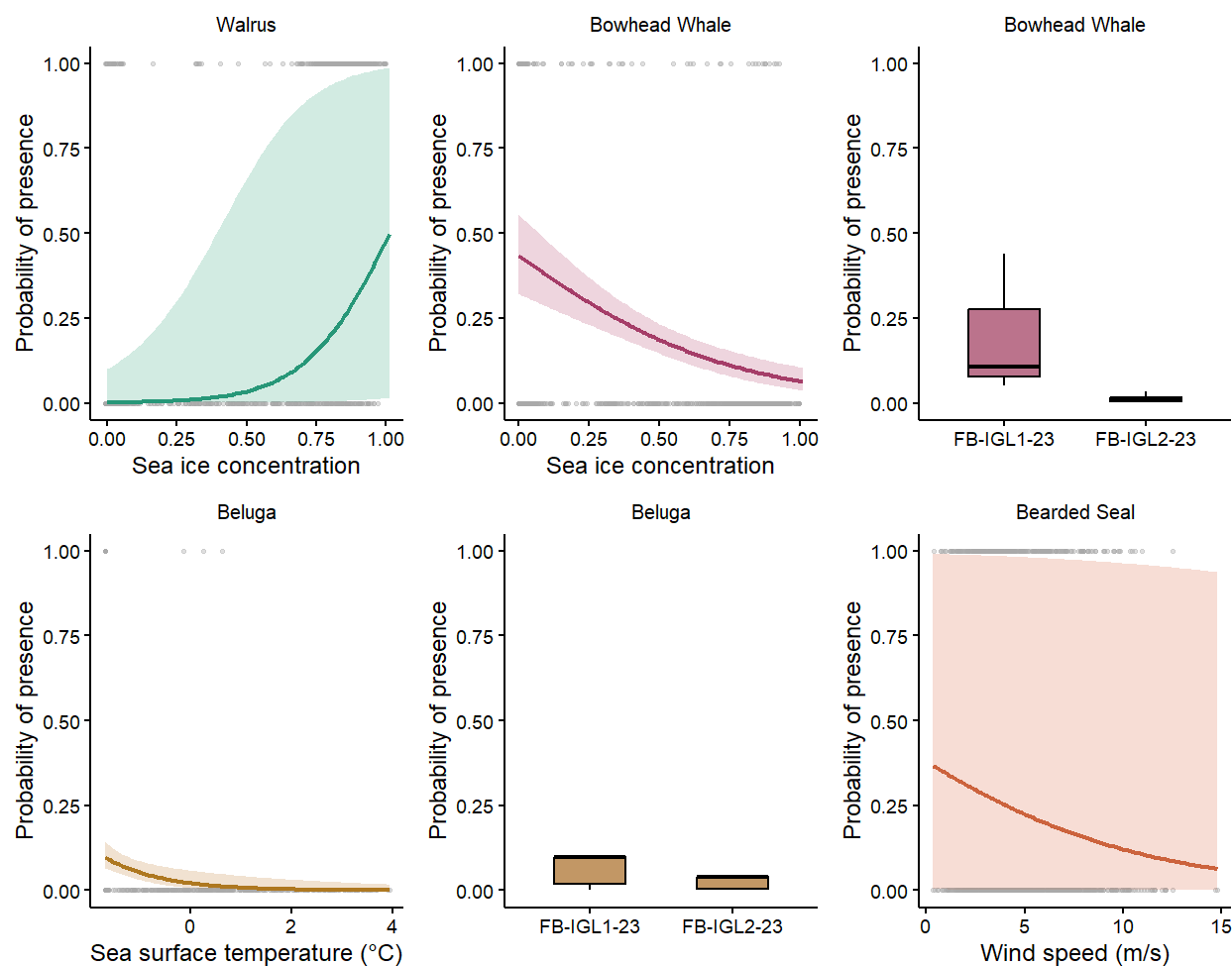


Figure S2.3 For each species, the probability of presence in relation to significant environmental predictors. Grey points = individual observations. Lines represent fitted probabilities from the best-supported logistic regression model with 95% confidence intervals (shaded). For species with a significant interaction between two predictors, the curves correspond to low (mean - 1 SD) and high (mean + 1 SD) values of the variable, calculated from the dataset.

Chapter 3 Impact of vessel traffic and proximity on walrus vocal behaviour in northwest Foxe Basin

3.1 Abstract

Shipping corridors increasingly overlap with marine mammal habitats, exposing species to vessel noise that often falls within their hearing ranges and can disrupt navigation, breeding, foraging, and social interactions. This study investigated the impacts of vessel traffic on Atlantic walrus (*Odobenus rosmarus rosmarus*) vocal activity in northern Foxe Basin, Nunavut, a region expected to see substantial increases in shipping in the coming years. Walrus vocal activity was monitored using a single hydrophone during the shipping season from August to October 2023. Automatic Identification System (AIS) data were used to extract ship ID, type, speed, and position within a 100 km buffer zone around the hydrophone for the same period. Walruses vocalized throughout the monitoring period, but hourly knock counts were 50% lower during the shipping season than before the first vessel arrival. During the shipping season, a decrease in walrus vocal activity was associated with higher vessel speeds and closer vessel proximity to the hydrophone. This decline may reflect acoustic masking by vessel noise, active reductions in vocal activity, or displacement from the area. The presence of two or more vessels in the area was associated with increased vocal activity, possibly reflecting a Lombard effect in walruses when faced with elevated ambient noise levels. No effect of vessel type was detected. Although the present study could not determine the exact cause of these responses to vessel disturbance, the results indicate that vessel traffic alters walrus acoustic behaviour, even at relatively low levels of shipping activity. Further research is needed to characterize walrus responses to vessel disturbance and determine whether specific thresholds of vessel activity, proximity, or noise levels exist. In the meantime, proactive conservation and management measures are needed before sustained increases in vessel traffic occur in the Foxe Basin region.

3.2 Introduction

Anthropogenic activities in the Arctic, including shipping, oil and mineral exploration, commercial fisheries, military operations, and tourism, are expected to intensify in the coming decades, as sea ice continues to decline (Erbe et al., 2019; Jaramillo et al., 2022). The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) reports a 25% increase in the number of vessels entering Arctic waters and a 75% increase in total distance travelled between 2013 and 2019 (Jaramillo et al., 2022). Shipping activity introduces many threats to Arctic ecosystems, including oil spills, ship strikes, habitat alteration, the introduction of exotic species, and underwater noise (Richardson et al., 1995; Erbe et al., 2018). In the Arctic, sea ice has historically limited vessel access and kept the underwater soundscape among the quietest globally. However, noise levels have doubled between 2013 and 2019 in some regions, with shipping noise increasingly dominating lower frequencies (Khopkar et al., 2026; Ladegaard et al., 2021; PAME, 2021).

Marine mammals rely fundamentally on sound for navigation, communication, foraging, and predator avoidance (Tyack, 2008). Consequently, shipping noise has become a major environmental concern because it overlaps with the acoustic frequencies used by marine mammals (PAME, 2021). Vessel noise, which typically occurs between 10 Hz and 1 kHz (PAME, 2021), can mask biologically important sounds by interfering with the detection, recognition, and discrimination of acoustic signals (Moore et al., 2012; Gomez et al., 2016). Acoustic masking can impair communication between signalers and receivers, interfere with echolocation, and reduce the ability to detect predators or environmental cues (Erbe, 2012). Such disruptions may reduce communication efficiency, affecting reproduction or foraging success (Erbe et al., 2018; Khopkar et al., 2026). Beyond acoustic masking, vessel noise can elicit a range of behavioural responses, including displacement, interruption of ongoing activities, and changes in movement and diving behaviour (Richardson et al., 1995; Moore et al., 2012; Gomez et al., 2016; Erbe et al., 2019). It may also alter vocal behaviour by reducing communication range or inducing changes in calling

rate, vocal intensity, and signal structure, as documented in several cetacean and pinniped species (Duarte et al., 2021; Hauser et al., 2018). However, responses to vessel noise are species- and context-dependent. For example, belugas have been reported to increase call rates in the presence of vessels, whereas narwhals reduced both vocal activity and movement (Finley et al., 1990). Repeated or prolonged disturbance can reduce individual fitness through disrupted behaviours, increased energetic costs, and physiological stress (Erbe et al., 2018)

Walrus spend up to 83% of their time in the water (Born et al., 1995; Gjertz et al., 2001) and their hearing sensitivity (0.1-15 kHz; Kastelein et al., 2002) overlaps directly with vessel noise frequencies (Khopkar et al., 2026). In Arctic waters, vessel noise can propagate over large distances, with modelling studies suggesting audibility beyond 100 km under quiet conditions (Halliday et al., 2017). Walrus rely on acoustic communication for social and reproductive behaviours, including male breeding displays and mother-calf interactions (Charrier et al., 2010; Sjare et al., 2003; Sjare, 1993; Sjare & Stirling, 1996). In water, they produce low-frequency calls, including knocks, bell sounds, whistles, and grunts (Larsen & Reichmuth, 2021; Sjare, 1993; Sjare & Stirling, 1996; Stirling et al., 1987; Verboom, 2023). Knocks, which can propagate over several kilometers, are the most frequently recorded underwater walrus calls and are commonly used as a proxy for their presence (Larsen & Reichmuth, 2021; Miksis-Olds et al., 2016; Ray and Watkins, 1975; Sjare et al., 2003; Sjare & Stirling, 1996). Because these calls are essential for communication, underwater noise may disrupt their transmission or detection, with potential consequences for breeding and mother-calf interactions (Stewart, 2012).

Walrus are considered among the Arctic marine mammals most vulnerable to vessel disturbance (Hauser et al., 2018). At haul-out sites, walrus respond to auditory, visual, and olfactory cues from vessels or aircraft by increasing vigilance, initiating escape responses, and stampedes, which can result in injury or mortality (Born et al., 1995; Fay et al., 1984; Higdon et al., 2022). In Chukchi Sea, vessel presence altered walrus diving behaviour and travel speed,

which may increase energetic costs (McFarland & Aerts, 2015). The intensity of these responses varies with factors such as previous exposure, age, sex, and health status (Erbe, 2012), with mothers and individuals accompanied by calves potentially being more sensitive to disturbance (Miller, 1982; Salter, 1979). Prolonged disturbances may also cause animals to abandon haul-out sites (Kovacs, 2016), or abandonment of dependent young, while stampede provoked by anthropogenic disturbance could lead to stress-induced abortions and trampling of young (Fay et al., 1984). However, most studies of walrus disturbance have focused on responses at haul-out sites, leaving underwater acoustic responses comparatively understudied. While telemetry has been used to investigate shipping effects on walruses (Taylor et al., 2023), Coppolaro et al. (2025) documented decreased vocalization rates during vessel encounters in northern Hudson Bay, providing, to our knowledge, the only prior acoustic evidence of walrus vocal response to shipping noise. Since walruses heavily depend on the marine environment, PAM offers a critical window into walrus underwater behaviour that direct observation cannot provide, addressing significant gaps in the understanding of noise impacts on this species. Although limited knowledge is available, it is believed that disturbance in vocalizations may lead to impacts on foraging, breeding, and ultimately survival (Erbe, 2012).

These concerns are particularly relevant in Foxe Basin, Nunavut, which hosts one of Canada's largest Atlantic walrus aggregations (DFO, 2019). Although vessel traffic in Foxe Basin is currently limited (Dawson et al., 2017), industrial development is expected to increase shipping in the region, raising ocean noise levels and exposure for marine wildlife (Stewart et al., 2020; Winship & Jones, 2023). Current regulations may not fully protect walruses from disturbance associated with vessel traffic. The Canadian Marine Mammal Regulations prohibit approaches closer than 100 m in water, 200 m on ice, and 300 m on shore for anchored ships (Marine Mammals Regulations. Fisheries Act. SOR/93-56, 2018). Vessel-generated underwater noise varies with ship size, load, speed, propulsion type, angle of approach, engine power, and the

number of ships present (Erbe et al., 2018; McKenna et al., 2013; Ross, 1976; Trevorrow et al., 2008). These characteristics shape the marine soundscape experienced by marine mammals and may therefore influence their acoustic behaviour differently. Improving our understanding of how walrus respond to the presence of vessels in the water is therefore essential for informing shipping regulations and conservation in this region.

This chapter investigates the potential disturbance of vessel traffic on walrus vocal behaviour in Foxe Basin. Specifically, it examines how walrus vocal activity varies with vessel presence and characteristics to assess potential responses to increasing maritime activity in the region. The present study aims to (1) compare walrus vocal activity before and during the shipping season and (2) assess whether vessel characteristics (e.g., vessel type, speed, and distance) influence walrus vocal activity. Although most documented responses to disturbance have occurred at haul-outs and over short distances, walrus have often shown escape responses, with reaction magnitude varying by prior exposure and disturbance intensity (Born et al., 1995; COSEWIC, 2017; Fay, 1984; Salter, 1979). Given their limited prior exposure to anthropogenic noise, walrus vocal activity was predicted to decline during the shipping season, particularly in response to icebreakers, higher vessel speed, and closer proximity, which are associated with elevated noise levels (Roth et al., 2013). Such decreases may result from acoustic masking by vessel noise, active reductions in vocal activity, or displacement from the area. This study addresses a significant gap in our understanding of walrus acoustic responses to vessel disturbance, with findings intended to inform shipping guidelines and conservation measures for the species in this region.

3.3 Methods

3.3.1 Study area

Foxe Basin, located in the central Canadian Arctic, is connected to Fury and Hecla Strait to the northwest and Hudson Strait to the southeast. Coastal Inuit communities along the basin include Igloolik (Iglulik, ᐃᓖᓗᓕᓴ) and Sanirajak (ᓂᓱᓴᓴᓴ) (Figure 3.1). The basin is characterized by a full seasonal sea ice cycle, with freeze-up typically occurring in November and break-up in June (Hochheim & Barber, 2014; Kowal et al., 2024). Most vessel traffic enters the area via Hudson Strait or Fury and Hecla Strait, primarily for the resupply of communities and icebreaker operations for navigation through seasonal ice (Andrews et al., 2018). Walrus summer in northern FB typically around islands and on pack ice before moving at the floe edge during winter, mainly around Rowley Island (COSEWIC, 2006; Stewart, 2008; Figure S3.1). If ice is not available, walrus will move towards terrestrial haul-outs. Walrus haul-outs (*uglit*) in northern FB are at Tern Island, Jens Munk Island, and Tangle Island, according to the database (accessible at: <https://geo.abds.is/geonetwork/srv/eng/catalog.search#/map>; Cubaynes et al., 2026).

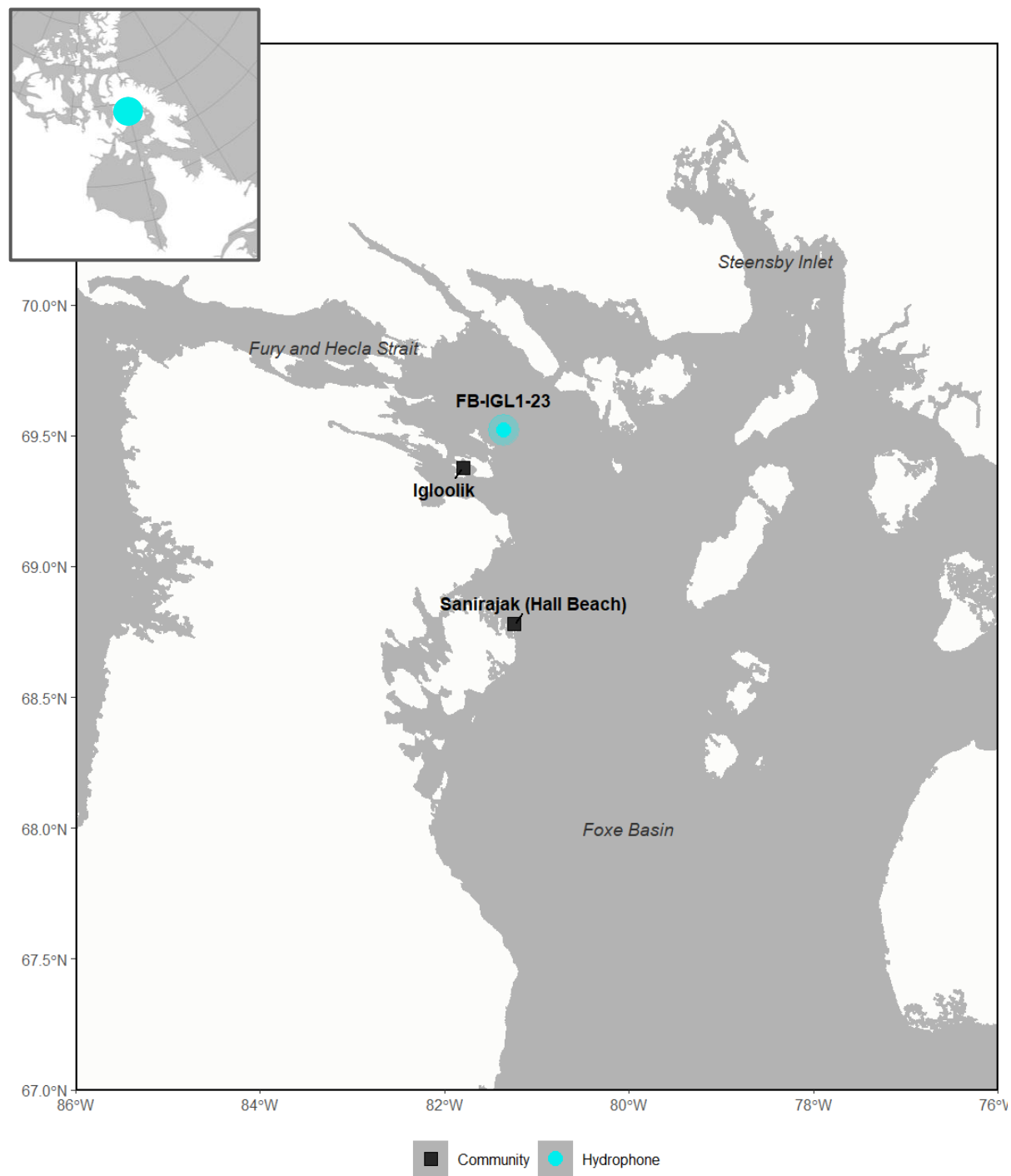


Figure 3.1 Map of Foxe Basin and the coastal communities, with the hydrophone mooring FB-IGL1-23 location.

A total of 26 transits by 21 vessels transited within the 100 km monitoring radius around the hydrophone FB-IGL1-23 between August and October 2023 (Table S3.1; Figure S3.2), comprising ten General Cargo Ships, five Icebreakers, three vessels of Unknown type, two Chemical Tankers, and one Other Activities vessel (Figure 3.2). Vessel presence totalled 507h over three months. Vessel traffic was concentrated in September, which recorded the greatest number of vessels ($n = 10$) and transits ($n = 11$), and accounted for most of ship-presence hours, followed by October (9 vessels) and August (3 vessels). Most vessels followed a main shipping corridor running from southern FB through Fury and Hecla Strait toward the Gulf of Boothia. Several vessels made stops at the communities of Igloolik and Sanirajak, and one vessel classified as Other Activities transited to Steensby Inlet.

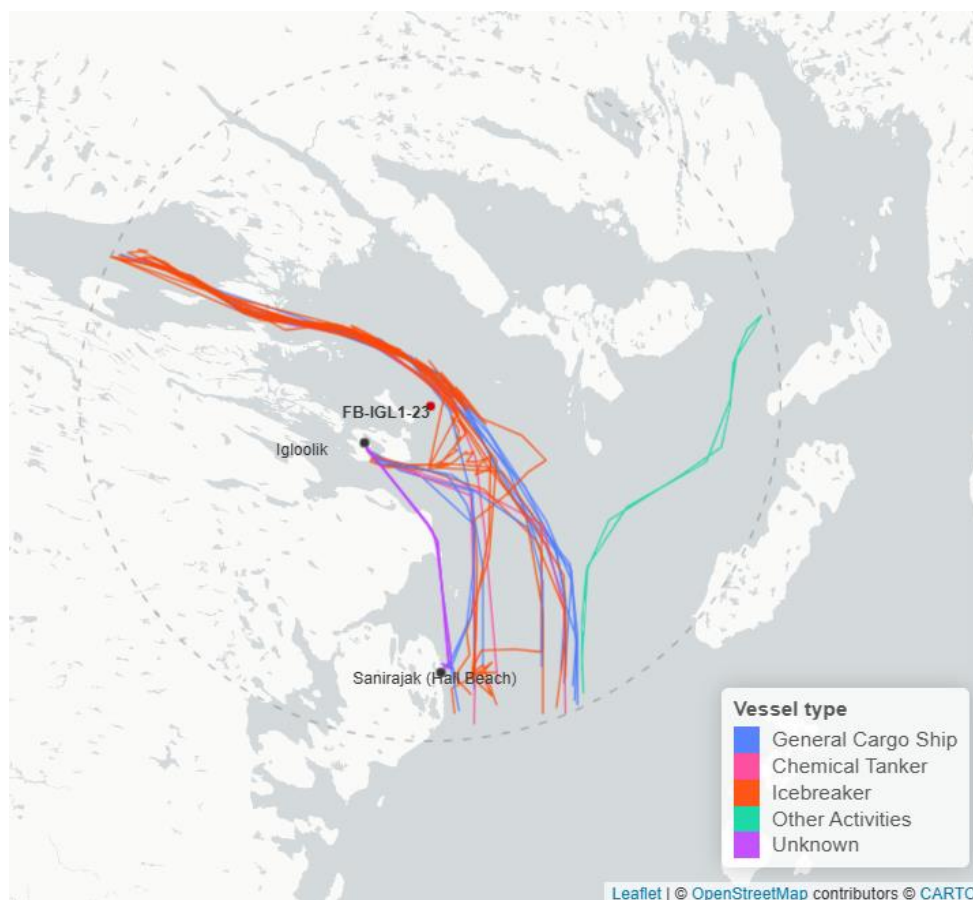


Figure 3.2. Ship tracks by vessel type (general cargo ship, chemical tanker, icebreaker, other activities, unknown), from August to October 2023 within a 100 km radius from the hydrophone FB-IGL1-23.

3.3.2 Acoustic data collection

Underwater acoustic data were collected using an autonomous hydrophone (Soundtrap ST600HF; Oceans Instruments, NZ) deployed in the north of Igloolik (69.51913°N, 81.36013°W; Figure 3.1). The mooring was deployed at 6.6 km from the coast and at a depth of 59 m and consisted of an anchor, acoustic release (Vemco VR2AR, INNOVASEA), the hydrophone, and a buoy connected by a rope (Figure S3.3). The deployment site was selected in collaboration with Inuit researchers from Igloolik and Sanirajak, based on local knowledge of critical walrus habitats, especially foraging areas, and the proximity to the shipping corridor. Specifically, Inuit researchers identified areas of interest and potential hydrophone deployment locations on a map. This approach was guided by concerns raised by the communities regarding future increases in shipping activity and the need to document walrus behaviour in response to vessels.

The hydrophone recorded from 27 June 2023 to 21 June 2024, with a duty cycle set to 6 minutes on and 54 minutes off, yielding 8,808 recordings (.wav format) in total, of which 2,208 (August to October 2023, corresponding to the main shipping period) were used for this chapter. The hydrophone recorded with no set gain at a sample rate of 192 kHz and a Nyquist frequency of 96 kHz. This high sampling rate allows for more detailed recordings, preserving the vocalization structure with higher frequency resolution in spectrograms.

3.3.3 Acoustic data analysis

For each 6 min recording, a spectrogram was generated using the sound analysis software Raven Pro (version 1.6.5; Raven Pro, 2024; Figure 3.3). Recordings were analyzed manually and aurally. For each recording, the number of knocks was manually counted. Visual and aural assessment of knocks was based on the literature description of a knock (Sjare et al., 2003; Sjare & Stirling, 1996; Stirling et al., 1987). A knock count was validated if (1) its start and end points were clearly distinguishable on the spectrogram, and (2) its signal contour was well-defined.

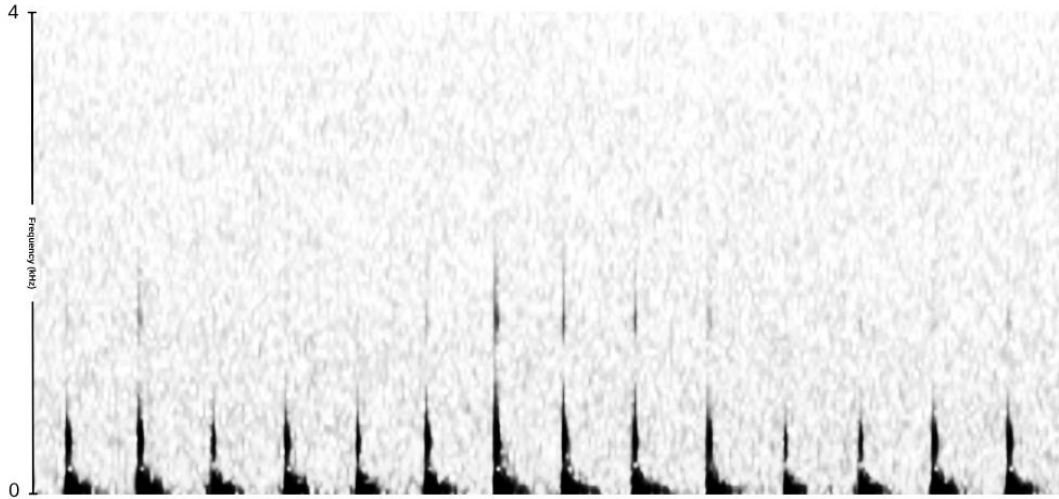


Figure 3.3. Spectrogram of walrus knock from recordings at FB-IGL1-23.

3.3.4 AIS data analysis

AIS data collection

Vessel location data for the Canadian Arctic were extracted from the Automatic Identification System (AIS) via the Arctic Ship Traffic Data (ASTD) System, with an access level 2, maintained by the Protection of the Arctic Marine Environment (PAME). AIS data were filtered from August to October 2023, corresponding to the shipping season. A 100 km radius around the hydrophone deployment location was created and overlaid with AIS data points, as large vessel noise has been reported to propagate over 100 km in the Canadian Arctic (Halliday et al., 2017). This buffer zone is referred to as the study area hereafter. Motorboats could not be included in the AIS data set as they do not carry AIS transceivers. For each AIS point, ship characteristics such as ship identification number (ship ID), ship type, and coordinates were extracted where the data were available. Ship ID is a unique identifier assigned by ASTD for each ship and is renewed monthly. All analyses were performed in R version 4.4.3.

AIS data processing

The data were cleaned to remove erroneous AIS positions, including duplicate vessel tracks, positions falling on land, and isolated points that were not associated with any vessel track. Vessel speed and distance to the hydrophone were computed from the latitude and longitude coordinates of each point. Vessels in port, moored or moving ≤ 1 knot, were retained as the study aims to understand the general effect of vessel presence in the area. For each hour, vessel direction relative to the hydrophone was classified as *approaching* (decreasing distance) or *departing* (increasing distance).

Missing AIS points can occur during a transit, due to data loss while navigating, producing temporal gaps in a ship track. Each gap was identified by its duration (hours), the coordinates of the last observed position before the gap (p_0) and the first observed position after the gap (p_1), and the vessel speed at p_0 and p_1 . For each gap between p_0 at time t_0 and p_1 at time t_1 , one position was interpolated per missing hour until the next p_1 was reached. This approach assumes constant linear movement between consecutive observed positions (Figure S3.4). Only the gaps lasting less than or equal to 24 hours within the same transit were used for the interpolation. A total of 117 positions were interpolated across 11 vessels to fill 40 gaps (Table S3.2). For each month, ship tracks were generated for each vessel (identified by ship transit) (Figure S3.5).

Terrestrial features (e.g., islands, coastal topography) can obstruct the sound propagation between the vessel and the hydrophone. A binary land barrier variable was assigned for each AIS point. A line was drawn between each vessel position and the hydrophone location. If the line was intersected by land, the position was flagged *land_barrier* = yes.

To match the hour of the recordings, AIS data points were rounded down to the hour (using the *floor_date* function). Of 2,208 hourly recordings, 507 were successfully matched to AIS vessel data. For each hour, only the closest vessel to the hydrophone was retained from all vessels present within the study area, selecting it as the primary predictor of acoustic exposure. In addition,

the number of vessels present during that hour was recorded and categorized as 1 vessel or 2+ vessels to account for the vessel traffic context.

3.3.5 Statistical analysis

Effect of vessel exposure on walrus vocal activity

Hourly knock counts were compared between two categories of vessel exposure: “*prior shipping season*”, from August 1st to 23rd 2023, before the first vessel arrival within the study area, and “*shipping season*”, from August 24th to October 31st, 2023, corresponding to the active shipping season in a 100km buffer zone. Vessel exposure (prior shipping season vs shipping season) on walrus vocal activity was tested with a Generalized Linear Mixed Model (GLMM), using the *glmmTMB* package in R. Hourly knock counts were modelled with a negative binomial distribution with a linear mean-variance relationship (*nb1*), used for the overdispersion in the counts. Vessel exposure (prior shipping season vs shipping season) was included as a fixed effect, and a random intercept for day (*1|day*) was included to account for the non-independence of hours recorded on the same day. The effect of shipping season was expressed as a rate ratio, and model significance was assessed using the Wald z statistic and a likelihood-ratio test (Bolker et al., 2009; Burnham & Anderson, 2002) comparing the full model with an intercept-only model.

Effect of vessel characteristics on walrus vocal activity

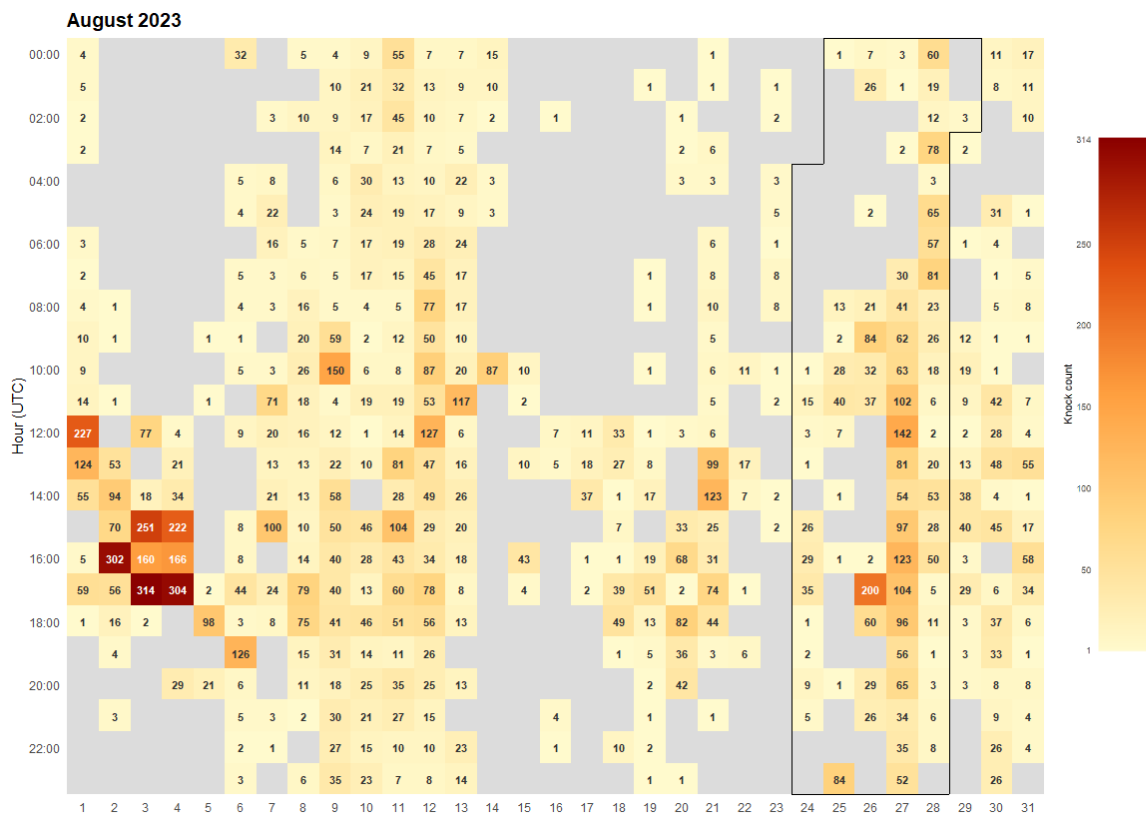
To examine whether vessel characteristics were associated with walrus knock counts, only hours with vessel presence (n = 507) were analyzed for this part. A negative binomial GLMM, with a linear mean-variance relationship (*nb1*), was fitted using the *glmmTMB* package. The response variable was the hourly walrus knock count. Candidate terms tested included vessel category (1 vessel, 2+ vessels), vessel type (General Cargo, Icebreaker, Chemical Tanker, Unknown, Other Activities), land barrier (yes/no), direction (approaching/leaving), vessel speed (knots), and distance to hydrophone (km). All two-way interactions between candidate predictors were included in the candidate model set. Continuous predictors were scaled. Random effect was (*1|day*), for the non-independence of hours recorded on the same day. Candidate models were evaluated

using the *dredge* function from the *MuMIn* package, and the best model was selected based on AICc. Model fit was assessed using residual diagnostics implemented in the DHARMA package.

3.4 Results

3.4.1 Walrus vocal activity in the study area

A total of 2,208 hourly recordings from August to October 2023 were analyzed for walrus knock detections. Walrus acoustic presence was detected in 929 recordings (42.1% of files), with hourly walrus knock counts ranging from 0 to 314, with an overall mean of 8.9 knocks per recording (Figure 3.4).



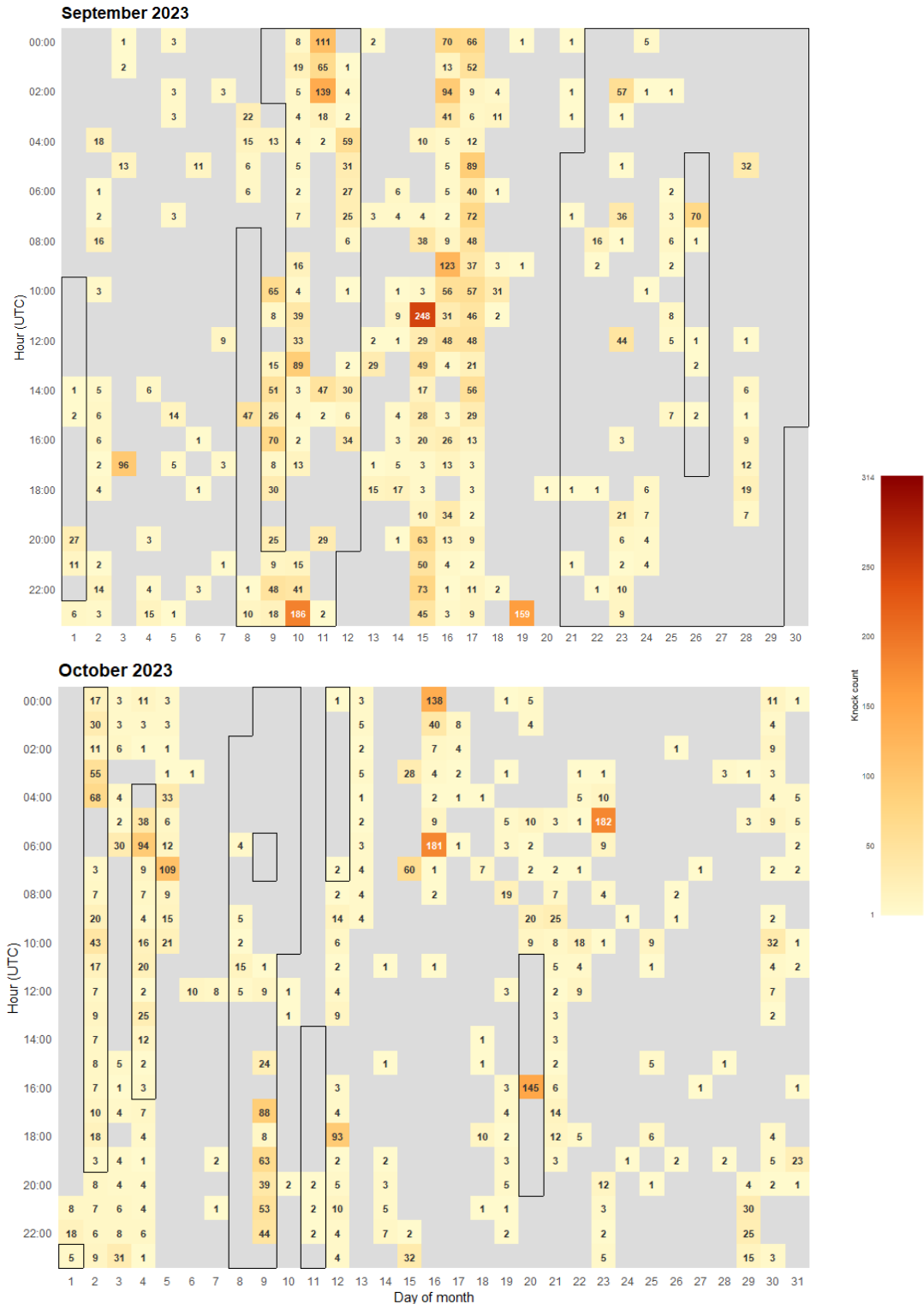


Figure 3.4 Hourly walrus knock detections and vessel presence at hydrophone FB-IGL1-23 deployed in Foxe Basin from August to October 2023. Each cell represents one hour; colour reflects knock count (yellow = low, dark red = high; grey = no detection). Black outlines indicate hours during which at least one vessel was present within 100 km around the hydrophone. Across all three months, outlined cells occurred at all hours of the day with no clear diel preference.

3.4.2 Effect of vessel exposure on walrus vocal activity

Mean hourly knock counts were significantly higher before any vessels were present in the area than during the shipping season (Figure 3.5). The negative binomial GLMM revealed a significant negative effect of the shipping season on hourly knock count (Wald $z = -2.84$, $p = 0.004$). A likelihood-ratio test confirmed that the inclusion of the shipping season significantly improved model fit over the null model ($\chi^2 = 7.79$, $df = 1$, $p = 0.005$). Hourly walrus knock counts were reduced by 50% during the shipping season compared with the period prior to vessel arrival (rate ratio = 0.50, 95% CI: 0.31-0.81).

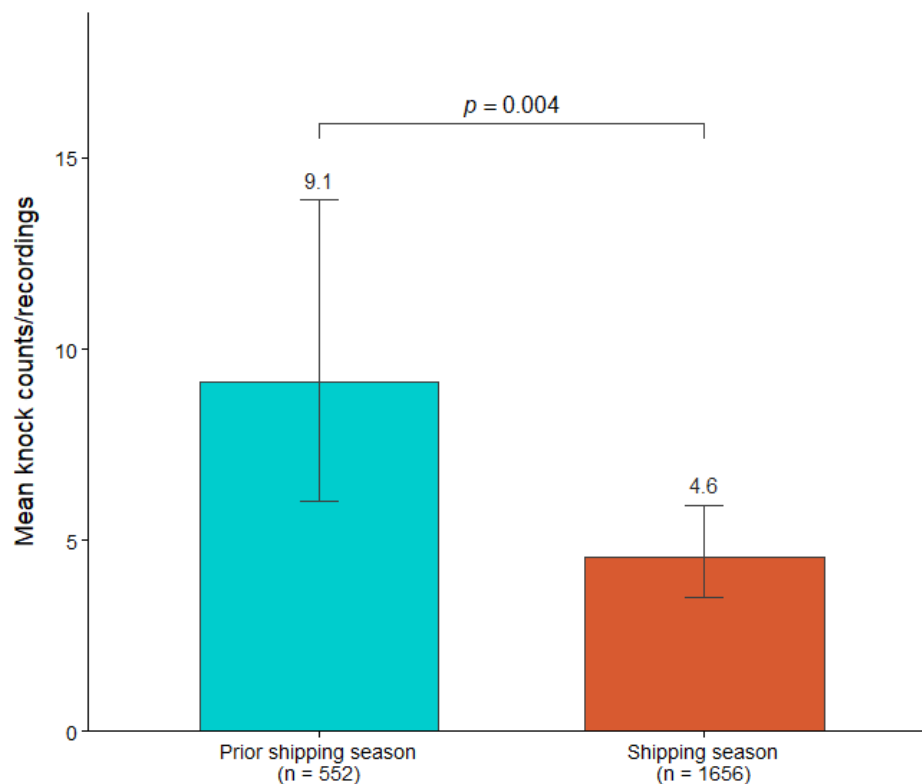


Figure 3.5 Mean knock detections per recording prior shipping season (August 1st to August 23rd, 2023) and during shipping season (August 24th to October 31st, 2023) with 95% CIs from the GLMM. Exposure periods compared with a negative binomial GLMM ($p = 0.004$).

3.4.3 Effect of vessel characteristics on walrus vocal activity

Of the 507 hours with vessel presence, 23 transits from 20 unique vessels were retained for the vessel characteristics analysis (Table 3.1). The nearest vessel to the hydrophone ranged from 4 to 98 km, and vessel speeds from 0 to 20.6 knots. Model selection identified considerable support among multiple candidate models, with the ten highest-ranked models having $\Delta AIC_c < 2$ (Table S3.3). The highest-ranked negative binomial GLMM included vessel category, vessel speed, distance to the hydrophone, and a distance to hydrophone x vessel speed interaction term. These predictors appeared frequently among the best-supported models, occurring in 10, 10, 8, and 6 of the ten top-ranked models, respectively. Candidate predictors land barrier, vessel type, and vessel direction were excluded from the best-supported model.

The best-supported model retained the following predictors: distance to hydrophone, vessel speed, vessel category, and the interaction between distance and vessel speed (Table 3.2; Figure 3.6). Knock counts increased with increasing distance between the vessel and the hydrophone ($\beta = 0.291$, $p = 0.031$; Figure S3.6A). Predicted knock counts increased from approximately 2.9 knocks per recording when vessels were 10 km from the hydrophone to 7.5 knocks per recording when vessels were 100 km away. Vessel speed was negatively associated with walrus knock counts ($\beta = -0.273$, $p = 0.008$; Figure S3.6B), with predicted knock counts decreasing from approximately 5.3 knocks per recording with slow-moving vessels to 2.3 knocks per recording at 15 knots.

Recordings where multiple vessels were present within the study area were associated with higher knock counts than those with a single vessel ($\beta = 0.537$, $p = 0.011$; Figure S3.6C). Predicted knock counts increased from approximately 4.2 knocks per recording during single-vessel exposure to 7.1 knocks per recording when two or more vessels were present. Although the *distance to hydrophone* $\times$ *vessel speed* interaction was retained in the best-supported model, it was not statistically significant ($\beta = -0.176$, $p = 0.123$; Figure S3.6D). Predicted relationships

suggested that the decrease in knock counts with increasing vessel speed was more pronounced at greater distances from the hydrophone. In contrast, predicted knock counts changed little with vessel speed when vessels were closer to the hydrophone. However, confidence intervals overlapped substantially across the range of predicted values.

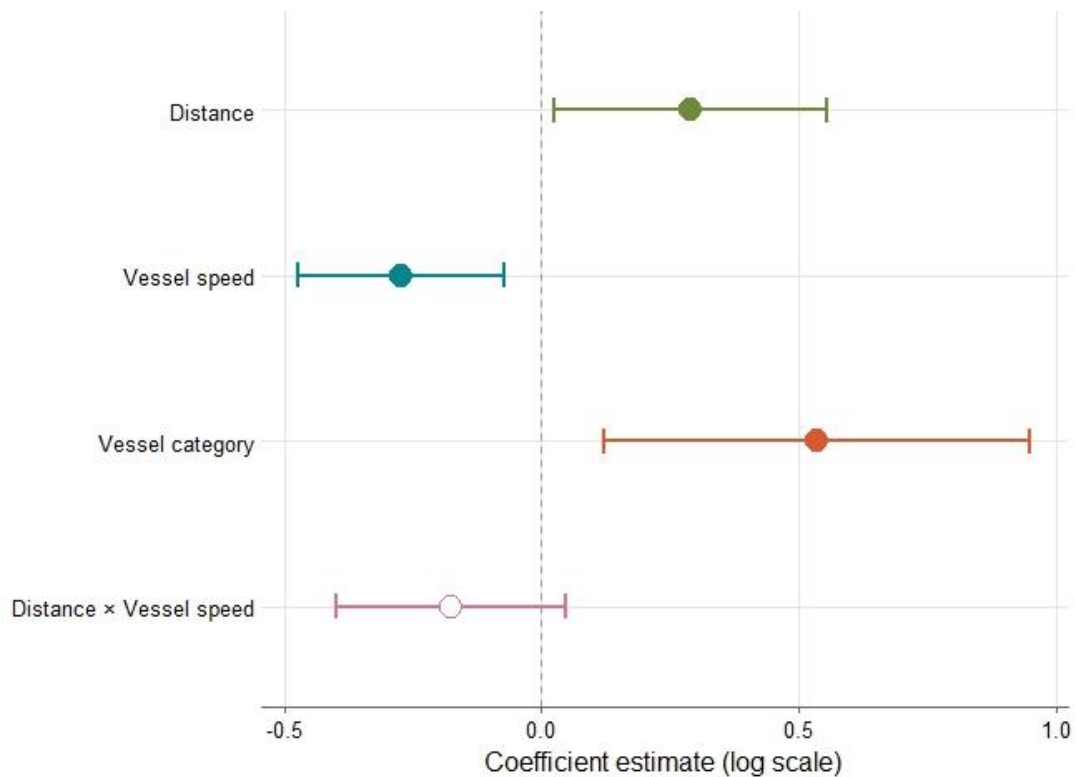


Figure 3.6 Coefficient estimates from the best-supported model and the retained predictors for walrus knock counts. Points represent coefficient estimates on the log scale with 95% confidence intervals. Filled circles = $p < 0.05$; empty circles = $p \geq 0.05$.

Table 3.1. Summary of vessel transits retained as the closest vessel to the hydrophone FB-IGL1-23 per hour, August-October 2023.

Ship ID	Transit	Vessel type	Month	Number of AIS points	Min speed (knots)	Max speed (knots)	Min distance (km)	Max distance (km)
368149789	1	General	October	12	7.72	12.16	6.8	97.3
368266998	1	General	September	9	3.51	15.23	11.1	84.3
369975789	1	General	October	9	6.98	14.30	4.5	91.6
370321789	1	General	October	11	2.60	17.89	9.0	96.9
370368789	1	General	September	10	4.72	12.85	6.0	91.4
439458164	1	Other	October	9	6.28	11.28	67.0	98.0
439460579	1	General	September	5	10.23	16.22	8.7	56.8
439460769	1	Chemical	September	60	0.00	14.25	23.1	53.7
439469789	1	Icebreaker	September	78	0.08	13.19	4.4	96.8
	2		October	16	0.00	12.46	4.0	91.0
439471922	1	General	September	3	10.21	15.15	8.8	36.4
439471929	1	General	August	29	0.00	14.91	22.7	95.4
439472040	1	General	September	20	0.00	15.65	23.4	89.3
439476797	1	Unknown	September	23	0.01	3.02	21.6	82.2
439489053	1	Unknown	September	26	0.01	3.27	23.4	82.1
439494162	1	Chemical	October	3	7.26	16.04	7.3	40.6
439496821	1	Unknown	August	65	0.01	2.29	23.3	81.4
439506789	1	Icebreaker	October	22	0.16	14.78	6.7	95.8
439527789	1	Icebreaker	September	12	0.66	12.33	54.8	95.3
	2		September	47	0.01	13.76	5.7	93.7
439528789	1	Icebreaker	October	8	7.39	16.61	5.4	86.3
439621789	1	Icebreaker	August	23	0.00	11.93	10.8	76.7
	2		October	7	9.33	20.57	9.0	84.5

Table 3.2. Parameter estimates from the final negative binomial GLMM for walrus knock counts. SE = standard error, z = Wald z statistic.

Predictor	Estimate	SE	z	p-value
Intercept	1.423	0.266	5.352	< 0.001
Distance to hydrophone	0.291	0.135	2.151	0.031
Vessel speed	-0.273	0.102	-2.669	0.008
Vessel category	0.537	0.211	2.541	0.011
Distance × speed	-0.176	0.114	-1.541	0.123

3.5 Discussion

PAM offers a critical window into disturbance responses that observations at haul-out sites cannot capture. Walrus reactions to vessel noise vary depending on their previous experiences (Born et al., 1995). Despite limited vessel traffic compared to other Arctic regions, hourly walrus knock counts were almost 50% lower during the shipping season than during the period preceding the first vessel arrival. A previous study in northern Hudson Bay has found an important decline in walrus vocal rate during and after vessel encounters within a 10 km area (Coppolaro et al., 2025). Similar effects have been documented in other species, with reduced beluga call rates (Halliday et al., 2019), reduced buzzing rates in narwhals (Tervo et al., 2021), and decreased in harp seal vocalizations (Terhune et al., 1979) in the presence of vessels. Although the present results indicated reduced vocal activity in response to shipping season, whether it was attributed to acoustic masking, active decrease in vocalization, or physical displacement could not be determined.

Effect of vessel proximity and speed

Walrus vocal activity declined with closer vessel distance and higher vessel speed, suggesting that both factors influenced the level of disturbance on walruses. These variables likely affected received vessel noise, as closer vessels generate higher sound levels at the receiver (McKenna et al., 2012), while faster vessels produce greater propeller cavitation noise (Ross, 1976; Wittekind, 2014). Increased underwater noise can interfere with marine mammal communication by reducing the ability of individuals to detect and recognize conspecific signals, particularly when vessel noise overlaps with the frequency range of animal vocalizations (Clark et al., 2009; Erbe et al., 2019). As vessels approach a receiver, vessel noise can extend into higher frequencies (McKenna et al., 2012), potentially increasing overlap with walrus vocalizations. Such masking effects may also reduce the communication space (Clark et al., 2009). For example, vessel noise from small vessels travelling at 5 knots reduced communication space by 26% in bottlenose dolphins and 58% in pilot whales (Jensen et al., 2009). Similarly, transiting commercial vessels reduced communication space by 63-87.4% for Bryde's whales (Hatch et al., 2012; Putland et al., 2017). Walruses may also actively reduce their vocal activity when exposed to vessel noise. Similar reductions in calling rates have been documented in several marine mammal species, including narwhals exposed to an ore carrier (Finley et al., 1990), beaked whales exposed to sonar (Tyack et al., 2011), and harp seals when exposed to shipping (Terhune et al., 1979). Remaining silent in response to unusual sounds may represent a behavioural strategy to noise disturbance (Richardson et al., 1995).

Reduced vocal detections may also result from behavioural displacement, where individuals leave the area or avoid vessels. Walruses have been documented to exhibit avoidance responses to disturbance (COSEWIC, 2017; DFO, 2019), including entering the water when ships approach (Born et al., 1995), and moving several kilometres away from vessels (Fay et al., 1984). Such responses could reduce the number of vocal detections as individuals move away from the source of disturbance. Displacement may also increase associated energetic costs or limit access

to preferred foraging areas. In addition, vessel speed may represent a dual stressor as a physical and acoustic disturbance. Higher speed can increase collision risk, and ship strikes have been reported as a concern by communities (Higdon et al., 2022). It was not possible to determine the exact mechanism explaining a reduction in walrus vocal activity. Acoustic masking, reduced vocal activity, and potential displacement are not mutually exclusive explanations and may have contributed simultaneously to the observed decline. For example, individuals may reduce their vocal activity while actively leaving the area, while simultaneously experiencing masking of their calls by vessel noise. Predicted increased vessel traffic and longer shipping seasons could increase vessel noise exposure, with potential consequences for walrus communication and energy budgets.

Although, the interaction between distance and vessel speed was retained in the best-supported model, it was not statistically significant. The direction of the interaction suggests that the negative effect of vessel speed on walrus vocal activity was greater when vessels were farther away, while vocal activity changed little with speed at close range. Near the hydrophone, noise levels may already be high enough to mask vocalizations regardless of speed (Chion et al., 2017). Furthermore, distant vessels generally contribute less to local sound levels due to transmission loss (Zakarauskas et al., 1990), which may explain the increase in walrus vocal activity at great distance from a vessel. However, it does not imply that distant vessels have no impact. Hildebrand (2009) suggested long-range propagation of ship noise, as cavitation noise can be detected even when no ships are around. In Foxe Basin, acoustic modelling predicted that an ore carrier could generate noise levels exceeding 100 dB over distances greater than 100 km (DFO, 2012), and that marine mammals could detect the signal at 100 km (Halliday et al., 2017). Further acoustic modelling would improve understanding of vessel noise propagation in the region.

Effect of the presence of multiple vessels

Recordings during which two or more vessels were present within the study area were associated with higher knock counts than recordings with a single vessel, contrary to our initial expectation that increased vessel presence would reduce vocal activity. However, multiple vessels may raise ambient noise levels beyond a threshold, which could potentially trigger compensatory changes in vocal behaviour (Hotchkin & Parks, 2013). Potential vocal adjustment is the Lombard effect, whereby individuals increase the amplitude or modify the frequency of their vocalizations in response to elevated background noise. It increases the likelihood of being acoustically detected in a noisy environment (Lombard, 1911). Denes (2014) found evidence that walrus adjust their vocalizations in response to increased ambient noise levels by increasing call amplitude, suggesting that walrus can modulate their vocalizations to maintain acoustic communication. Similar responses have been reported across many marine species, including belugas (Lesage et al., 1999), killer whales (Foote et al., 2004; Holt et al., 2011), manatees (Miksis-Olds & Tyack, 2009), minke whales (Helble et al., 2020), and right whales (Parks et al., 2007, 2010). One possible explanation is that walrus responses may depend on the level of acoustic disturbance experienced. The reduced vocal activity observed with closer and faster vessels may reflect responses occurring below a disturbance threshold, which results in decreased calling. In contrast, higher background noise levels generated by multiple vessels may exceed this threshold and trigger compensatory vocal adjustments to maintain communication (Hotchkin & Parks, 2013). Denser vessel traffic may also reduce walrus' ability to avoid vessels and associated noise, as individuals are more likely to encounter vessels repeatedly within their habitat. Under these conditions, maintaining acoustic contact with conspecifics may become more important, potentially triggering adjustments in vocal behaviour. Although no measures of frequency, amplitude, and signal-to-noise ratio were done on walrus knocks in this study, the higher detection count during periods with multiple vessels could be consistent with a compensatory response. Further studies are needed to determine a potential Lombard effect with vessel presence.

Surprisingly, no effect of vessel type on walrus vocal activity was detected, despite icebreakers actively breaking ice. Icebreakers generally have higher noise levels (Garlich-Miller et al., 2011) due to repeated manoeuvres during icebreaking, frequent changes in speed and direction, and increased propeller cavitation (Roth et al., 2013). Although underwater noise varies among vessel types, the amount of noise reaching walruses also depends on how the vessel is operating, not just on its type. Alternatively, walruses may respond once a relatively low disturbance threshold is exceeded, regardless of vessel category. The contrasting responses found in this study highlight the complexity of walrus responses to vessel noise. Walruses may reduce their vocal activity under some disturbance while adjusting their vocal behaviour under others. Although no mechanisms can be confirmed from this study alone, changes in vocal behaviour may have consequences on communication efficiency between individuals and potentially influence energetic costs associated with disturbance.

3.5.1 Limitations

Several methodological limitations can affect the interpretation of these results. AIS data can provide an incomplete picture of vessel activity. Small vessels, including motorboats, do not carry AIS transceivers and therefore could not be included in this analysis. Small vessels emit noise at higher frequencies than larger vessels due to differences in propeller size and blade rate (Erbe, 2012). Despite higher frequencies travelling less far than lower frequencies, Coppolaro et al. (2025) still found that small vessels in northern Hudson Bay were impacting walrus vocal activity. The lack of including small vessels in the study might affect the real representation of vessel traffic and the impact on walrus behaviour.

Walruses undertake seasonal migrations during the open water season, moving toward terrestrial haul-outs when sea ice is no longer available (Orr et al., 1986; Stewart, 2008). Because this study was conducted during the summer shipping season, the observed reduction in vocal activity may reflect both seasonal movements and behavioural responses to vessel disturbance,

which are not mutually exclusive. However, the year-round detection of walrus knocks at both sites (Chapter 2) indicates that at least some individuals remained vocally active near the hydrophones even during the open-water season. Telemetry studies could help determine the extent to which the effects detected in this study are associated with seasonal movements, behavioural responses to vessel disturbance, or a combination of both.

Finally, no calculations of ambient noise levels or received sound pressure levels were made at the hydrophone location. Without these measurements, it is not possible to directly link changes in knock counts to specific noise exposure thresholds, to assess masking potential, or to compare conditions against established behavioural disturbance thresholds.

3.5.2 Conservation and management implications

The findings of this study have important implications for the conservation and management of the Atlantic Walrus in Foxe Basin. The species is already considered vulnerable to climate change due to its restricted diet and strong site fidelity to haul-outs and feeding grounds (Born et al., 1995; Wickson, 2021). Concerns regarding disturbance from shipping and industrial development in the region have been raised by local communities (Carter et al., 2019; DFO, 2012; Qikiqtani Inuit Association, 2014, 2019). To this day, Foxe Basin has had limited vessel traffic compared to other Arctic regions (Dawson et al., 2017), which is an opportunity to implement proactive conservation measures. Shipping regulations and mitigation measures will be most effective when implemented in advance of high shipping activity rather than retrospectively (Huntington, 2009), making Foxe Basin a strong candidate for this approach.

The results of this study suggest that existing regulatory measures may not adequately address the full extent of shipping-related disturbance experienced by walruses. Current Canadian Marine Mammal Regulations prohibit approaches within 100 m of walruses in water, 200 m on ice, and 300 m on shore (Marine Mammals Regulations. Fisheries Act. SOR/93-56, 2018). However, these regulations apply only to tourism and recreational vessel activity, not to vessels in transit,

such as cargo ships. Although this study was not designed to determine specific buffer distances or noise thresholds, the influence of vessel distance on walrus behaviour suggests that disturbance effects extend to vessels in transit, well beyond the distances currently recognized under Canadian regulations.

Several mitigation measures have been proposed in the literature. Speed reductions have been shown to lower underwater radiated noise levels (Macgillivray et al., 2019; MacGillivray & Li, 2018; Pine et al., 2018; Trounce et al., 2019), though slower speeds also imply longer travel times, increased fuel costs, and prolonged noise exposure (Chion et al., 2017; McKenna et al., 2013; Megannety, 2011). Vessels can also improve their design through changes in the blade and wake design of the propeller to reduce cavitation noise and, therefore, underwater noise (Spence & Fischer, 2017). In 2019, Transport Canada launched the Quiet Vessel Initiative (QVI), a federal funding program designed to reduce underwater vessel noise in Canada by supporting the retrofitting of existing vessels and the development of quieter vessel technologies (Transport Canada, 2021).

Finally, the development of low-impact shipping corridors by the Government of Canada provides an opportunity to reduce overlap between vessel routes and sensitive marine mammal habitats through seasonal or geographically targeted measures (Carter et al., 2019; Dawson et al., 2020; Dawson & Song, 2023). However, these corridors remain voluntary, meaning participation is not guaranteed. Industrial development and the growth of Arctic shipping are increasing pressures in the region, and coastal communities in Foxe Basin will be among the first to bear their impacts. Shipping regulations that slow or reroute vessels without considering Inuit realities risk disrupting the marine resupply networks on which these communities depend for essential food and health provisions. Any shipping policy must therefore be developed in close collaboration with both industries and Inuit communities (Porta et al., 2017), integrating preferred

corridors, areas to avoid, seasonal restrictions, and culturally sensitive areas identified through Inuit traditional knowledge alongside Western science (Dawson & Song, 2023).

3.6 Conclusion

This study provides evidence that vessel traffic affects walrus vocal activity in Foxe Basin, even under limited shipping. The decline in vocal activity during the shipping season and the significant effects of vessel proximity and speed suggest that walruses are acoustically sensitive to vessel presence at distances and speeds not currently addressed by Canadian marine mammal regulations. Increased vocal activity in the presence of multiple vessels may indicate a potential Lombard effect in response to elevated noise disturbance, although further investigation is required. Foxe Basin represents a relatively rare opportunity to implement proactive conservation measures. The approved Mary River Iron Mine Project and longer open water seasons are expected to increase vessel traffic in the region, which could amplify the impacts documented here. As industrial development in the Arctic continues, ensuring that conservation measures are co-developed with the communities whose livelihoods depend on the marine environment will be essential to achieving outcomes that are both ecologically sound and socially equitable.

3.7 Literature cited

- Andrews, J., Babb, D., & Barber, D. G. (2018). Climate change and sea ice: Shipping in Hudson Bay, Hudson Strait, and Foxe Basin (1980–2016), 6: 19. *Elem Sci Anth*, 6(19).
- Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., & White, J. S. S. (2009). Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology and Evolution*, 24(3), 127–135. <https://doi.org/10.1016/j.tree.2008.10.008>
- Born, E. W., Gjertz, I., & Reeves, R. R. (1995). *Population assessment of Atlantic walrus (Odobenus rosmarus rosmarus L.)*.
- Burnham, K. P., & Anderson, D. R. (2002). Model Selection and Multimodel Inference. In *Model Selection and Multimodel Inference*. Springer New York. <https://doi.org/10.1007/B97636>
- Carter, N. A., Dawson, J., & Weber, M. (2019). *Arctic Corridors and Northern Voices: Governing marine transportation in the Canadian Arctic (Coral Harbour, Nunavut community report)*. <https://doi.org/10.20381/RUOR38505>
- Charrier, I., Aubin, T., & Mathevon, N. (2010). Mother-calf vocal communication in Atlantic walrus: A worst weld experimental study. *Animal Cognition*, 13(3), 471–482. <https://doi.org/10.1007/s10071-009-0298-9>
- Chion, C., Lacrois, D., Dupras, J., Turgeon, S., McQuinn, I. H., Michaud, R., Ménard, N., & Parrott, L. (2017). Underwater acoustic impacts of shipping management measures: Results from a social-ecological model of boat and whale movements in the St. Lawrence River Estuary (Canada). *Ecological Modelling*, 354, 72–87. <https://doi.org/10.1016/J.ECOLMODEL.2017.03.014>
- Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: intuitions, analysis, and implication. *Marine Ecology Progress Series*, 395, 201–222. <https://doi.org/10.3354/MEPS08402>
- Coppolaro, V. L. M., Ausen, E. L., Loseto, L. L., & Marcoux, M. (2025). Vessel traffic disrupts walrus vocal behavior in a proposed marine protected area. *Frontiers in Marine Science*, 12. <https://doi.org/10.3389/fmars.2025.1658328>
- COSEWIC. (2006). *COSEWIC assessment and update status report on the Atlantic walrus, Odobenus rosmarus rosmarus, in Canada*. Committee on the Status of Endangered Wildlife in Canada.
- COSEWIC. (2017). *COSEWIC Assessment and Status Report Atlantic Walrus Odobenus rosmarus rosmarus High Arctic population Central-Low Arctic population Nova Scotia-Newfoundland-Gulf of St. Lawrence population in Canada High Arctic population-SPECIAL CONCERN Central-Low Arctic population-SPECIAL CONCERN Nova Scotia-Newfoundland-Gulf of St. Lawrence population-EXTINCT 2017*. www.sararegistry.gc.ca/status/status_e.cfm
- Cubaynes, H. C., Matthews, C. J. D., Garde, E., Gavrillo, M., Heide-Jørgensen, M. P., Higdon, J. W., Kovacs, K. M., Leskova, M., Lydersen, C., Solovyev, B., Vergara-Pena, A., & Fretwell, P. T. (2026). A distribution-wide dataset of Atlantic walrus terrestrial haul-out sites. *Scientific Data* 2026 13:1, 13(1), 808-. <https://doi.org/10.1038/s41597-026-07210-6>

- Dawson, J., Carter, N., van Luijk, N., Parker, C., Weber, M., Cook, A., Grey, K., & Provencher, J. (2020). Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. *Environmental Science & Policy*, 105, 19–36. <https://doi.org/10.1016/J.ENVSCI.2019.11.013>
- Dawson, J., Mussels, O., Copland, L., & Carter, N. (2017). *Shipping Trends in Nunavut from 1990-2015: A report prepared for the Nunavut General Monitoring Program*. www.espg.ca
- Dawson, J., & Song, G. (2023). Governing Canadian Arctic Shipping through Low-impact Shipping Corridors. In *Shipping in Inuit Nunangat* (pp. 351–374). <https://brill.com/edcollchap-0a/book/9789004508576/BP000027.xml>
- Denes, S. L. (2014). *Ocean environmental effects on walrus communication*. The Pennsylvania State University.
- DFO. (2012). *Technical Review of Baffinland's Mary River Project Draft Environmental Impact Statement (EIS)*.
- DFO. (2019). *Mitigation Buffer Zones for Atlantic Walrus (Odobenus rosmarus rosmarus) in the Nunavut Settlement Area*.
- Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., & Harding, H. R. (2021). The soundscape of the Anthropocene ocean. *Science*, 371(6529), eaba4658.
- Erbe, C. (2012). Effects of underwater noise on marine mammals. *The Effects of Noise on Aquatic Life*, 17–22.
- Erbe, C., Dunlop, R., & Dolman, S. (2018). *Effects of Noise on Marine Mammals*. 66, 277–309. https://doi.org/10.1007/978-1-4939-8574-6_10
- Erbe, C., Marley, S. A., Schoeman, R. P., Smith, J. N., Trigg, L. E., & Embling, C. B. (2019). The Effects of Ship Noise on Marine Mammals—A Review. In *Frontiers in Marine Science* (Vol. 6). Frontiers Media S.A. <https://doi.org/10.3389/fmars.2019.00606>
- Fay, F. H. , Kelly, B. P. , Gehnrich, P. H. , & Hoover, A. A. (1984). *Modern populations, migrations, demography, trophics, and historical status of the Pacific walrus*. . <https://www.govinfo.gov/app/details/GOVPUB-I-e4afaac7a5139b5907a945b920ebc663>
- Finley, K. J. , Miller, G. W. , Davis, R. A., & Greene, C. R. (1990). Reactions of belugas, *Delphinapterus leucas* and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high Arctic. *Canadian Bulletin of Fisheries and Aquatic Sciences*, 224, 97–117. <https://eurekamag.com/research/021/640/021640975.php>
- Garlich-Miller, J., Maccracken, J. G., Snyder, J., Meehan, R., Myers, M., Wilder, J. M., Lance, E., & Matz, A. (2011). *STATUS REVIEW OF THE PACIFIC WALRUS (Odobenus rosmarus divergens)* .
- Gjertz, I., Griffiths, D., Krafft, B. A., Lydersen, C., & Wiig. (2001). Diving and haul-out patterns of walruses *Odobenus rosmarus* on Svalbard. *Polar Biology*, 24(5), 314–319. <https://doi.org/10.1007/s0030000000211>

- Gomez, C., Lawson, J. W., Wright, A. J., Buren, A. D., Tollit, D., & Lesage, V. (2016). A systematic review on the behavioural responses of wild marine mammals to noise: the disparity between science and policy. *Canadian Journal of Zoology*, 94(12), 801–819.
- Halliday, W. D., Insley, S. J., Hilliard, R. C., De Jong, T., & Pine, M. K. (2017). Potential impacts of shipping noise on marine mammals in the western Canadian arctic. *Marine Pollution Bulletin*, 123(1–2), 73–82.
- Halliday, W. D., Scharffenberg, K., Macphee, S., Hilliard, R. C., Mouy, X., Whalen, D., Loseto, L. L., & Insley, S. J. (2019). Beluga vocalizations decrease in response to vessel traffic in the Mackenzie River Estuary. *Arctic*, 72(4), 337–346. <https://doi.org/10.14430/ARCTIC69294>
- Hatch, L. T., Clark, C. W., Van Parijs, S. M., Frankel, A. S., & Ponirakis, D. W. (2012). Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary. *Conservation Biology*, 26(6), 983–994. <https://doi.org/10.1111/J.1523-1739.2012.01908.X>;REQUESTEDJOURNAL:JOURNAL:15231739;WGROU:STRING:PU
BLICATION
- Hauser, D. D. W., Laidre, K. L., & Stern, H. L. (2018). Vulnerability of arctic marine mammals to vessel traffic in the increasingly ice-free northwest passage and Northern Sea Route. *Proceedings of the National Academy of Sciences of the United States of America*, 115(29), 7617–7622. <https://doi.org/10.1073/pnas.1803543115>
- Helble, T. A., Guazzo, R. A., Martin, C. R., Durbach, I. N., Alongi, G. C., Martin, S. W., Boyle, J. K., Henderson, ; E Elizabeth, & Henderson, E. E. (2020). Lombard effect: Minke whale boing call source levels vary with natural variations in ocean noise. *The Journal of the Acoustical Society of America*, 147(2), 698–712. <https://doi.org/10.1121/10.0000596>
- Higdon, J. W., Stewart, D. B., & Stewart, R. E. A. (2022). *Atlantic walrus (Odobenus rosmarus rosmarus) in northern Hudson Bay-status, research needs, and monitoring opportunities Prepared for Oceans North under contract to Higdon Wildlife Consulting* (.).
- Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, 395, 5–20. <https://doi.org/10.3354/MEPS08353>
- Hochheim, K., & Barber, D. (2014). An update on the ice climatology of the Hudson Bay system. *Arctic, Antarctic, and Alpine Research*, 46(1), 66–83. <https://doi.org/10.1657/1938-4246-46.1.66>
- Holt, M. M., Noren, D. P., & Emmons, C. K. (2011). Effects of noise levels and call types on the source levels of killer whale calls. *The Journal of the Acoustical Society of America*, 130(5), 3100–3106. <https://doi.org/10.1121/1.3641446>
- Hotchkin, C., & Parks, S. (2013). The Lombard effect and other noise-induced vocal modifications: Insight from mammalian communication systems. *Biological Reviews*, 88(4), 809–824.
- Huntington, H. P. (2009). A preliminary assessment of threats to arctic marine mammals and their conservation in the coming decades. *Marine Policy*, 33(1), 77–82. <https://doi.org/10.1016/J.MARPOL.2008.04.003>
- Jaramillo, P., S. Kahn Ribeiro, P. Newman, O.E. Diemuodeke, T. Kajino, D.S. Lee, S.B. Nugroho, X. Ou, A. Hammer Strømman, & J. Whitehead. (2022). Transport. In *IPCC, 2022: Climate*

- Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)].
- Jensen, F. H., Bejder, L., Wahlberg, M., Soto, N. A., Johnson, M., & Madsen, P. T. (2009). Vessel noise effects on delphinid communication. *Marine Ecology Progress Series*, 395, 161–175. <https://doi.org/10.3354/MEPS08204>
- Kastelein, R. A., Mosterd, P., van Santen, B., Hagedoorn, M., & de Haan, D. (2002). Underwater audiogram of a Pacific walrus (*Odobenus rosmarus divergens*) measured with narrow-band frequency-modulated signals. *The Journal of the Acoustical Society of America*, 112(5), 2173–2182. <https://doi.org/10.1121/1.1508783>
- Khopkar, S., Yeo, M., Seo, H., & Sul La, H. (2026). Underwater Noise, Marine Mammal Impacts, and Monitoring strategies in the Arctic ocean. *Ocean Science Journal*, 61:18, 16.
- Kovacs, K. M. (2016). *Odobenus rosmarus ssp. rosmarus*. *The IUCN red list of threatened species 2016*.
- Kowal, S., Gough, W. A., & Butler, K. (2024). Seasonal sea ice of Foxe Basin, Canada: Spatial and temporal evolution, 1971- 2018. *Elementa*, 12(1). <https://doi.org/10.1525/elementa.2024.00033>
- Ladegaard, M., Macauley, J., Simon, M., Laidre, K. L., Mitseva, A., Videsen, S., Pedersen, M. B., Tougaard, J., & Madsen, P. T. (2021). Soundscape and ambient noise levels of the Arctic waters around Greenland. *Scientific Reports 2021* 11:1, 11(1), 23360-. <https://doi.org/10.1038/s41598-021-02255-6>
- Larsen, O. N., & Reichmuth, C. (2021). Walrus produce intense impulse sounds by clap-induced cavitation during breeding displays. *Royal Society Open Science*, 8(6). <https://doi.org/10.1098/rsos.210197>
- Lesage, V., Barrette, C., Kingsley, M. C. S., & Sjare, B. (1999). The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science*, 15(1), 65–84. <https://doi.org/10.1111/J.1748-7692.1999.TB00782.X;PAGE:STRING:ARTICLE/CHAPTER>
- Lombard, E. (1911). Le signe de l'elevation de la voix. *Annales Des Maladies de l'Oreille et Du Larynx*, 37, 101–119.
- MacGillivray, A. O., & Li, Z. (2018). Reductions in underwater radiated noise from shipping during the 2017 Haro Strait vessel slowdown trial. *The Journal of the Acoustical Society of America*, 144(3_Supplement), 1731–1731. <https://doi.org/10.1121/1.5067678>
- Macgillivray, A. O., Li, Z., David, J., Hannay, E., Trounce, K. B., Robinson, O. M., & Hannay, D. E. (2019). Slowing deep-sea commercial vessels reduces underwater radiated noise. *The Journal of the Acoustical Society of America*, 146(1), 340–351. <https://doi.org/10.1121/1.5116140>
- Marine Mammals Regulations. Fisheries Act. SOR/93-56 (2018). <http://laws-lois.justice.gc.ca>

- McFarland, S. E., & Aerts, L. A. M. (2015). *Assessing disturbance responses of Pacific Walrus (Odobenus rosmarus divergens) to vessel presence in the Chukchi Sea (Abstract)*. .
- McKenna, M. F., Ross, D., Wiggins, S. M., & Hildebrand, J. A. (2012). Underwater radiated noise from modern commercial ships. *The Journal of the Acoustical Society of America*, 131(1), 92–103. <https://doi.org/10.1121/1.3664100>
- McKenna, M. F., Wiggins, S. M., & Hildebrand, J. A. (2013). Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. *Scientific Reports* 2013 3:1, 3(1), 1760-. <https://doi.org/10.1038/srep01760>
- Megannety, M. (2011). *A Review of the Planned Shipping Activity for the Baffinland Mary River Project: Assessing the Hazards to Marine Mammals and Migratory Birds and Identifying Gaps in Proposed Mitigation Measures*.
- Miksis-Olds, J. L., & Tyack, P. L. (2009). Manatee (*Trichechus manatus*) vocalization usage in relation to environmental noise levels. *The Journal of the Acoustical Society of America*, 125(3), 1806–1815. <https://doi.org/10.1121/1.3068455>
- Miksis-Olds, J. L., Van Opzeeland, I. C., Van Parijs, S. M., & Jones, J. (2016). Pinniped sounds in the polar oceans. *Listening in the Ocean*, 257–308.
- Miller, E. H. (1982). Herd organization and female threat behaviour in Atlantic walruses *Odobenus rosmarus rosmarus* (L.). *Mammalia*, 46, 29–34.
- Moore, S. E., Reeves, R. R., Southall, B. L., Ragen, T. J., Suydam, R. S., & Clark, C. W. (2012). A New Framework for Assessing the Effects of Anthropogenic Sound on Marine Mammals in a Rapidly Changing Arctic. *BioScience*, 62(3), 289–295. <https://doi.org/10.1525/bio.2012.62.3.10>
- Orr, J. R., Renooy, B., & Dhalke, L. (1986). *Information from hunts and surveys of walrus (Odobenus rosmarus) in northern Foxe Basin, Northwest Territories, 1982-1984*.
- PAME. (2021). *Protection of the Arctic Marine Environment Working Group - UNDERWATER NOISE POLLUTION FROM SHIPPING IN THE ARCTIC*.
- Parks, S. E., Clark, C. W., & Tyack, P. L. (2007). Short- and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication. *The Journal of the Acoustical Society of America*, 122(6), 3725–3731. <https://doi.org/10.1121/1.2799904>
- Parks, S. E., Johnson, M., Nowacek, D., & Tyack, P. L. (2010). Individual right whales call louder in increased environmental noise. *Biology Letters*, 7(1), 33. <https://doi.org/10.1098/RSBL.2010.0451>
- Pine, M. K., Hannay, D. E., Insley, S. J., Halliday, W. D., & Juanes, F. (2018). Assessing vessel slowdown for reducing auditory masking for marine mammals and fish of the western Canadian Arctic. *Marine Pollution Bulletin*, 135, 290–302. <https://doi.org/10.1016/J.MARPOLBUL.2018.07.031>
- Porta, L., Abou-Abssi, E., Dawson, J., & Mussells, O. (2017). Shipping corridors as a framework for advancing marine law and policy in the Canadian Arctic. *Ocean and Coastal Law Journal*, 22(1), 63.

- Putland, R. L., Merchant, N. D., Farcas, A., & Radford, C. A. (2017). Vessel noise cuts down communication space for vocalizing fish and marine mammals. *Global Change Biology*, 24(4), 1708–1721. <https://doi.org/10.1111/GCB.13996>
- Qikiqtani Inuit Association. (2014). *Qikiqtani Inuit Association's final written submission for Baffinland Iron Mines Corporation, Mary River Project, Addendum to the Final Environmental Impact Statement*.
- Qikiqtani Inuit Association. (2019). *UQAUSIRISIMAJAVUT: What we have said. The Inuit view of how oil and gas development could impact our lives*. <https://www.qia.ca/wp-content/uploads/2019/03/QIA-SEA-Summary.pdf>
- Ray and Watkins. (1975). Social function of underwater sounds in walrus. *Rapp. P.-v. Réun. Cons. Int. Explor. Mer*, 169, 524–526.
- Richardson, W. J., Greene Jr C. R., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise*. Academic press.
- Rojano-Donate, L., Lamoni, L., Tougaard, J., & Findlay, C. R. (2024). Effect of Vessel Noise on Marine Mammals and Measures to Reduce Impact. *The Effects of Noise on Aquatic Life: Principles and Practical Considerations*, 1755–1771. https://doi.org/10.1007/978-3-031-50256-9_138/SAVE-RESEARCH
- Ross, Donald. (1976). *Mechanics of underwater noise* (Pergamon Press). Pergamon.
- Roth, E. H., Schmidt, V., Hildebrand, J. A., & Wiggins, S. M. (2013). Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean. *The Journal of the Acoustical Society of America*, 133(4), 1971–1980. <https://doi.org/10.1121/1.4790356>
- Salter, R. E. (1979). Site utilization, activity budgets, and disturbance responses of Atlantic walruses during terrestrial haul-out. *Can. J. Zool.*, 57(6), 1169–1180.
- Sjare, B. L. (1993). *Vocalizations and breeding behavior of Atlantic walruses in the Canadian High Arctic*.
- Sjare, B., & Stirling, I. (1996). The breeding behavior of Atlantic walruses, *Odobenus rosmarus rosmarus*, in the Canadian High Arctic. *Canadian Journal of Zoology*, 74(5), 897–911. <https://doi.org/10.1139/z96-103>
- Sjare, B., Stirling, I., & Spencer, C. (2003). Structural variation in the songs of Atlantic walruses breeding in the Canadian High Arctic. *Aquatic Mammals*, 29(2), 297–318.
- Spence, J. H., & Fischer, R. W. (2017). Requirements for Reducing Underwater Noise from Ships. *IEEE Journal of Oceanic Engineering*, 42(2), 388–398. <https://doi.org/10.1109/JOE.2016.2578198>
- Stewart, D. B., Higdon, J. W., & Stewart, R. E. A. (2020). *Threats and Effects Pathways of Shipping Related to Non-renewable Resource Developments on Atlantic Walruses (Odobenus Rosmarus Rosmarus) in Hudson Strait and Foxe Basin, Nunavut*. Fisheries and Oceans Canada= Pêches et océans Canada.
- Stewart, R. E. A. (2008). Redefining walrus stocks in Canada. *Arctic*, 61(3), 292–308.

- Stewart, R. E. A. (2012). *Review of Atlantic Walrus (Odobenus rosmarus rosmarus) in Canada. Research Document.* <https://oaresource.library.carleton.ca/wcl/2016/20160811/Fs70-5-2002-091-eng.pdf>
- Stirling, I., Calvert, W., & Spencer, C. (1987). Evidence of stereotyped underwater vocalizations of male Atlantic walruses (*Odobenus rosmarus rosmarus*) . *Canadian Journal of Zoology*, 65(9), 2311–2321. <https://doi.org/10.1139/z87-348>
- Taylor, R. L., Jay, C. V., Beatty, W. S., Fischbach, A. S., Quakenbush, L. T., & Crawford, J. A. (2023). Exploring effects of vessels on walrus behaviors using telemetry, automatic identification system data and matching. *Ecosphere*, 14(3). <https://doi.org/10.1002/ecs2.4433>
- Terhune, J. M., Stewart, R. E. A., & Ronald, K. (1979). Influence of vessel noises on underwater vocal activity of harp seals. *https://doi.org/10.1139/Z79-170*, 57(6), 1337–1338. <https://doi.org/10.1139/z79-170>
- Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Conrad, A. S., Samson, A. L., Garde, E., Hansen, R. G., & Mads Peter, H. J. (2021). Narwhals react to ship noise and airgun pulses embedded in background noise. *Biology Letters*, 17(11). <https://doi.org/10.1098/rsbl.2021.0220>
- Transport Canada. (2021). *Quiet Vessel Initiative.* <https://tc.canada.ca/en/programs/quiet-vessel-initiative>. (Accessed 19 Juin 2026).
- Trevorrow, M. V., Vasiliev, B., & Vagle, S. (2008). Directionality and maneuvering effects on a surface ship underwater acoustic signature. *The Journal of the Acoustical Society of America*, 124(2), 767–778. <https://doi.org/10.1121/1.2939128>
- Trounce, K., Robinson, O., MacGillivray, A., Hannay, D., Wood, J., Tollit, D., & Joy, R. (2019). The effects of vessel slowdowns on foraging habitat of the southern resident killer whales. *Proceedings of Meetings on Acoustics*, 37(1). <https://doi.org/10.1121/2.0001230/982233>
- Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy*, 89(3), 549–558.
- Tyack, P. L., Zimmer, W. M. X., Moretti, D., Southall, B. L., Claridge, D. E., Durban, J. W., Clark, C. W., D'Amico, A., DiMarzio, N., Jarvis, S., McCarthy, E., Morrissey, R., Ward, J., & Boyd, I. L. (2011). Beaked Whales Respond to Simulated and Actual Navy Sonar. *PLOS ONE*, 6(3), e17009. <https://doi.org/10.1371/JOURNAL.PONE.0017009>
- Verboom, W. C. (2023). *Analysis of Walrus (Odobenus rosmarus divergens) rutting whistles.*
- Wickson, F. (2021). Atlantic walrus management, regulation and conservation. In *The Atlantic Walrus: Multidisciplinary Insights into Human-Animal Interactions* (pp. 251–262). Elsevier. <https://doi.org/10.1016/B978-0-12-817430-2.00005-4>
- Winship, K. A., & Jones, B. L. (2023). Acoustic Monitoring of Professionally Managed Marine Mammals for Health and Welfare Insights. In *Animals* (Vol. 13, Number 13). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/ani13132124>
- Wittekind, D. K. (2014). A simple model for the underwater noise source levels of ships. *Journal of Ship Production and Design*, 30(1), 1–8.

Zakarauskas, P., Chapman, D. M. F., & Staal, P. R. (1990). Underwater acoustic ambient noise levels on the eastern Canadian continental shelf. *The Journal of the Acoustical Society of America*, 87(5), 2064–2071. <https://doi.org/10.1121/1.39933>

3.8 Supplementary materials

Table S3.1 Summary of all ship IDs and transits recorded within the 100 km buffer zone around the hydrophone FB-IGL1-23, Foxe Basin, August-October 2023.

Ship ID	Transit	Type	Month	Number of AIS points	Min speed (knots)	Max speed (knots)	Min dist (km)	Max dist (km)
368149789	1	General	October	11	7.71	12.13	7.0	95.5
368266998	1	General	September	9	3.50	15.19	11.3	84.5
369975789	1	General	October	11	6.96	14.26	4.6	91.8
370321789	1	General	October	11	2.59	17.84	9.1	97.1
370368789	1	General	September	11	4.71	12.82	6.2	91.6
439458164	1	Other	September	10	5.08	9.04	64.8	94.3
	2		October	9	6.27	11.25	67.2	98.5
439460579	1	General	September	8	10.21	16.17	8.9	85.6
439460769	1	Chemical	September	108	0.00	16.98	23.0	100.0
439469789	1	Icebreaker	September	81	0.08	13.15	4.5	97.2
	2		October	19	0.00	12.44	4.2	91.1
439471922	1	General	September	8	10.19	15.85	8.7	83.0
439471929	1	General	August	117	0.00	14.87	22.6	95.5
439472040	1	General	September	69	0.00	15.62	23.3	89.4
439476797	1	Unknown	September	53	0.01	2.91	23.3	82.3
439481818	1	General	September	7	9.64	18.29	6.7	83.7
439489053	1	Unknown	September	53	0.02	3.15	23.3	82.4
439494162	1	Chemical	October	10	7.24	16.00	7.4	90.2
439496821	1	Unknown	August	110	0.00	3.22	23.2	81.9
439506789	1	Icebreaker	October	22	0.16	14.73	6.9	96.0
439527789	1	Icebreaker	September	17	0.66	12.30	36.7	95.6
	2		September	9	7.07	13.59	14.7	89.1
	3		September	64	0.01	16.58	5.7	93.9
439528789	1	Icebreaker	October	9	7.37	16.57	5.6	86.7
439621789	1	Icebreaker	August	61	0.00	11.90	10.8	97.4
	2		October	7	4.66	20.51	9.1	84.7

Table S3.2 AIS positions that were interpolated for vessels transiting within 100 km around FB-IGL1-23 during August-October 2023. For each gap between p_0 at time t_0 and p_1 at time t_1 , one position was interpolated per missing hour until the next p_1 was reached. This approach assumes constant linear movement between consecutive observed positions. The number of AIS points is the number of interpolated positions within the corresponding transit.

Ship ID	Transit	Type	Month	Number of AIS points
370321789	1	General Cargo	October	1
439460769	1	Chemical Tanker	September	4
439469789	1	Icebreaker	September	3
	2		October	1
439471929	1	General Cargo	August	6
439472040	1	General Cargo	September	5
439476797	1	Unknown	September	22
439489053	1	Unknown	September	20
439496821	1	Unknown	August	48
439506789	1	Icebreaker	October	1
439527789	1	Icebreaker	September	1
439527789	2		September	2
439621789	1	Icebreaker	August	2
439621789	2		October	1
370321789	1	General Cargo Ship	October	1

Table S3.3 Model selection, ranked by AICc, with the ten first best-supported models. + = predictor retained. All models include (1|day) as a random effect.

Rank	Intercept	Vessel type	Direction	Distance	Land barrier	Speed	Vessel cat.	Dist x speed	Dist x vessel cat.	Speed x vessel cat.	df	AICc	ΔAICc	logLik	Weight
1	1.423			+		+	+	+			7	2277.5	0.00	-1131.65	0.019
2	1.409			+		+	+				6	2277.8	0.26	-1132.81	0.017
3	1.426					+	+				5	2278.3	0.74	-1134.07	0.013
4	1.412			+		+	+			+	7	2278.8	1.32	-1132.31	0.010
5	1.354		+	+		+	+	+			8	2279.0	1.45	-1131.35	0.009

6	1.423		+		+	+	+		+	8	2279.2	1.68	-1131.46	0.008
7	1.338		+	+		+	+			7	2279.2	1.68	-1132.49	0.008
8	1.343		+			+	+			6	2279.5	1.93	-1133.65	0.007
9	1.402			+	+	+	+	+		8	2279.5	1.95	-1131.59	0.007
10	1.426			+		+	+	+	+	8	2279.6	2.05	-1131.64	0.007

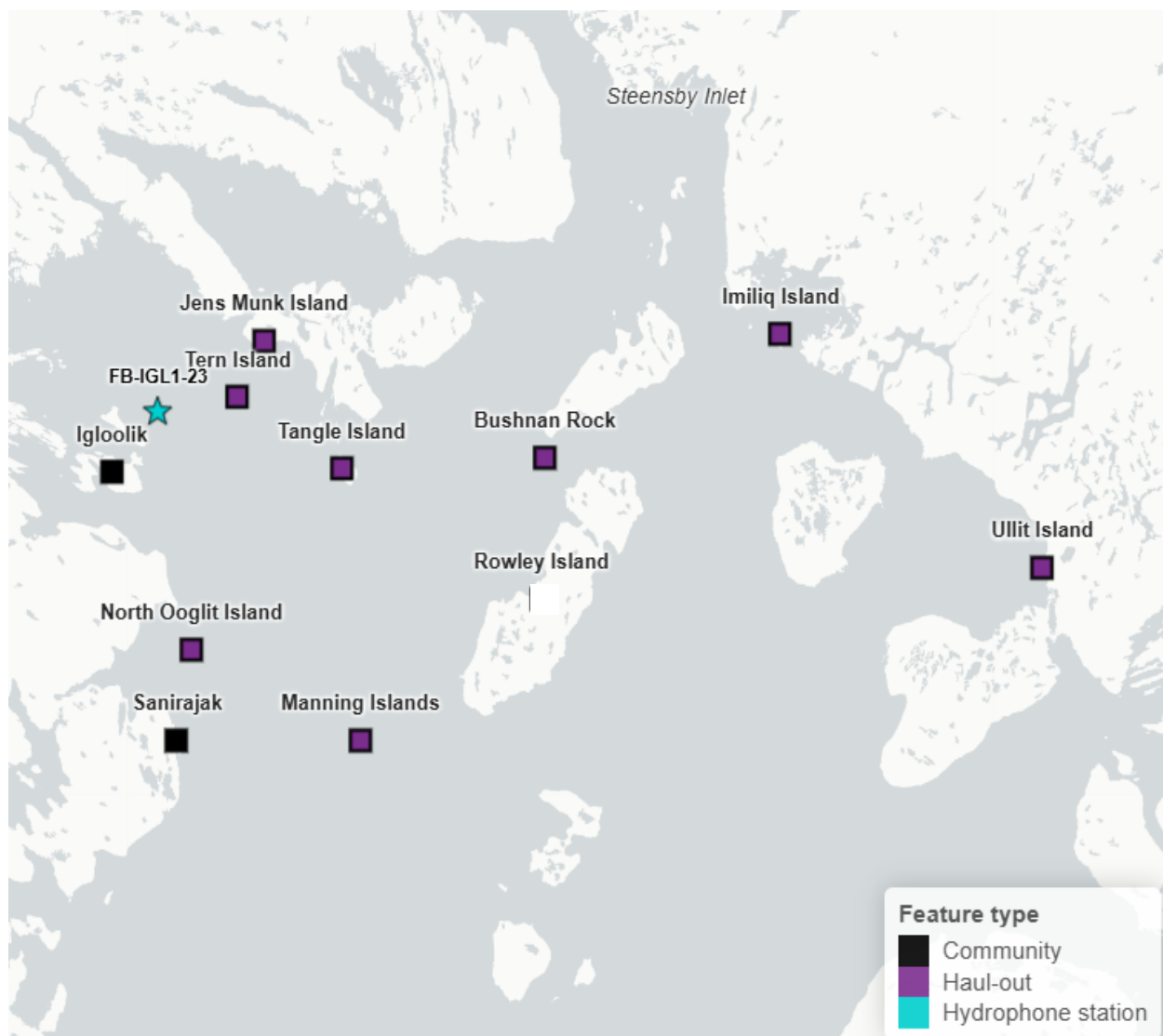


Figure S3.1 Map of the documented haul-outs (purple square) in Northern Foxe Basin, with the hydrophone location FB-IGL1-23 (blue star), and the communities of Igloolik and Sanirajak. In Inuktitut: Tangle Island is Nuvuklit and Tern Island is Siuraq. Haul-out coordinates were available on CAFF – Arctic Biodiversity Data Service (ABDS): <https://geo.abds.is/geonetwork/srv/eng/catalog.search#/metadata/fcdc5e58-3318-4a02-a484-8ecb7cfb66e2>.

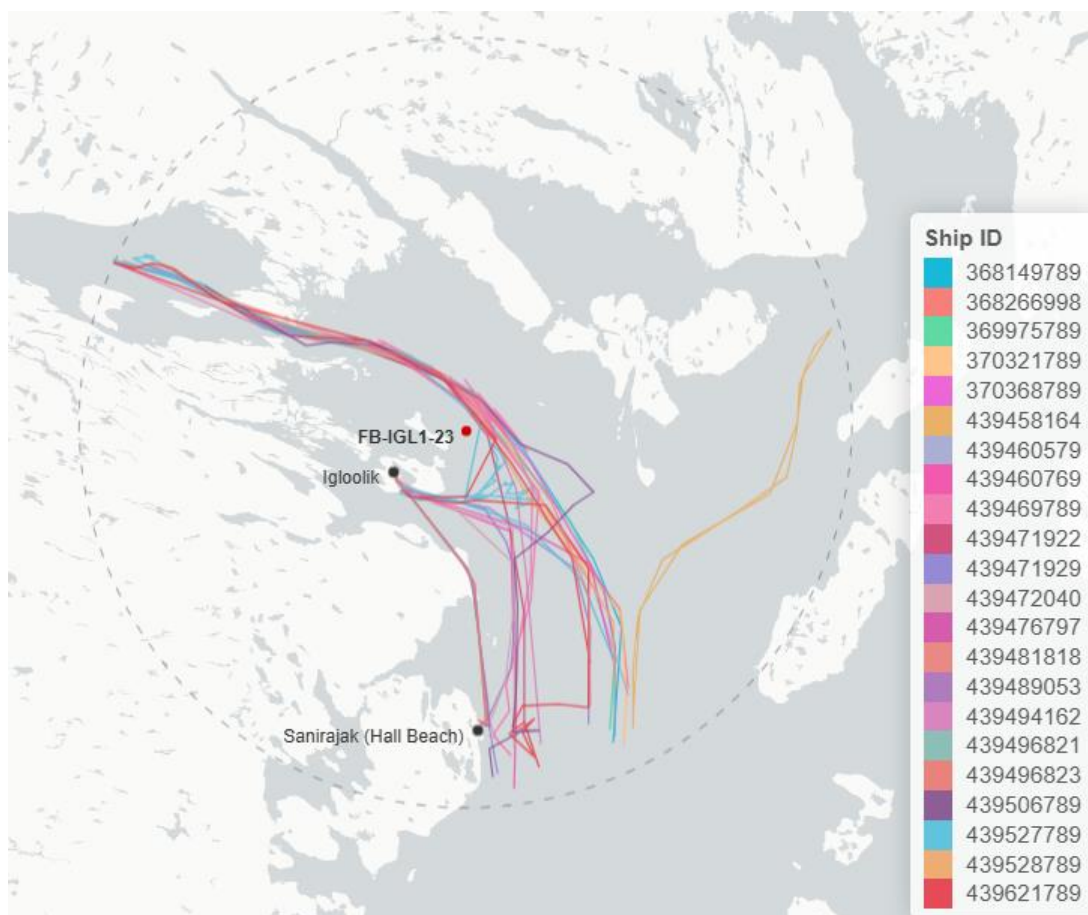


Figure S3.2 Map of shipping tracks a 100km around the hydrophone FB-IGL1-23 in northern Foxe Basin during August-October 2023. The different colors represent different ship ID.

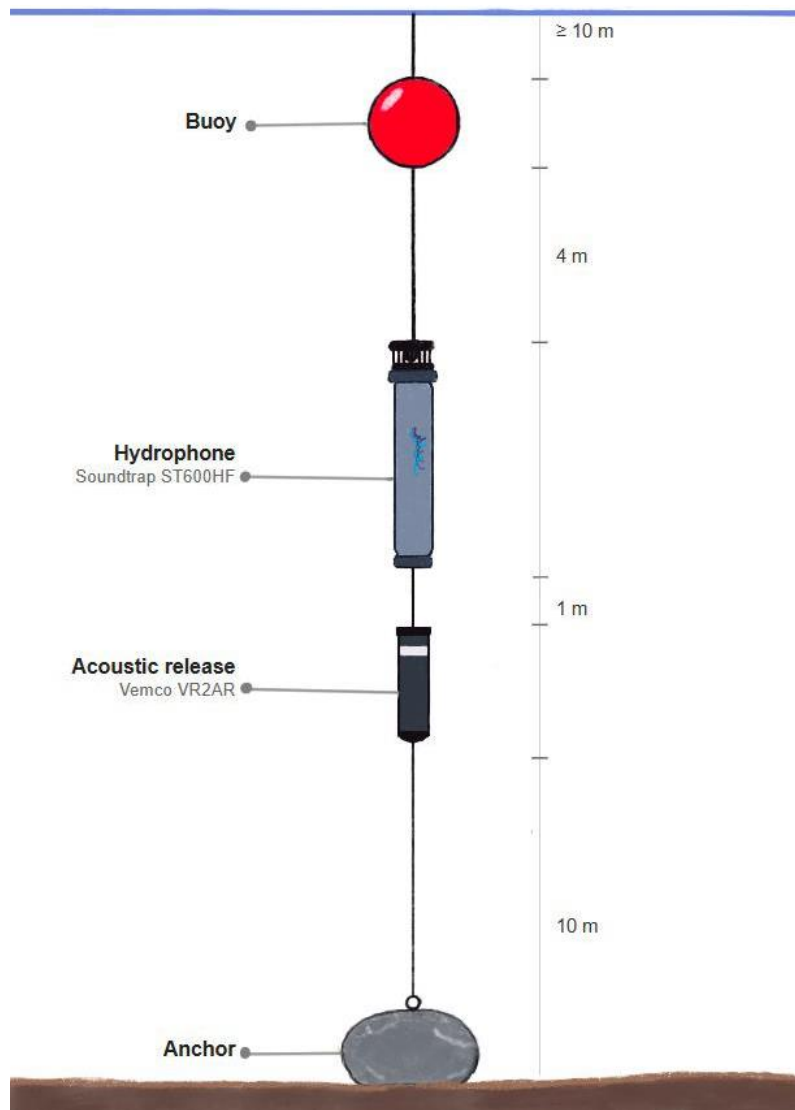


Figure S3.3 Diagram of a mooring equipped with a buoy, a hydrophone Soundtrap ST600HF, an acoustic release VEMCO VR2AR, and an anchor. Deployed at FB-IGL1-23 between 2023 and 2024. Drawn on Procreate, version 5.3, Savage Interactive Pty Ltd.



Figure S3.4 Example of interpolated AIS positions (blue points) and three interpolated positions (orange points) for transit 1 of the Icebreaker (ship ID: 439469789) in September 2023. The inset (top right) shows a close-up of the two interpolated positions nearest the hydrophone FB-IGL1-23 (cyan point). The dashed circle represents the 100 km buffer zone used in the study.

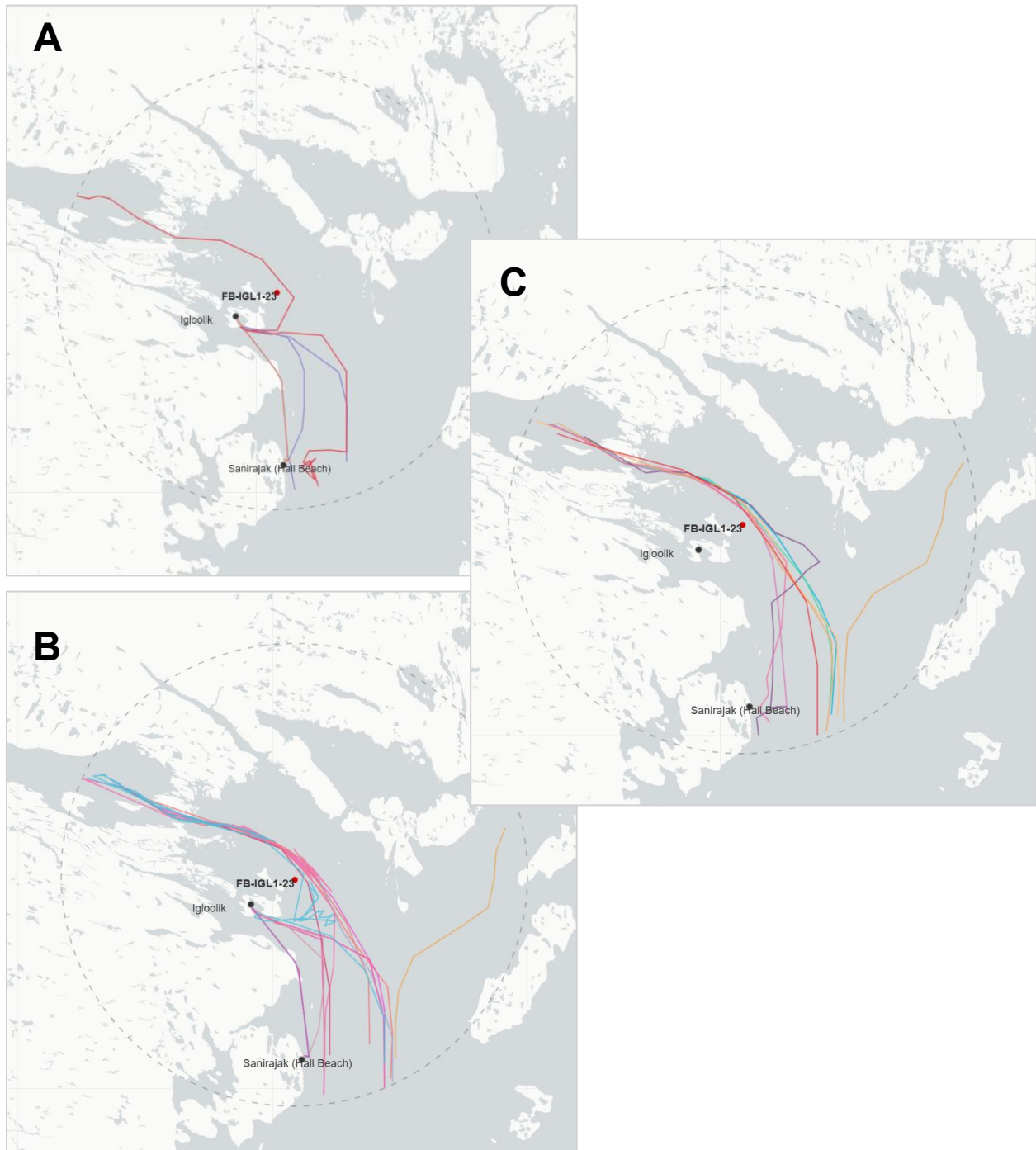


Figure S3.5 Map of shipping tracks, after cleaning the AIS data and interpolating the AIS points, in northern Foxe Basin during (A) August, (B) September, and (C) October 2023. The different colors represent different transit.

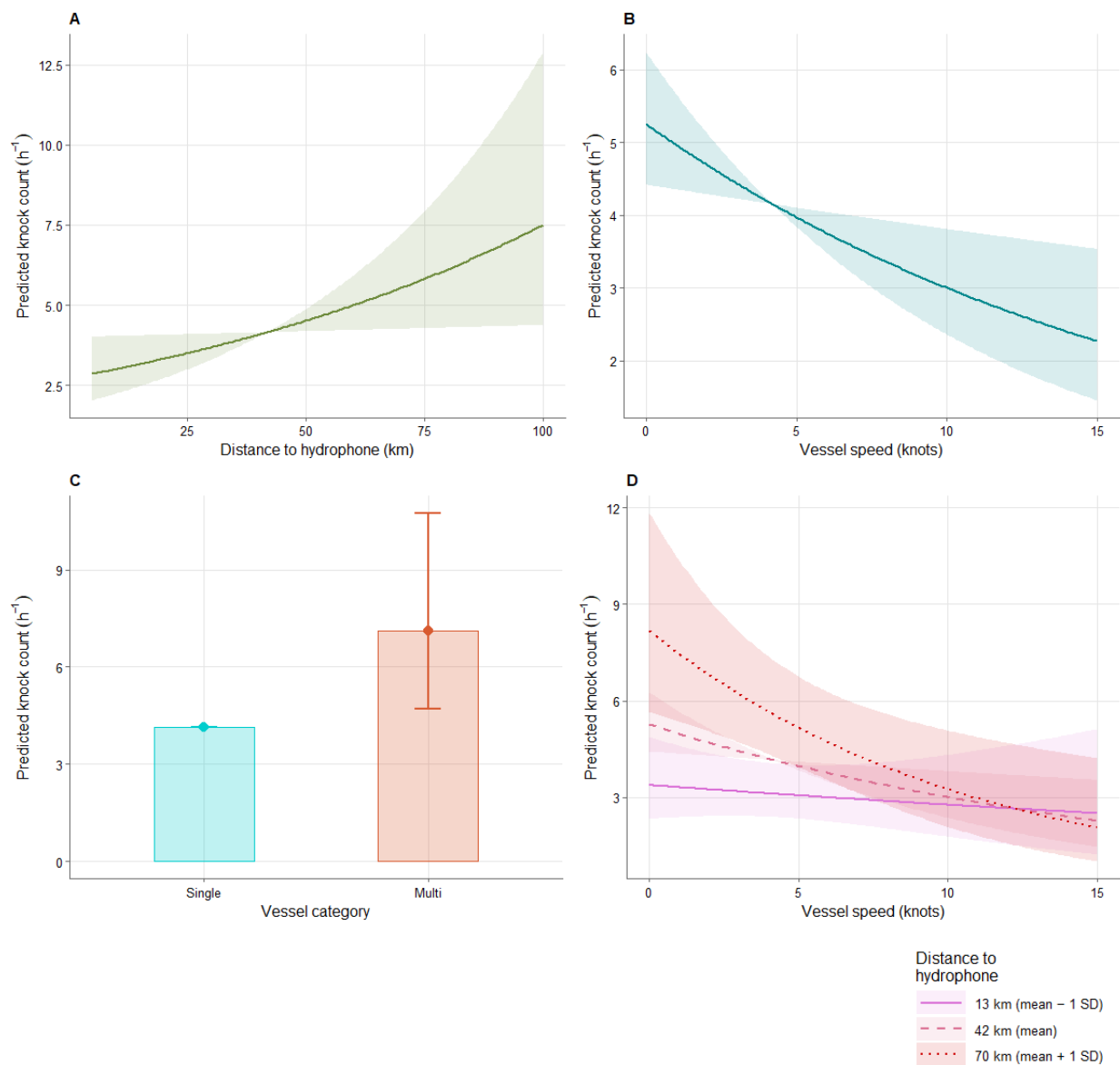


Figure S3.6 Predicted walrus knock counts with distance to hydrophone, vessel speed, and vessel category, derived from the negative binomial GLMM. (A) Predicted knock count in relation to distance between the vessel and the hydrophone (km). (B) Predicted knock count in relation to vessel speed (knots). (C) Predicted knock count by vessel category (single vessel vs. multiple vessels). (D) Predicted knock count in relation to vessel speed (knots) at three distances to the hydrophone (13 km, 42 km, and 70 km), chosen to represent the mean and $\pm$ one standard deviation of observed vessel distances to show how the effect of speed on knock counts changes with proximity to the hydrophone. Shaded areas and error bars represent 95% confidence

Chapter 4 General Conclusion

4.1 Summary

This research was divided into two distinct data chapters, both based on the manual analysis of acoustic recordings collected in Foxe Basin. Chapter 2 assessed temporal patterns of daily vocal presence of the walrus, bowhead whale, beluga, bearded seal, and ringed seal at two monitoring locations. Walrus vocalizations were the most frequently detected among all five species, suggesting that northern Foxe Basin is a year-round habitat. Sea ice provides walrus with a platform for important life functions (Fay, 1982; Richard & Campbell, 1988), which was consistent with the relationship observed between walrus acoustic presence and sea ice concentration. Bowhead whale detections at FB-IGL1-23 followed a seasonal pattern consistent with the migratory cycle of the EC-WG population (Fortune et al., 2020; Heide-Jørgensen, 2003), with peak acoustic activity during summer and low sea ice concentration, when the area is used as a foraging and nursery ground. Higher vocal detections at FB-IGL1-23 suggest differences in habitat use between sites. Beluga vocalizations were detected during winter months, which lie outside of the sighting periods typically described for Foxe Basin. Their association with colder sea surface temperatures and differences between sites suggest that winter habitat use may be influenced by local environmental conditions. Bearded seal vocal detections were highly seasonal, with a peak during the breeding season and a decrease under higher wind speed, likely reflecting acoustic masking. Ringed seal vocalizations were the least frequently detected among the five species, and detections were concentrated during freeze-up. The co-occurrence of multiple species in northern Foxe Basin and the seasonal overlap in their acoustic activity suggest potential interactions and highlight the ecological importance and acoustic diversity of the area.

Chapter 3 investigated the effects of vessel traffic on walrus vocal activity in northern Foxe Basin during the 2023 shipping season, representing, to our knowledge, only the second study to document underwater vocal disturbance in Atlantic walrus (Coppolaro et al., 2025). Hourly knock counts were approximately 50% lower during the shipping season than preceding the first vessel

arrival, and vessel proximity and speed were found to impact walrus vocal activity. Detections declined as vessels approached the hydrophone and as speed increased. This could reflect acoustic masking, reduced vocal behaviour, or physical displacement, though it could not be distinguished in this study. Recordings with multiple vessels were associated with higher knock counts. A potential Lombard effect in walruses could explain higher vocal detections. Individuals modify their vocalizations, sometimes to higher frequencies, to maintain communication in response to elevated ambient noise (Lombard, 1911). Current Canadian Marine Mammal Regulations do not apply to vessels in transit (Marine Mammals Regulations. Fisheries Act. SOR/93-56, 2018) and, given the present results, may not adequately protect walruses from shipping disturbance. To face increasing vessel traffic, low-impact shipping corridors and quieter vessels are encouraged. Together, these chapters demonstrate the value of passive acoustic monitoring as a tool for both documenting species presence and detecting behavioural disturbances in the underwater environment.

4.2 Limitations

Although passive acoustic monitoring is a valuable tool for documenting vocalizations, it is subject to some limitations. The primary constraint of PAM is that an individual must vocalize for its presence to be detected. Consequently, the absence of vocalizations cannot be interpreted as the absence of the species *per se*. A lack of vocal presence can reflect acoustic masking, or inactivity, or a departure from the area. The results may underestimate the actual presence of each described species.

In Chapter 2, vocalizations were assessed for presence only, without classification by call type. Incorporating call type could have provided valuable context for interpreting species presence. For example, distinguishing whether belugas produced more echolocation clicks or social whistles during their time in Foxe Basin would have helped understand how individuals use the area. Environmental covariates were drawn from two data sources with different spatial

resolutions, which may have introduced some inconsistency in their relationship with species vocal presence, although the observed patterns remained ecologically consistent.

In Chapter 3, only knocks were used to infer walrus vocal presence around the hydrophone. Some studies on Pacific and Atlantic walrus have documented additional underwater vocalizations, including strums, grunts (Panova et al., 2026; Stirling et al., 1987a), barks (Charrier, 2021), whistles (Verboom, 2023), rasps, moans, and chuffs (Schevill et al., 1966; Schusterman & Reichmuth, 2008). It is therefore possible that not including these call types led to an underestimation of overall vocal activity, although knocks appear to be the primary and most frequent call type. Furthermore, acoustic parameters such as frequency, amplitude, duration, inter-knock intervals and signal-to-noise ratio were not measured for detected knocks. This limited the evaluation of a potential Lombard effect, as it was not possible to determine whether call characteristics changed in the presence of vessels.

4.3 Directions for future research

Future acoustic research in Foxe Basin should improve the spatial coverage of PAM for important walrus habitats. Several haul-out sites have been identified (Cubaynes et al., 2026), near the planned shipping routes associated with the Mary River Project, including Imiliq Island, Ullit Island, Bushnan Rock, and Steensby Inlet. As vessel traffic would occur within approximately 50 km of these haul-outs, deploying additional hydrophones in these areas would allow the monitoring of potential changes in walrus vocal behaviour as shipping activity increases.

Future research should also improve understanding of how walruses are exposed and respond to shipping noise. Foxe Basin is characterized by shallow waters, complex island topography, and seasonal sea ice, all of which can substantially influence sound propagation. Dedicated propagation studies are therefore needed to characterize how vessel noise is transmitted across the basin. At the same time, future studies should investigate whether

disturbance responses vary between males and females, among mother-pup pairs, or during the breeding season (Charrier, 2021).

Behavioural responses should be more clearly described to inform management decisions better. The results of this study may suggest a Lombard effect in response to increased vessel traffic, consistent with the findings of Denes (2014), which linked ambient noise to walrus call amplitude. Additional work should investigate this response further, including whether vocal compensation reaches a limit beyond which it is no longer effective, as observed in bearded seals (Fournet et al., 2021). Furthermore, telemetry studies could help elucidate how walruses respond to vessel disturbances and establish safe vessel distance and speed thresholds to minimize disturbance.

Finally, continued engagement and participation in long-standing collaborative research programs with Inuit communities around Foxe Basin should be maintained and expanded to the development of conservation and management measures that reflect local priorities and community realities.

4.4 Literature cited

- Charrier, I. (2021). Vocal communication in otariids and odobenids. In *Ethology and behavioral ecology of otariids and the odobenid* (pp. 265–289). Cham: Springer International Publishing.
- Coppolaro, V. L. M., Ausen, E. L., Loseto, L. L., & Marcoux, M. (2025). Vessel traffic disrupts walrus vocal behavior in a proposed marine protected area. *Frontiers in Marine Science*, 12. <https://doi.org/10.3389/fmars.2025.1658328>
- Cubaynes, H. C., Matthews, C. J. D., Garde, E., Gavrillo, M., Heide-Jørgensen, M. P., Higdon, J. W., Kovacs, K. M., Leskova, M., Lydersen, C., Solovyev, B., Vergara-Pena, A., & Fretwell, P. T. (2026). A distribution-wide dataset of Atlantic walrus terrestrial haul-out sites. *Scientific Data* 2026 13:1, 13(1), 808-. <https://doi.org/10.1038/s41597-026-07210-6>
- Denes, S. L. (2014). *Ocean environmental effects on walrus communication*. The Pennsylvania State University.
- Fay, F. H. (1982). Ecology and biology of the Pacific walrus, *Odobenus rosmarus divergens* Illiger. *North American Fauna*, (74), 1–279.
- Fortune, S. M. E., Ferguson, S. H., Trites, A. W., Leblanc, B., Lemay, V., Hudson, J. M., & Baumgartner, M. F. (2020). Seasonal diving and foraging behaviour of Eastern Canada-West Greenland bowhead whales. *Marine Ecology Progress Series*, 643, 197–217. <https://doi.org/10.3354/MEPS13356>
- Fournet, M. E. H., Silvestri, M., Clark, C. W., Klinck, H., & Rice, A. N. (2021). Limited vocal compensation for elevated ambient noise in bearded seals: implications for an industrializing Arctic Ocean. *Proceedings of the Royal Society B: Biological Sciences*, 288(1945). <https://doi.org/10.1098/rspb.2020.2712>
- Heide-Jørgensen MP, L. K. W. Ø. J. M. and others. (2003). From Greenland to Canada in Ten Days: Tracks of Bowhead Whales, *Balaena mysticetus*, across Baffin Bay. *Arctic*, 56, 21. <https://www.jstor.org/stable/40512155>
- Lombard, E. (1911). Le signe de l'elevation de la voix. *Annales Des Maladies de l'Oreille et Du Larynx*, 37, 101–119.
- Marine Mammals Regulations. Fisheries Act. SOR/93-56 (2018). <http://laws-lois.justice.gc.ca>
- Panova, E. M., Tolstoy, M. L., Belikov, R. A., & Bogomolova, I. M. (2026). Summer underwater vocalizations of male Atlantic walruses *Odobenus rosmarus rosmarus* near their terrestrial haul-out site. *Behavioural Processes*, 237, 105362. <https://doi.org/10.1016/j.beproc.2026.105362>
- Richard, P. R., & Campbell, R. R. (1988). Status of the Atlantic walrus, *Odobenus rosmarus rosmarus*, in Canada. *Canadian Field-Naturalist*. Ottawa ON, 102(2), 337–350.
- Schevill, W. E., Watkins, W. A., & Ray, C. (1966). Analysis of underwater *Odobenus* calls with remarks on the development and function of the pharyngeal pouches. *Zoologica: Scientific Contributions of the New York Zoological Society*, 51(10), 103–106. <https://doi.org/10.5962/P.203287>

- Schusterman, R. J., & Reichmuth, C. (2008). Novel sound production through contingency learning in the Pacific walrus (*Odobenus rosmarus divergens*). *Animal Cognition*, 11(2), 319–327. <https://doi.org/10.1007/s10071-007-0120-5>
- Stirling, I., Calvert, W., & Spencer, C. (1987). Evidence of stereotyped underwater vocalizations of male Atlantic walruses (*Odobenus rosmarus rosmarus*). *Canadian Journal of Zoology*, 65(9), 2311–2321. <https://doi.org/10.1139/z87-348>
- Verboom, W. C. (2023). *Analysis of Walrus (Odobenus rosmarus divergens) rutting whistles*. <https://www.researchgate.net/publication/367238635>