Arctic Science

OPEN ACCESS | Research Article

Seasonal and diurnal marine mammal presence in the proposed marine protected area of Southampton Island, Hudson Bay, Nunavut as revealed by passive acoustic monitoring

Veronica Laura Maria Coppolaro[a], **Kaushik Gupta**[a], **Lisa Loseto**[a,b], **C.J. Mundy**[a], **and Marianne Marcoux**[b]

[a]Centre for Earth Observation Sciences, University of Manitoba, Winnipeg, MB, Canada; [b]Freshwater Institute, Fisheries and Oceans Canada, Winnipeg, MB, Canada

Corresponding author: **Veronica Laura Maria Coppolaro** (email: coppolav@myumanitoba.ca)

Abstract

Marine protected areas contribute to mitigating the effects of human activities on marine ecosystems. The waters of Southampton Island, Nunavut, Canada are under consideration to become a marine protected area, but baseline information of marine mammal presence and habitat use is lacking. This study represents the first passive acoustic monitoring of marine mammals in this area, with data collected in 2018 and 2019. Bioacoustics analyses and generalized linear models were used to investigate species seasonal and temporal vocalization trends; infer behavior and habitat use from vocal cues; and explore vocal activity correlation with sea ice. Over a diel period, bearded seals (*Erignathus barbatus* (Erxleben, 1777)) and walruses (*Odobenus rosmarus* (Linnaeus, 1758)) were found to increase their vocal activity at night, whereas belugas (*Delphinapterus leucas* (Pallas, 1776)) mainly vocalized during daytime. Seasonally, bearded seals were recorded only during their breeding season at sea ice break-up, while walruses vocalized consistently throughout the open-water period outside their breeding season. Beluga vocal trends suggest their use of the area as a migratory corridor during sea ice break-up and freeze-up. Finally, bowhead whales (*Balaena mysticetus* Linnaeus, 1758) were recorded later than expected, concurrently with the onset of their mating vocal displays during the fall migration at sea ice freeze-up.

Key words: marine mammal vocalizations, passive acoustic monitoring, Arctic, marine protected area, GLM

Introduction

Protected areas are an important tool for ecosystem conservation both on land and at sea (Chape et al. 2005; González-Maya et al. 2015; Simard et al. 2016; Xavier da Silva et al. 2018; Pacifici et al. 2020; Ranius et al. 2023). Marine protected areas (MPAs) play a fundamental role in biodiversity conservation, habitat restoration, reduction of human disturbance, and sustainable management of marine and coastal ecosystems (Gallardo et al. 2017; Bruno et al. 2018; Sala et al. 2021; Schmidt et al. 2022). In the last decades, MPAs have also been recognized as an effective instrument to mitigate climate change impacts on marine ecosystems by limiting many of the stressors that affect the local fauna (Hopkins et al. 2016; CAFF and PAME 2017; Maestro et al. 2019; IPCC 2022). Despite their importance, MPAs cover around 8% of the ocean and only 3% is fully protected, compared to 15% of protected land and inland waters worldwide (Maestro et al. 2019; Sala et al. 2021; UNEP-WCMC and IUCN 2023). Given the growing pressure that climate change and the related increase in human activity in the ocean is exerting on marine species, establishing MPAs has become a compelling issue and a fundamental instrument for reaching the global goal of protecting 30% of the ocean by 2030 (IPCC 2022; Lalonde et al. 2022; UNEP, CBD and COP 2022; UNEP-WCMC and IUCN 2023). Among the most affected regions on the planet, the Arctic is currently experiencing rapid changes in its marine environment (Garcia-Soto et al. 2021; IPCC 2022). Its current warming rate is up to four times the global average, which contributes to a rapid decrease in sea ice thickness, extent, and seasonal coverage duration (Comiso and Hall 2014; Parkinson 2014; Crawford et al. 2021; IPCC 2022; Rantanen et al. 2022). Sea ice loss represents a significant threat to many Arctic species, which rely on it as a resting, hunting, and pupping platform (Stirling and Derocher 2012; Iacozza and Ferguson 2014), and benefit from it as a barrier to predators and competing species (Kingsley and Stirling 1991; Higdon et al. 2012; Florko et al. 2018). Moreover, decreasing sea ice and longer open-water periods lead to a more accessible Arctic Ocean, with a consequent expansion in human activities such as vessel traffic (Pizzolato et al. 2016; Andrews et al. 2018; Dawson et al. 2018; Stevenson et al. 2019). Altogether, climate change and human disturbance are expected to intensify their pressure on the Arctic environment with potential negative consequences on marine species at both the individual and population level (Tynan and DeMaster 1997; Burek et al. 2008; Laidre et al. 2008, 2015; Moore et al. 2012; Pirotta et al. 2018; Booth et al. 2020). Among the affected species, marine mammals are of particular interest as they are considered sentinels of their environment (Moore 2008; Fossi and Panti 2017; Hazen et al. 2019). Therefore, knowledge of marine mammal presence and habitat use is critical to determine hotspots, provide baseline information to monitor potential future changes in the ecosystem, and to inform conservation objectives in the assessment process of MPAs (Fossi and Panti 2017; Hazen et al. 2019). The waters around Southampton Island in Hudson Bay, Canada are characterized by an Arctic climate and experience a complete seasonal ice cover, which is undergoing rapid and persisting changes, including an increase in vessel traffic (Gagnon and Gough 2005; Andrews et al. 2018; Dawson et al. 2018). This area belongs to the Kivalliq Region of the Canadian territory of Nunavut and represents an ecological hotspot for many marine mammal species (Stewart and Lockhart 2005; DFO 2011; Carter et al. 2019; Yurkowski et al. 2019; Loewen et al. 2020). The Central-Low Arctic walrus (*Odobenus rosmarus* (Linnaeus, 1758)), the ringed seal (*Pusa hispida* Schreber, 1775), and the bearded seal (*Erignathus barbatus* (Erxleben, 1777)) are year-round residents, whereas the Eastern Canada-West Greenland (EC-WG) bowhead (*Balaena mysticetus* Linnaeus, 1758) and the Western Hudson Bay beluga (*Delphinapterus leucas* (Pallas, 1776)) whale populations migrate to this area every summer (DFO 2011; AMAP 2013; Carter et al. 2019; Yurkowski et al. 2019; Loewen et al. 2020). The region is also known to be occasionally used by Northern Hudson Bay narwhals (*Monodon monoceros* Linnaeus, 1758) and Northwest Atlantic harp seals (*Pagophilus groenlandicus* (Erxleben, 1777)), and increasingly by Eastern Canadian Arctic killer whales (*Orcinus orca* (Linnaeus, 1758)) (Higdon et al. 2012; NCRI 2012; Loewen et al. 2020). Many of these species are listed as Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). The Inuit community of Salliq—ᓴᓪᓕᖅ (or Sallit—ᓴᓪᓖᑦ) / Coral Harbour is the only community on the Island and has a population of around 1000 inhabitants (Statistics Canada 2023). The community relies on the marine areas surrounding Southampton Island for subsistence harvesting of several of the aforementioned species (Hay et al. 2000; Hoover et al. 2013; Carter et al. 2019; Loewen et al. 2020). Due to the importance as both a marine mammal hotspot and as harvesting ground for local communities, this region was recognized as an area of interest (AOI) by Fisheries and Oceans Canada (DFO) in 2019 and is currently under consideration to become an MPA under the Ocean Act (1996) (Loewen et al. 2020). Despite these efforts, decreasing sea ice and increasing vessel traffic in and around the AOI pose potential threats to the ecosystem, hence understanding the impact that they might have on marine mammals in this key area is urgent (Carter et al. 2019; Loewen et al. 2020). However, baseline information on marine mammal use of the AOI is currently sparse (Carter et al. 2019; Yurkowski et al. 2019; Loewen et al. 2020). To improve our knowledge on marine mammal habitat use in this area and provide information that can support the creation of an MPA, we collected data using passive acoustic monitoring (PAM). PAM is a non-invasive tool for long-term data collection in marine areas (Sousa-Lima et al. 2013; Henderson et al. 2018; Heenehan et al. 2019; Davis et al. 2020), which has been successfully used to record biological and anthropogenic sounds in the Arctic and has contributed to the monitoring and managing of MPAs (Marcoux et al. 2017; Halliday et al. 2019; Kline et al. 2020; Castellote et al. 2013, 2021). In this study, we address current knowledge gaps on marine mammal presence and use of the Southampton Island AOI using PAM. Specifically, the objectives of this paper are to (1) provide a baseline of marine mammal occupancy of the AOI based on underwater vocal activity of both resident and migratory species; (2) investigate marine mammal use of the area by analyzing species-specific vocal cues and their seasonal and diurnal trends; and (3) explore the influence of sea ice on species acoustic presence by studying the potential correlation between sea ice concentration (SIC) and marine mammal acoustic detections.

Materials and methods

1 Data collection

Passive acoustic underwater data were collected in the marine area south of Southampton Island in Hudson Bay, Nunavut, Canada (Fig. 1). Three hydrophones were deployed during two field campaigns; hydrophones in Evans Strait (ES) and South of Coats Island (CI) were installed in June 2018 around 197 km apart, whereas the hydrophone in South Bay (SB) was deployed in September 2019 at a distance of 33 km from the community of Salliq and around 95 and 234 km from the previous deployment locations of hydrophones ES and CI, respectively. Hydrophones ES and SB were deployed inside the Southampton Island AOI, whereas CI was located outside of its borders (Fig. 1). Each hydrophone was part of a set of instruments connected to each other in a chain-like style and was deployed as a distinct oceanographic mooring anchored to the seabed (Fig. A1). All moorings were deployed as part of the Southampton Island Marine Ecosystem Project (SIMEP) (Mundy 2022), and hydrophones were opportunistically installed on the moorings as a pilot project. The 2018 acoustic dataset was collected using a TR-ORCA hydrophone by Turbulent Research (https://turbulentresearch.com/tr-orca), whereas the 2019 dataset was collected using an AURAL-M2 hydrophone by Multi-Électronique (http://www.multi-electronique.com/aural.html). Deployment information such as location, survey period, and deployment depth, together with hydrophone settings are presented in Table 1. The TR-ORCA hydrophones recorded at a sample rate of 192 kHz with no set gain, while the AURAL-M2 used a sample rate of 32 kHz and a gain of 16 dB. The duty cycle of 55 min on and 5 min off was the same for the two hydrophone types.

2 Data processing

2.1 Bioacoustic data collection and analyses

Acoustic data were analyzed to investigate marine mammal seasonal presence and diurnal vocal trends in the prox-

Fig. 1. Map of the study area showing hydrophone locations in Evans Strait (ES), South of Coats Island (CI), and in South Bay (SB). The extent of the Southampton Island area of interest is shown in turquoise. The map was created in RStudio with shapefiles from the Flanders Marine Institute (2018) and Fisheries and Oceans Canada. The coordinate reference system is GCS_North_American_1983 and the projection is Lambert Conformal Conic.

Table 1. Mooring deployment information and hydrophone settings.

Mooring name	Hydrophone type	Period analyzed (DD/MM/YYYY)	Number of available recordings	Coordinates	Hydrophone depth (m)	Ocean floor (m)	Sample rate (kHz)	Duty cycle (min)	Gain (dB)
ES	TR ORCA	5 June 2018–6 December 2018	3054	63°11′00.1″N 81°58′52.4″W	142	194	192	5 ON/55 OFF	0
CI	TR ORCA	16 June 2018–31 July 2018	1096	61°45′36.8″N 84°18′10.3″W	150	179	192	5 ON/55 OFF	0
SB	AURAL-M2	2 September 2019–30 November 2019	2160	63°48′15.4″N 83°17′02.6″W	34	52	32	5 ON/55 OFF	16

imity of each mooring location. A total of 7543 5-min audio files were manually analyzed using the sound analysis software Raven Pro, version 1.6.4 (Raven Pro 2023). Species vocalizations were examined both aurally and visually by creating spectrograms in Raven Pro using a Hann window of 6000 samples with 50% overlap. This provides frequency resolutions of 33.3 and 5.3 Hz, and time resolutions of 0.02 and 0.1 s for the 2018 and 2019 surveys, respectively. Using different resolutions to analyze datasets inhibits direct comparisons of some vocalization characteristics. However, it did not impact the detection of species acoustic presence and the description of vocal behavior performed in this study. Spectrograms were analyzed by zooming in and viewing windows of 16 s time range and 3 kHz frequency range. Spectrogram contrast and brightness were adjusted during the analysis when required. To account for the different sample rates used during the 2018 and 2019 surveys (Table 1), the Nyquist frequency (Shannon 1949) derived from the lowest sample rate between the two survey recorders (around 16 kHz) was set as a common maximum frequency threshold during the analysis of spectrograms. This frequency enabled the monitoring of bearded seal mating trills (Stirling et al. 1983; Cleator et al. 1989); walrus knocks (Stirling et al. 1983; Sjare et al. 2003); most of beluga calls and whistles (Sjare and Smith 1986; Chmelnitsky and Ferguson 2012; Garland et al. 2015); and bowhead whale songs (Stafford et al. 2008; Tervo et al. 2009), while it excluded high-frequency vocalizations such as most part of odontocete echolocation clicks (Au et al. 1985; Miller et al. 1995; Zahn et al. 2021). Species identification analysis focused on this list of specific vocalization types since they are better characterized in the literature compared to grunts and moans. Any vocalizations that could not be clearly assigned to a species were not included in this work to avoid potential species misclassification. Nonetheless, all vocalizations recognized as marine mammal sounds were included in the analysis of the marine mammal community vocal activity. Marine mammal species identification was accomplished by comparing the vocalizations detected to the material available in the literature; by consulting experienced researchers in the field of bioacoustics and by searching dedicated online sound libraries such as the Discovery of Sound in the Sea audio gallery (https://dosits.org/), the Watkins Marine Mammal Sound Database (https://whoicf2.whoi.edu/science/B/whalesounds/index.cfm), and the Macaulay library of the Cornell Lab of Ornithology (https://www.macaulaylibrary.org/). Acoustic data were annotated in Raven Pro, while the numerical and graphical data analyses were performed in R statistical software (R Core Team 2022) using RStudio (R Studio Team 2022).

2.2 Sea ice concentration data

To investigate the potential correlation between marine mammal acoustic presence and local sea ice extent, satellite imaging was used to obtain SIC above each hydrophone location. SIC was derived from the EUMETSAT OSI-SAF (EUMETSAT 2019) Special Sensor Microwave Imager/Sounder. This product provides daily SIC data brightness temperature which has a 25 × 25 km spatial resolution. SIC over an area was calculated as the proportion of ice in one grid pixel over each hydrophone position. The 25-km range corresponds roughly to the average distance traveled by bearded seal and walrus vocalizations (Cleator et al. 1989; Sjare and Stirling 1996). All pre-processing and SIC analyses were conducted using ArcGIS 10.6 (ESRI 2018) and R.

2.3 Statistical analyses

2.3.1 Diurnal analyses

Species-specific vocalizations were extracted from the three hydrophone datasets and days were divided into quarters (between 00:00 and 05:59, 06:00 and 11:59, 12:00 and 17:59, 18:00 and 23:59), following the methodology of Halliday et al. (2019). Generalized linear models (GLMs) were run to investigate potential diurnal trends in species vocal activity. A binomial distribution was selected as the link function in the GLMs, using the total number of recorded hours per quarter of day as weights. Marine mammal acoustic presence was set as the response variable and defined as the proportion of hours with species vocalizations over the total number of hours recorded in a quarter of day. Quarter of day, month, season, and recording location were set as independent variables. Seasons were defined based on local light levels, which were extracted from the National Research Council of Canada's sunrise/sunset calculator for each hydrophone location (NRCC 2022). Day and night were delimited by local sunrise and sunset times, whereas twilight was defined as the time of day when the centre of the sun is found 6 degrees below the horizon (civil twilight, NRCC 2022). Summer was defined as the period with no twilight and fall as the following period with twilight. No spring or winter data were collected. For each species, multiple GLMs were run, including all combinations of the previously mentioned independent variables. Models were tested for overdispersion using the R package DHARMA (Hartig 2016) and runs were repeated using a quasi-binomial distribution. The resulting improvement was minimal and did not justify the introduction of quasi-likelihood information criteria (Wang et al. 2015). Goodness of model fit was quantified by calculating the McFadden R^2 coefficient and corresponding p value, while model selection was based on model performance by considering the Akaike's information criterion (AIC) and the amount of deviance explained. If needed, Bonferroni corrections for multiple testing were introduced when assessing the statistical difference between independent variable subgroups. Diurnal trends in species-specific vocalizations were also investigated by dividing days based on local light levels at each hydrophone location (NRCC 2022). Light level groups included day, night, and twilight, which were defined as explained in the previous section. GLMs were run using a binomial distribution as the link function and the total number of recorded hours per light level group as weights. Species acoustic presence was set as the response variable and quantified as the proportion of hours with vocalizations over the total number of hours in each light level group. Light level, month, recording location, and season were set as independent variables. Multiple GLMs were run including all combinations of the abovementioned independent variables. Model fit and performance were tested as explained above.

2.3.2 Sea ice analyses

The seasonal vocal activity of the whole marine mammal community was analyzed against the SIC trend at each hydrophone location. When comparing the three locations, percentages of files with marine mammal vocalizations over the total number of recorded files were used to account for the differences in recording effort between hydrophones. This main difference was due to some malfunctioning of the TR-ORCA mounted on mooring ES that resulted in a substantial number of corrupted files from September onwards (Table 1). Individual species vocal activity was also analyzed against the SIC trend. GLMs were run on the dataset recorded by hydrophone ES, since it spanned over periods of different SIC. A binomial distribution was selected as the link function in the GLMs, using the total number of recorded hours per week as weights. The proportion of species vocalizations per week was set as the response variable, whereas season, week, and SIC class as the predictors. SIC classes were defined by first averaging daily SIC per week and then dividing in classes based on common definitions of sea ice conditions (Cavalieri et al. 1999; Stirling and Parkinson 2006; Walsh et al. 2022). Weekly SIC was divided in three classes: *sea ice break-up* when SIC was between 80% and 15% during the spring/early summer break-up period; *open water* when SIC was below 15%; and *sea ice freeze-up* when SIC increased from 15% to 80% during the fall freeze-up. No recordings took place during consolidated sea ice (SIC higher than 80%). Multiple GLMs were run including all combinations of the predictors. Autocorrelation in the model residuals was tested using the Durbin–Watson function in the R *car* package (Fox 2002). Model fit and performance were tested following the methodology described in the above sections.

Results

A total of 6310 5-min files were available for analysis after removing all corrupted files: 3054 files for hydrophone ES, 1096 for hydrophone CI, and 2160 for hydrophone SB (Table 1). The percentages of files that included marine mammal vocalizations over the total available number of files recorded at each hydrophone location were 39% for ES, 29% for CI, and 46% for SB. These percentages combined represented 40% of the total available files from the three datasets. Four marine mammal species were identified in the recordings: bearded seal, beluga, walrus, and bowhead whale. Of the total number of files with marine mammal vocalizations, 29% contained bearded seal trills, 37% walrus knocks, 13% beluga calls and whistles, and 7% bowhead whale songs. Examples of spectrograms of recorded vocalizations for each species are given in Fig. 2, and the corresponding recordings are provided in the Supplementary material.

Diurnal vocalization trends

Bearded seal trills were recorded throughout June and in July (Table 2). However, bearded seal acoustic detections were rare in July and were excluded from the diurnal analyses. The model of the quarter of day analysis that best explained bearded seal vocal activity included the variables quarter of day and hydrophone location (AIC = 861.48, deviance explained = 6.7%) (Table A1). Results from this model showed that bearded seal vocal activity was significantly lower during the second quarter of day ($p < 0.001$) compared to the rest of the time (Fig. 3A), and that bearded seal vocalizations at hydrophone ES were significantly higher than at hydrophone CI ($p < 0.001$). Similarly, the best model for the light level analysis included the variables light level and hydrophone location (AIC = 743.61, deviance explained = 5.3%) (Table A2). Bearded seal vocal activity was significantly higher at night than during the day ($p < 0.01$) (Fig. 4A). Bearded seal vocal activity decreased rapidly at sunrise, which in this region is around 2:00 local time in June; reached a minimum in the morning between 8:00 and 9:00; and slowly increased during late morning to reach maximum values in the afternoon around 17:00 (Fig. 5A).

Walrus knocks were recorded from June to November (Table 2). Since walrus acoustic detections were rare in June, they were not included in the analyses. The model that best explained walrus vocalization trends included quarter of day, month, and season (AIC = 1415, deviance explained = 11%) (Table A1). Another model with equivalent AIC value (AIC = 1416.7) and same deviance explained, included quarter of day, hydrophone location, month, and season as response variables (Table A1). Walrus vocal activity was significantly lower in summer than in fall, in September compared to the other months, and during the third quarter of day (all with $p < 0.001$) (Fig. 3B). Results from the light level analysis are in agreement with these findings; the best model for walrus vocal activity included light level, month, and season (AIC = 1219.1, deviance explained = 7.6%), although the model that included hydrophone location as well displayed an equivalent AIC (AIC = 1220.9) (Table A2). Walrus vocal activity was significantly lower during the day compared to periods of night ($p < 0.001$) and twilight ($p < 0.01$) (Fig. 4B). A comparison between the quarter of day and the light level analyses shows that walrus activity was higher during the morning twilight, compared to the evening one. As for bearded seal vocalizations, walrus vocal activity showed a trough in the middle of the day around 14:00 local time (Fig. 5B). The duration of this reduced vocal presence varied among months and was longer in the fall compared to the summer (Fig. 5B).

Beluga vocalizations were recorded in June and July and then again from September to November, while they were absent in August (Table 2). Beluga acoustic detections in September were rare and hence excluded from the analyses. The model that best explained beluga vocal activity included all response variables: quarter of day, hydrophone location, month, and season (AIC = 1225.2, deviance explained = 20%) (Table A1). Overall, no significant difference in vocalizations was found between summer and fall. Vocalizations were significantly higher in June than in July, and in October compared to November (both with $p < 0.001$). Beluga vocal activity was significantly higher during the middle of the day, corresponding to the third quarter of day ($p < 0.001$) (Fig. 3C). The beluga vocal activity recorded at hydrophone ES was the highest of the three locations ($p < 0.001$). The light level analysis showed that the model that best explained beluga vocal activity included light level, hydrophone location, month, and season (AIC = 922.64, deviance explained = 21.7%) (Table A2). In agreement with the results of the quarter of day analysis, this model also showed that beluga vocal activity was significantly higher during the day than at night ($p < 0.001$), whereas activity during twilight periods did not show any statistically significant difference with the rest of the light level groups (Fig. 4C). Minimum beluga vocal activity was recorded between 23:00 and 3:00 local time (Fig. 5C).

Bowhead whale songs were recorded from October to December (Table 2). However, only one recording in December included bowhead whale songs and was not included in the analyses. The best model that explained bowhead whale vo-

Fig. 2. Spectrograms of examples of recorded species-specific vocalizations: (A) bearded seal trills, (B) walrus knocks, (C) beluga calls and whistles, and (D) bowhead whale song. The *X* axis shows time, and the *Y* axis shows frequency. The color bars above each spectrogram display the corresponding sound intensity.

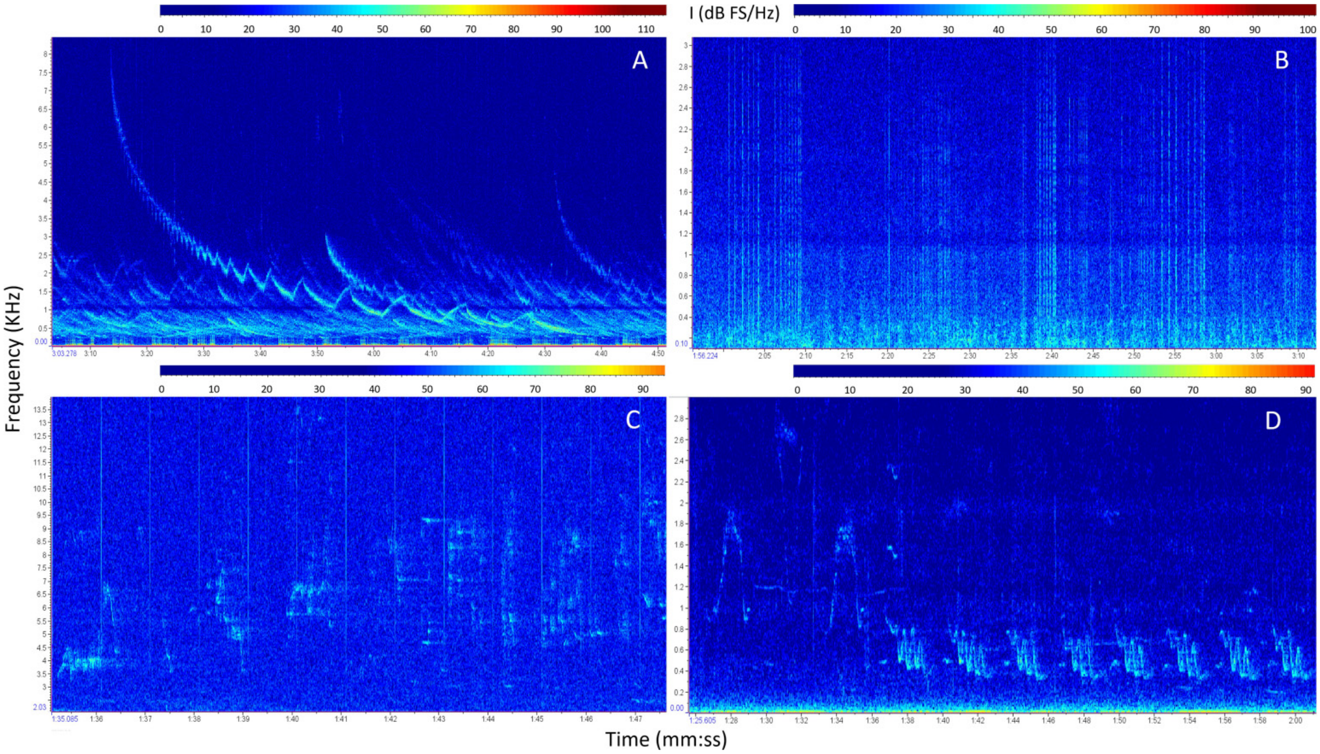
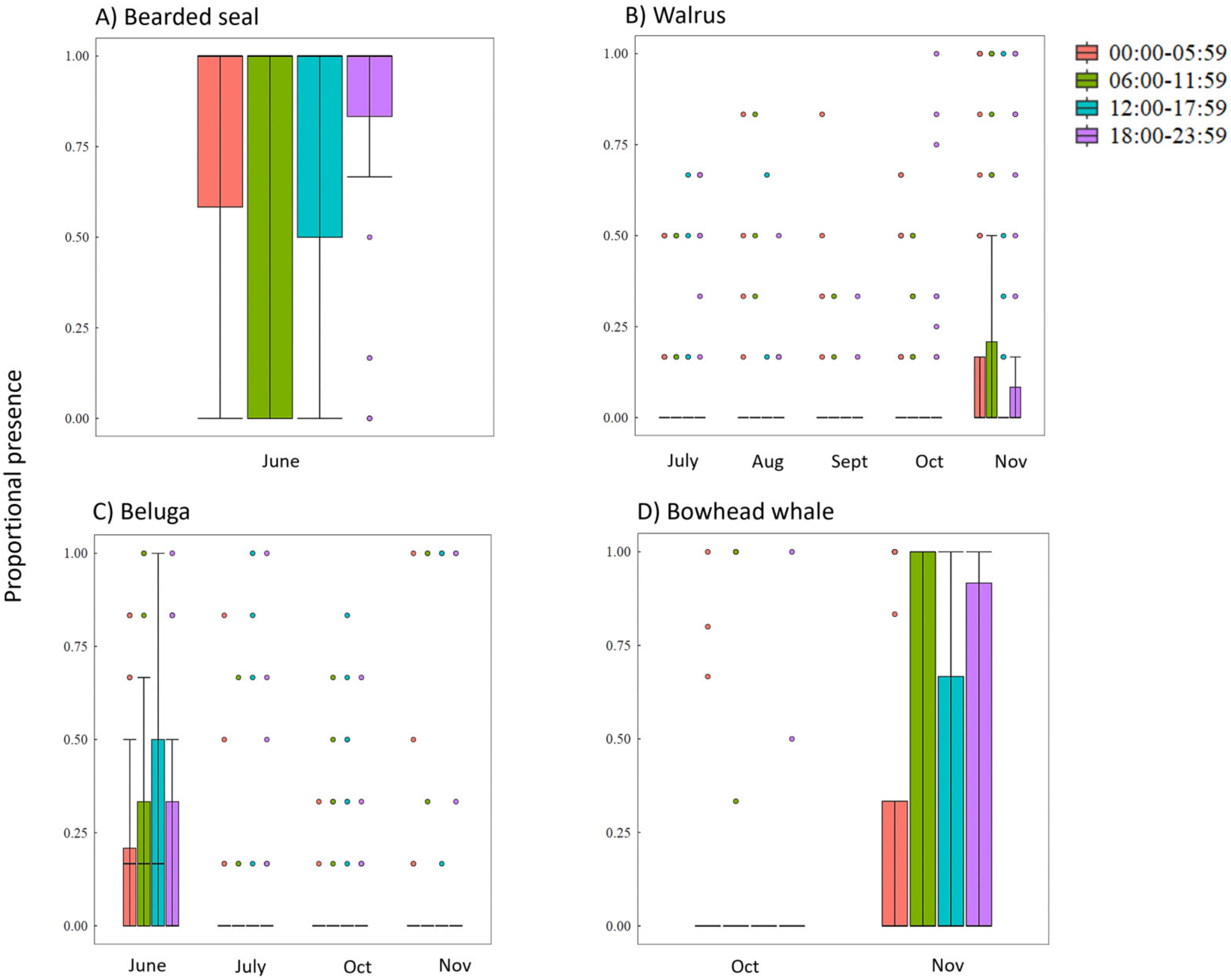


Table 2. Summary of seasonal acoustic presence of detected species. The upper and lower tables show results from the 2018 and 2019 surveys, respectively. For each month, solid color represents presence of species vocalizations, line pattern represents absence, and white indicates no recorded data.

Species	Hydrophone	Months						
2018		**June**	**July**	**August**	**September**	**October**	**November**	**December**
Bearded seal	ES	■	■	▤	▤	▤	▤	▤
	CI	■	■					
Walrus	ES	■	■	■	■	■	■	▤
	CI	■	■					
Beluga	ES	■	■	▤	■	■	■	▤
	CI	■	■					
Bowhead whale	ES	▤	▤	▤	▤	■	■	■
	CI	▤	▤					
2019		**June**	**July**	**August**	**September**	**October**	**November**	**December**
Bearded seal	SB				▤	▤	▤	
Walrus	SB				■	■	■	
Beluga	SB				▤	■	■	
Bowhead whale	SB				▤	▤	■	

Fig. 3. Boxplots of the proportional detection of species vocalizations during each quarter of day as a function of months for the three hydrophones cumulatively. Each box represents the interquantile range; the line inside the box displays the mean; and the whiskers delimit the maximum and minimum values. Each recorded species is presented in a separate plot, and quarters of day are displayed in different colors. Note: months with rare or no detections are not displayed.

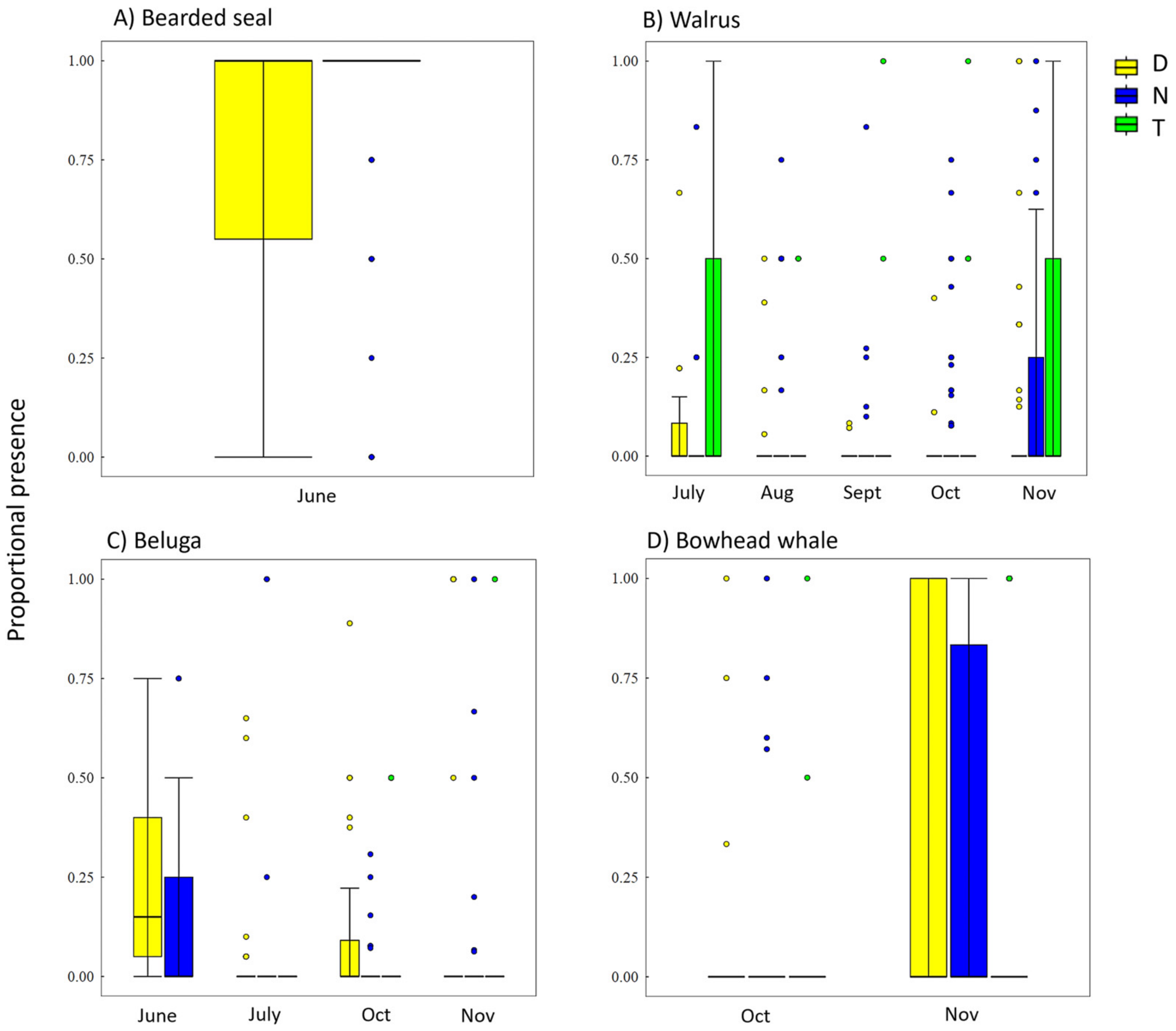


cal activity included month and hydrophone location as response variables (AIC = 706.1, deviance explained = 25.6%), whereas quarter of day did not contribute significantly (Table A1). Overall, bowhead whale vocalizations were higher in November than in October and at hydrophone ES compared to the other locations (both with $p < 0.001$) (Fig. 3D). The light level analysis showed that the best model included hydrophone location and month as explanatory variables (AIC = 654.83, deviance explained = 25.4%), although the model with light level as well showed an equivalent AIC (AIC = 653.35) (Table A2). A difference was found between bowhead whale vocal activity during twilight periods and daytime ($p < 0.05$), but no statistically significant difference was observed between the rest of the light level groups (Fig. 4D). Overall, no diel trend in bowhead whale singing activity was observed (Fig. 5D).

Vocalization relation with sea ice concentration

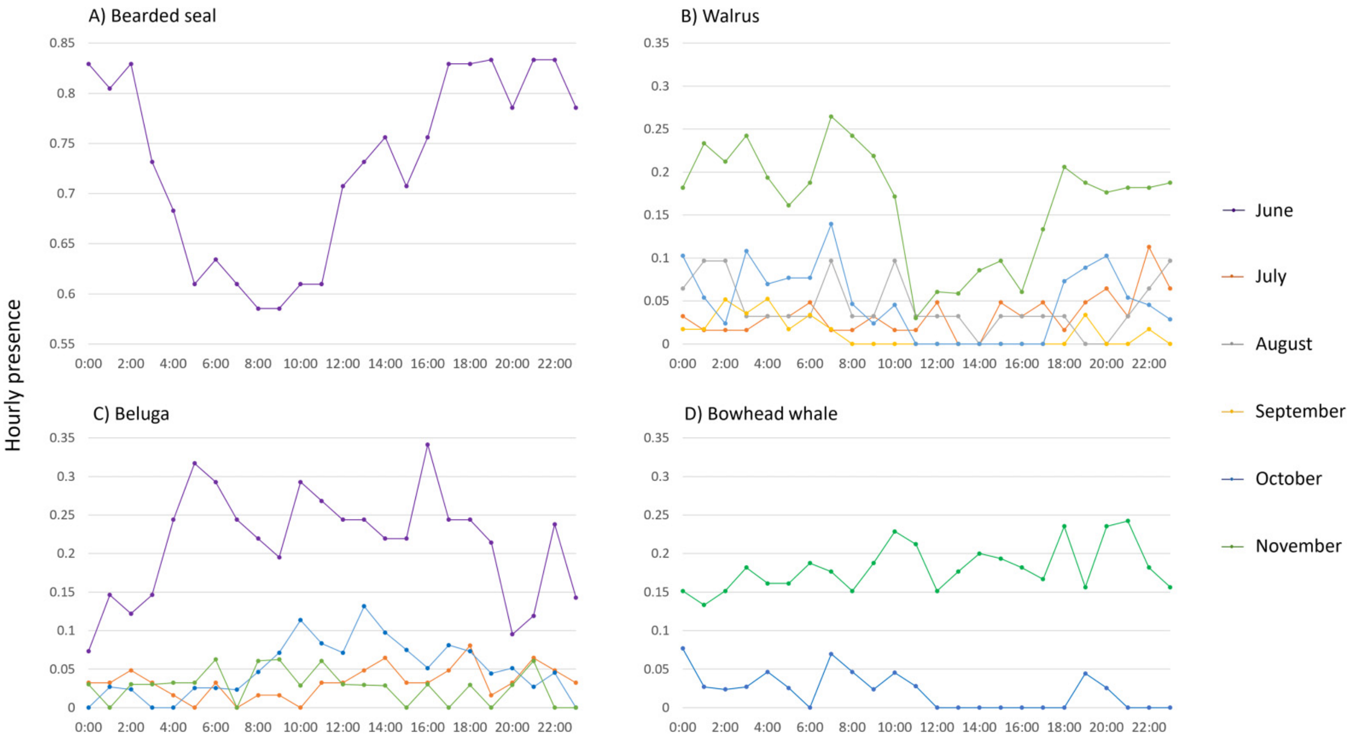
Hydrophone ES was the only unit that recorded during all three SIC classes, while hydrophone CI and SB mainly recorded during sea ice break-up and freeze-up, respectively. The marine mammal community vocal activity was high during sea ice break-up and decreased towards the open-water season at hydrophone ES and CI and showed an overall increasing trend during sea ice freeze-up at hydrophone ES (Fig. 6). All marine mammal species demonstrated seasonal variability in their vocal activity. Bearded seals were mainly detected in early summer from June to the beginning of July, while walruses between early summer and fall, with highest vocal activity in November. Belugas were recorded from early summer to fall with a trough in August, whereas bowhead whales were only detected in fall with maximum values in November (Table 2 and Figs. 7, A2, and A3). Bearded seal

Fig. 4. Boxplots of the proportional detection of species vocalizations for different light level groups as a function of months for the three hydrophones cumulatively. Each box represents the interquantile range; the line inside the box displays the mean; and the whiskers delimit the maximum and minimum values. Each recorded species is presented in a separate plot and light levels are displayed in different colors (D = day, N = night, T = twilight). Note: months with rare or no detections are not displayed.



trills at hydrophone ES were only recorded in June and ended just before the open-water season in early July, when SIC decreased below 20% (Fig. 7A). A similar trend was found at hydrophone CI, where bearded seal vocal activity decreased drastically when SIC dropped below 40% at the end of June and no trills were recorded during the open-water period (Fig. A2-A). At ES, walrus knocks were recorded during the open-water season with significantly lower vocal activity levels compared to bearded seals (Fig. 7B). While walrus recordings at CI were too rare to identify any seasonal trends (Fig. A2-B), walrus vocal activity at SB increased during sea ice freeze-up with maximum values reached in late November when SIC exceeded 50% (Fig. A3-A). Beluga vocal activity at ES was high during sea ice break-up; almost completely absent during the open-water period; and increased again just before local sea ice freeze-up (Fig. 7C). Similarly, the highest beluga vocal activity recorded at CI was recorded between late June and early July and stopped when SIC decreased below 30% (Fig. A2-C). In contrast, belugas at SB were mainly recorded during the open-water period and only rarely at sea ice freeze-up (Fig. A3-B). At hydrophone ES, recordings of bowhead whale songs started during the late open-water period and continued during sea ice freeze-up with high levels of vocal activity (Fig. 7D). Bowhead whale singing at hydrophone SB was recorded during sea ice freeze-up starting in late November, when SIC was already above 50% (Fig. A3-C). Overall, during sea ice freeze-

Fig. 5. Species hourly vocalization trends for the three hydrophones cumulatively. Each plot displays local time on the *X* axis and hourly presence of each marine mammal species on the *Y* axis. Hourly presence was defined as the proportion of files with species-specific vocalizations recorded by any of the hydrophones during each hour of the day and for a specific month over the total number of files recorded during the same period. Each recorded species is presented in a separate plot and different colors represent months. Note: the *Y*-scale used for bearded seal vocalizations is different than for the rest of the species.



up most of the marine mammal vocalizations recorded at ES and SB were bowhead whale songs (Figs. 7D and A3-C). Bearded seal, walrus, and bowhead whale vocalizations were each recorded during one sea ice class only. Instead, beluga vocalizations recorded at hydrophone ES ranged across different sea ice classes, which allowed to test a potential correlation between seasonal vocalization trends and SIC. The model that best explained beluga vocal activity included SIC class, season, and week as explanatory variables (AIC = 196.36, deviance explained = 13.5%) (Table A3). Beluga vocalizations were significantly higher in summer than in fall ($p < 0.001$), and during sea ice break-up compared to periods of open water ($p < 0.001$).

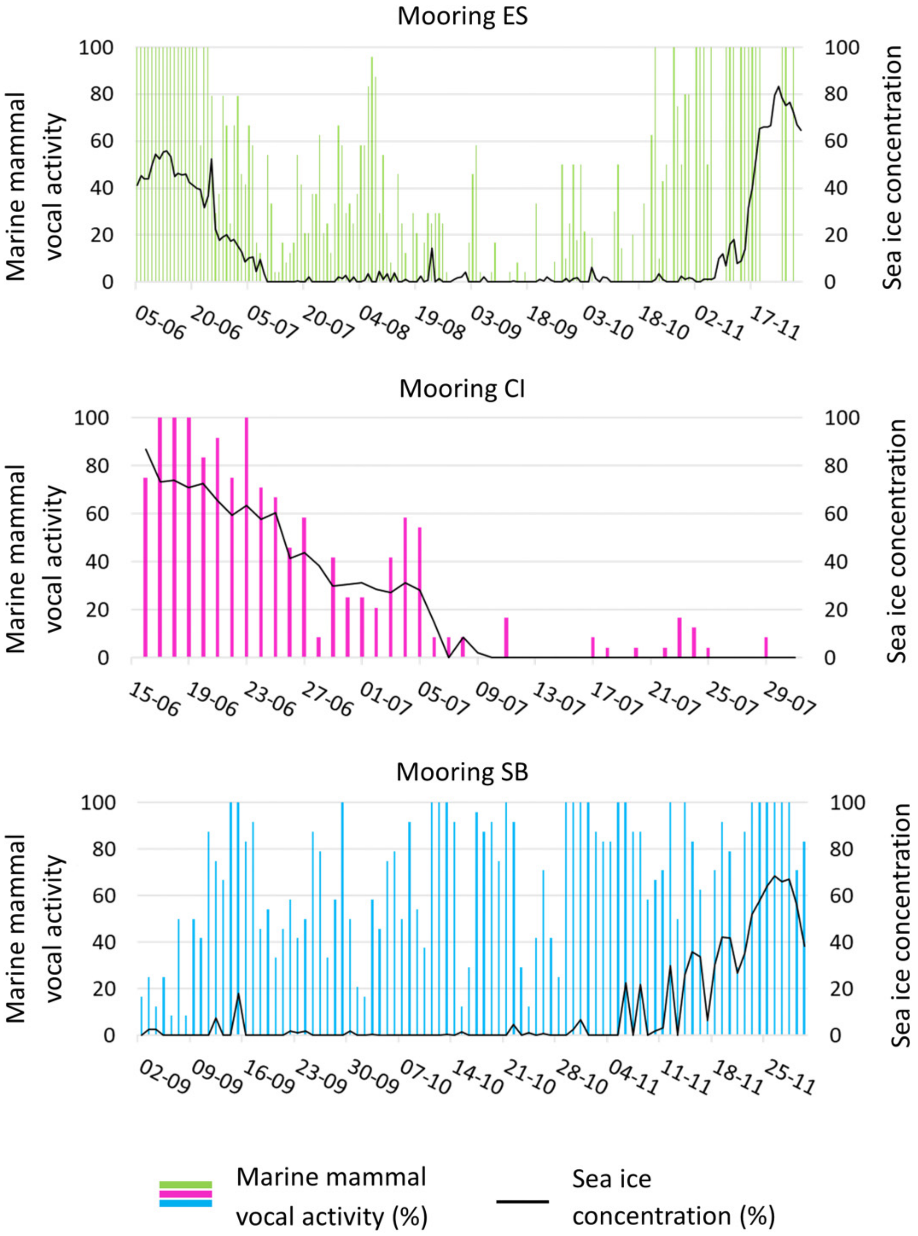
Discussion

The variety of vocalizations detected across seasons and species contribute to confirming the Southern part of the Southampton Island AOI as a high-use area for at least four endemic Arctic marine mammal species. Despite some similarities between beluga and narwhal vocalizations, narwhal acoustic presence was deemed improbable due to the absence of typical narwhal pulsed calls in the datasets and given the rarity of narwhal sightings in the study area (GN 2012; NWMB 2013; Loewen et al. 2020).

Diurnal vocalization trends

The diurnal trend recorded suggests a relationship between light levels and bearded seal vocal activity, which increased at nighttime and decreased towards the middle of the day. Information on bearded seal acoustic behavior in the sub-Arctic is lacking; however, in the High Arctic, bearded seal underwater vocal activity is known to decrease during the day compared to night-time (Cleator et al. 1989; Van Parijs et al. 2001; Frouin-Mouy et al. 2016). At high latitudes, bearded seal breeding season goes from March to late June (Burns 1981; Cleator et al. 1989; Van Parijs et al. 2001; Jones et al. 2014; Frouin-Mouy et al. 2016, 2017; Halliday et al. 2017). While some studies found clear peaks in bearded seal vocal activity early in the morning and late in the evening throughout the year (Van Parijs et al. 2001; Frouin-Mouy et al. 2016; Halliday et al. 2019) and during the entire breeding season (McLaren 1958; Burns 1981; Cleator 1996), others recorded weak or no diel trends during the end of the breeding season (Cleator et al. 1989; Halliday et al. 2017). Overall, this acoustic trend could be linked to bearded seal haul-out habits. Bearded seals tend to haul-out during periods of maximum sunlight to thermoregulate, molt, and pup, whereas in the evening they return to the water to forage and potentially socialize (Cleator et al. 1989; Krafft et al. 2000; Van Parijs et al. 2001). Similar haul-out trends have been observed in other pinnipeds (Thomas and DeMaster 1982; Green and Burton 1988; Van Parijs et al. 1999; Heide-Jørgensen et al. 2014). This

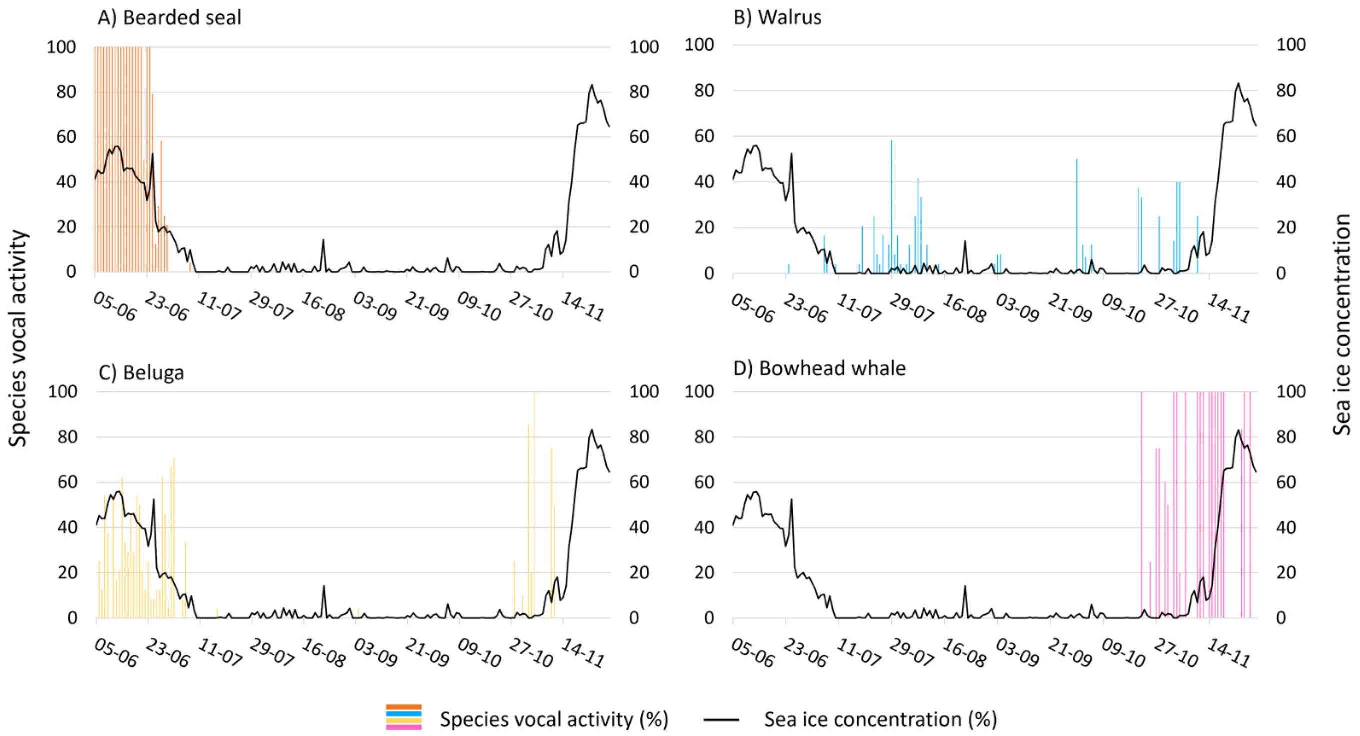
Fig. 6. Marine mammal community vocal activity (color bars) and local sea ice concentration (SIC) (black line) as a function of day at each hydrophone location. Each panel shows data for a single hydrophone. The *X* axis displays the date; the left *Y* axis shows vocal activity expressed as the percentage of hours in a day that included marine mammal vocalizations over the total number of hours recorded during the corresponding day; the right *Y* axis shows the percentage SIC above each hydrophone location.



suggests that bearded seals spend more time in the water at night; hence, the abrupt decrease in vocal activity during the day might be explained in terms of haul-out habits, due to a reduced number of individuals in the water during daytime, and by the tendency of males to emit breeding calls when more females can be exposed to it (Van Parijs et al. 2001; Frouin-Mouy et al. 2016). Finally, although bearded seal vocal activity decreased during June, the proportion between the number of files with trill detections and the total files recorded at each hour of the day remained higher than 50%. This result could reflect the presence of at least some bearded seals vocalizing underwater at all hours of the day. Since bearded seal trills can be recorded between 30 and 45 km from the source (Cleator et al. 1989; Stirling et al. 1983), our results might include detections of individuals vocalizing in a wide area around the hydrophone locations.

Our diel analyses show an abrupt decrease in walrus calling activity during the middle of the day and reveal that walruses in this area are more vocally active underwater during night and morning twilight. As for bearded seals, this trend could link to walrus physiological requirements. Summer data from satellite transmitters and visual surveys show that walruses take advantage of the hours of maximum sunlight to molt and thermoregulate on the ice (Salter 1979;

Fig. 7. Seasonal trend of individual species vocal activity (color bars) and local sea ice concentration (SIC) (black line) at hydrophone Evans Strait (ES). Each recorded species is presented in a separate plot. The *X* axis shows the date; the left *Y* axis shows the percentage of vocal activity for each species; and the right *Y* axis shows the percentage SIC.



Stirling et al. 1983; Born and Knutsen 1997; Heide-Jørgensen et al. 2014). The haul-out timing reported in the literature corresponds well to the period of decrease in walrus vocalizations recorded in this study. Moreover, Inuit knowledge on walrus habits inform on their tendency for morning feeding and afternoon haul-out, which would explain our recorded peak in morning twilight vocalizations (Loughry 1955; Born and Knutsen 1997). Compared to bearded seals, the decrease in walrus vocal activity occurred later in the day and often reached low or null values, suggesting that, at certain hours of the day, no walrus was vocalizing in the recording area. Also, the underwater propagation range of walrus vocalizations is around 10 km (Sjare and Stirling 1996; Sjare et al. 2003) which restricts the monitoring distance compared to bearded seals.

Belugas are known to emit a wide range of vocalizations that can, in some cases, be linked to different behaviors and activities. In this study, we focussed on calls and whistles, which are generally associated with communication and social activities, and did not collect clicks, which are linked to foraging and navigation (Au et al. 1985; Chmelnitsky and Ferguson 2012; Panova et al. 2012; Castellote et al. 2020). Most beluga vocalizations detected in this study were emitted during the daytime. PAM studies of beluga summer diel vocal trends found in the literature give discordant results. Some studies show peaks in beluga vocal activity during daylight periods (Scharffenberg et al. 2019; Booy et al. 2021), others at night (Roy and Simard 2015), whereas no diel vocal patterns were found in another study (Halliday et al. 2017). Moreover, year-long monitoring revealed opposite vocal trends during the day in separate parts of the St. Lawrence estuary (Giard et al. 2020). Spatial and temporal changes in acoustic detections might reflect movements and habitat use rather than implying diurnal trends in acoustic behavior. Variables such as tide, prey availability, and disturbance might influence vocalization patterns and should be included in future studies. Finally, differences between studies could also depend on the type of vocalization recorded. Overall, this study suggests that belugas use the area for socializing, which mainly occurs during daytime. However, without expanding the recording frequency range and (or) including visual observations, we are unable to investigate additional beluga behavior and to interpret the decrease in calls as part of a diel vocal pattern or as movements towards different locations.

Bowhead whales emit a wide variety of vocalizations that can change with the season. Our analyses focussed on songs, which are mainly used as mating vocal displays during the winter breeding season (Reese et al. 2001; Tervo et al. 2009; Stafford et al. 2012; Ahonen et al. 2017). Our results show no significant correlation between bowhead whale singing activity and quarters of day or light levels. Previous work on bowhead whale diel vocal patterns led to mixed results that vary with season and type of vocalizations analyzed. One spring study reported higher detection rates of songs and moans during daylight hours compared to night-time (Cummings and Holliday 1987). To the contrary, one fall study found higher detections of bowhead whale calls during night-time compared to daylight periods (Blackwell et al. 2007).

Similarly, a year-round study that analyzed both songs and calls recorded an increase in bowhead whale detection rates during evening hours (Diogou et al. 2023). Another study (Johnson 2013) focussed exclusively on songs emitted during spring migrations and recorded bowhead whale singing during the entire day with no significant differences between hours, in agreement with our fall results. As for belugas, the recorded vocalization pattern could link to bowhead whale movements more than being the result of an actual change in singing activity. Our results show that recording location and month play a fundamental role in explaining bowhead whale singing trends, suggesting that these recordings are more strongly associated to movements than for the rest of the species in this study. Indeed, the fact that bowhead whale songs were recorded continuously throughout the day could make this species relatively easier to monitor using just PAM compared to species that display diel vocal patterns and require additional monitoring techniques to verify their presence during silent periods.

Vocalization relation with sea ice concentration

Marine mammal vocal activity showed maximum values during the month of June and early July at both hydrophone ES and CI. This period corresponds to the end of the sea ice break-up in the study area (Gagnon and Gough 2005; Andrews et al. 2018; Carter et al. 2019). Bearded seal and beluga were the main species that contributed to the overall detections. Local knowledge identifies bearded seals as resident species that can be found in the Southampton Island AOI year-round (GN 2012; Carter et al. 2019). Although most PAM studies of bearded seals have occurred in the High Arctic (Stirling et al. 1983; Van Parijs et al. 2001; Frouin-Mouy et al. 2017; Escobar-Amado et al. 2022), the reported vocal seasonality seems to agree with the results of this study. High bearded seal vocal activity is known to occur during sea ice break-up, which corresponds to the end of their breeding season (Burns 1981; Cleator et al. 1989; Van Parijs et al. 2001; Jones et al. 2014; Frouin-Mouy et al. 2016, 2017; Halliday et al. 2017). In June, bearded seal trills were recorded as often as 24 h per day; such values are typical of the breeding season, when male bearded seals continuously emit trills to attract females (MacIntyre et al. 2013; Halliday et al. 2017). The lack of data recorded before the sea ice break-up inhibits a potential determination of the start of bearded seal breeding season in the study area. Correlation between SIC and bearded seal vocal activity was not assessed in this study; however, bearded seal vocalizations decreased abruptly at the end of June, going from maximum values to no recorded calls in less than a week. No trills were recorded after the beginning of July, which corresponds to the end of the sea ice break-up period in the area (Hochheim and Barber 2014; Andrews et al. 2018; Carter et al. 2019). In most PAM studies, bearded seal vocalizations decreased in late June/early July followed by no detections during the open-water period (Hannay et al. 2013; Jones et al. 2014; Frouin-Mouy et al. 2016; Halliday et al. 2017). In the Beaufort and Chukchi Sea, bearded seals vocalizations were recorded year-round but still showed a decrease during the open-water season (MacIntyre et al. 2013, 2015). When comparing hydrophone detections in this study, ES recorded more hours with trills compared to CI, which could indicate that ES provides preferred breeding habitat for bearded seals. Results of the GLM show that beluga vocal activity was high during periods of opening sea ice and in the summer. Beluga is a migratory species that seasonally occupies the waters of the Southampton Island AOI (Finley et al. 1982; GN 2012; Higdon 2017; Carter et al. 2019; Yurkowski et al. 2019). Most Western Hudson Bay belugas overwinter in Hudson Strait and migrate in spring and early summer to different areas of Hudson Bay when the sea ice starts to break up (Sergeant 1973; Reeves and Mitchell 1989; Richard 2010; Higdon 2017; Loewen et al. 2020). Although data were not collected earlier in the season, the timing of the first beluga vocalizations recorded in this study at sea ice break-up coincides with their known arrival time in the region, which happens during the general spring migration between May and June (Finley et al. 1982; Higdon 2017). Most belugas then use the waters of ES and the southern coast of Southampton Island as a migratory corridor towards other summering areas (Finley et al. 1982; Higdon 2017). Interviews with Salliq community members revealed that belugas can be found around CI and close to the southern coast of Southampton Island during the summer, and that some belugas spend the whole open-water season in South Bay, with maximum presence in July and August (GN 2012; Higdon 2017; Carter et al. 2019; Loewen et al. 2020). This suggests that beluga summer arrival in the AOI happens when local SIC has already started to decrease, in agreement with local knowledge and with beluga migratory behavior reported for other areas of the Arctic (Smith et al. 2007; Heide-Jørgensen et al. 2010; Hannay et al. 2013; Hauser et al. 2017).

In this study, no walrus knocks nor bowhead whale songs were recorded during sea ice break-up. Walruses might have been too distant from our hydrophones for their vocalizations to be recorded at this time. In this area, walruses are known to spend the winter close to the Southern coast of Southampton Island, along the floe edge (Orr and Rebizant 1987; Loewen et al. 2020; Higdon et al. 2022), which was around 40 km from ES, the closest hydrophone recording during the break-up period. Bowhead whales are known to produce moans, grunts, and simple calls in late spring and summer, whereas they mainly shift to songs during their breeding season in the winter (Blackwell et al. 2007; Tervo et al. 2009; Stafford et al. 2012; Ahonen et al. 2017; Thomisch et al. 2022). Since our analyses only included songs, we were unable to determine whether bowhead whales occurred in the study area during the sea ice break-up period and hence no information is available regarding their arrival time in the study area.

The period of open water shows an overall decrease in marine mammal vocal activity that follows the reduction in SIC at hydrophone ES and CI. Recordings from hydrophone SB, instead, show high marine mammal vocal activity from the last part of the open-water season until the freeze-up period. Compared to the other two hydrophones, SB was deployed in a bay and in relatively shallow waters; hence, the high vocal activity could indicate that the shallow habitat of this coastal region is preferred, at least during the final period of open water. However, to prove this, it would be necessary to record data synchronously at all three hydrophone locations. Many of the vocalizations recorded at hydrophone SB during the open-water period were grunts and moans that we could not unambiguously attribute to a specific species; still, they provide information on marine mammal seasonal occupancy. No bearded seal trills were recorded during the open-water period. We hypothesize this to be linked to a general reduction in vocal activity at the end of their breeding season, as it happens for many seal species (Van Parijs et al. 1999; Van Opzeeland et al. 2010; MacIntyre et al. 2013; Llobet et al. 2021). A reduction in vocal activity does not necessarily correspond to a reduction in presence. Frouin-Mouy et al. (2017), for example, observed bearded seals outside their breeding season near their hydrophone locations but did not record any trills. In some cases, instead, bearded seal trills were recorded year-round, including during open-water periods (MacIntyre et al. 2013, 2015). There could be regional differences in bearded seal vocal behavior and (or) mating strategies, which might explain different acoustic detections. For example, the presence of territorial males that maintain territories year-round using vocal displays compared to roaming males that do not is likely to change the underwater soundscape of the area (Van Parijs et al. 2002, 2004; MacIntyre et al. 2013). Salliq community members report bearded seal observations in our study area during the open-water period (GN 2012; Carter et al. 2019). This leads us to hypothesize that bearded seals in this region might stop vocalizing in summer or switch to different types of vocalizations that were not included in our analyses. The absence of trills might also imply that male bearded seals in this area do not maintain local territories year-round or that the main local mating strategy depends on roaming males. Walrus knocks dominated the open-water period at hydrophone ES and SB, whereas walrus vocal activity was rare at hydrophone CI. The waters south of Southampton Island are one of the most important walrus hotspots in Hudson Bay (Loughry 1955; Orr and Rebizant 1987; Born et al. 1995; Cobb 2011; GN 2012; Loewen et al. 2020; Higdon et al. 2022), supported by year-round observations of walruses (Orr and Rebizant 1987; GN 2012; Carter et al. 2019; Loewen et al. 2020). Local knowledge reports walruses moving towards ES and CI in early summer taking advantage of the seasonal ice retreat to feed in shallow waters (GN 2012; COSEWIC 2017; Carter et al. 2019); this behavior agrees with the timing of our detections in the area. Most of the studies on walrus vocalizations focussed on their breeding season, which goes from January to April in the High Arctic (Mansfield 1958; Fay et al. 1984; Stirling et al. 1987; Sjare and Stirling 1996; Born 2003), although rare sightings of copulation were recorded in June and early July (Mansfield 1958; Miller and Boness 1982). During the breeding period, males emit specific sequences of knocks and other sounds to maintain territories, access to females, and compete with other males (Ray and Watkins 1975; Fay et al. 1984; Stirling et al. 1983, 1987; Sjare and Stirling 1996; Sjare et al. 2003; Larsen and Reichmuth 2021). Female walruses are also able to produce knocks, although they are reported to be less vocally active than males (Schusterman and Reichmuth 2008). Mock mating behavior was observed in the summer for walruses around CI, and subadults were reported to become sexually active after the main mating season and associate with females in late spring and summer (Ray and Watkins 1975; Miller and Boness 1982; Fay et al. 1984). Since little information is available on walrus vocal behavior outside the breeding season, we formulated different hypotheses to explain the knocks recorded in this study. The presence of knocks during the open-water season could potentially reveal a later breeding period for walruses in our study area compared to the High Arctic; it could represent sub-adult male vocal behavior aimed at learning territory protection and female courtship techniques; or it might be linked to different behaviors, such as the intense summer feeding in this area, although walrus use of knocks for foraging is still not well understood. Finally, Pacific walruses in the Chukchi Sea have been recorded emitting knocks year-round (Mouy et al. 2012; Hannay et al. 2013; Rideout et al. 2013), whereas, to our knowledge, no Atlantic walrus knocks have been reported in Hudson Bay outside the breeding season. Hence, our results provide novel information on walrus vocal behavior and contribute to confirming their use of the AOI during the open-water period. Belugas are known to be a loquacious species (Schevill and Lawrence 1949; Chmelnitsky and Ferguson 2012; Giard et al. 2020; Simard et al. 2023). The rare recordings of beluga vocalizations during the open-water period at all hydrophone locations suggest that they transit through the study area in spring but spend the summer elsewhere. Traditional knowledge provides valuable information on their presence in South Bay during the summer (GN 2012; Carter et al. 2019). Unfortunately, hydrophone SB only recorded from September onwards; hence, beluga presence in early summer in this area could not be investigated. Hydrophone ES recorded belugas a second time shortly before the sea ice freeze-up. Belugas are known to transit through the Southampton Island AOI between October and December during their fall migration (McDonald et al. 1995; Stewart and Lockhart 2005; Smith et al. 2007; COSEWIC 2020). A peak in beluga vocal activity was recorded in mid-October at hydrophone SB and then in late October/early November at hydrophone ES. However, conclusions on beluga local movements cannot be drawn with certainty since hydrophone ES and SB recorded during different years. In this study, bowhead whale songs were first recorded towards the final part of the open-water season and continued until the end of the monitoring period. Although most bowhead whale songs have been recorded in winter and early spring in areas of high SIC (Stafford et al. 2012; Ahonen et al. 2017), bowhead whale singing during open-water periods is not unusual (Hannay et al. 2013; Thomisch et al. 2022). The high marine productivity of the waters around Southampton Island contributes to making this area an important summer ground and a migration corridor for bowhead whales (Reeves et al. 1983; Cosens and Blouw 2003; Cobb 2011; Higdon 2017; Carter et al. 2019). Although most individuals of the EC-WG population spend the summer in Frozen Strait and Southern Foxe Basin or aggregate to the West in Roes Welcome Sound (Cosens and Innes 2000; Cosens and Blouw 2003; Nielsen et al. 2015; Higdon 2017), some move to the waters south of Southampton Island, which is a summer calf rearing area (DFO 1999; Hay et al. 2000; Cosens and

Blouw 2003; Higdon 2017; Loewen et al. 2020). Our recordings during open water also agree with bowhead whale visual observations made by Salliq residents in summer and early fall north of CI and in South Bay (Hay et al. 2000; GN 2012; Carter et al. 2019). Recordings of the marine mammal community during sea ice freeze-up show an overall increase compared to the open-water period, reflecting a shift in marine mammal habitat use and behavior during this time. Walrus vocalizations at hydrophone SB followed an increasing trend with SIC, with recordings beginning during the final period of open water in late September and increasing towards November. At hydrophone ES, instead, all walrus vocalizations stopped in early November. Since in the AOI sea ice starts forming close to the coast (Hochheim and Barber 2010; Andrews et al. 2018; Gupta et al. 2022), walruses in this area may follow the sea ice and prefer shallow, coastal areas during freeze-up. Further data are needed to test this hypothesis. Walruses prefer sea ice as a hauling platform (Salter 1979; Fay et al. 1984; GN 2012; Hannay et al. 2013) and change their seasonal distribution depending on sea ice phenology, including break-up and freeze-up timing, features, and local concentration (Orr and Rebizant 1987; Mansfield and St. Aubin 1991; Jay and Hills 2005; Rideout et al. 2013; MacCracken et al. 2017; Chou et al. 2020). Moreover, visual observations in the study area report high numbers of walruses occupying haul-out sites along the northern coast of CI in late summer; during sea ice freeze-up, walrus then move eastward through ES and towards South Bay and the southeastern coast of Southampton Island (Loughrey 1955; Orr and Rebizant 1987; GN 2012; Carter et al. 2019). However, information on walrus movements in the Southampton Island AOI in fall and winter is lacking and acquiring further data on their seasonal local migrations has been recognized as a research priority by the community of Salliq (COSEWIC 2017; Carter et al. 2019; Loewen et al. 2020). Beluga vocalizations were rare during sea ice freeze-up, reinforcing the hypothesis that they migrate out of the AOI towards their wintering grounds before the formation of high SIC. This eastbound movement may be a response to sea ice formation, as recorded for belugas in other areas of the Arctic (Heide-Jørgensen et al. 2010; Hauser et al. 2017; Stafford et al. 2021). The decrease in beluga recordings in late October and early November integrates information from local knowledge, which reports belugas leaving South Bay when the sea ice starts forming and the last beluga hunts happening in November (GN 2012; Carter et al. 2019). Singing bowhead whales were recorded during the freeze-up period until the end of the surveys in early December and end of November for hydrophone ES and SB, respectively. During this period, bowhead whales sang continuous, distinctive, and repetitive songs, similar to what is reported from other areas of the Arctic (Stafford et al. 2012; Ahonen et al. 2017; Thomisch et al. 2022). Both bowhead whale vocal activity in late fall/early winter and the onset of mating vocal behavior in this area have not been recorded before. Correlation between bowhead whale vocal activity and sea ice was not tested in this study; however, occurrence of singing shows a general increase with SIC. A similar fall trend of increasing vocal activity with SIC was found in other studies on bowhead whale vocalizations (for example, Hannay et al. 2013) and might also be linked to a better sound transmission under a dense sea ice cover (Diachok and Winokur 1974; Stafford et al. 2012). Bowhead whales are known to begin their fall migrations in relation to advancing sea ice (Laidre et al. 2008; Ferguson et al. 2010; Hannay et al. 2013; Stafford et al. 2021). This study shows that bowhead whales occupy the region of ES during sea ice freeze-up, potentially using it as a migration corridor between their summer and winter grounds (Reeves et al. 1983; COSEWIC 2009; Ferguson et al. 2010; Higdon 2017). Information on bowhead whale fall presence and migration movements in the AOI is sparse. Tag data from one study reported that bowhead whales transit the study area between late September and October (Nielsen et al. 2015), which corresponds to the latest period of bowhead whale hunting for Salliq community members (Carter et al. 2019). In the winter, there have only been rare sightings of bowhead whales at the floe edge along the southwestern coast of Southampton Island (Hay et al. 2000). Without additional data, we are unable to tell whether the vocalization trend recorded in this study in late fall is linked to a change in bowhead whale distribution or to previous detection limitations. Finally, recorded singing behavior in late fall could suggest that bowhead whales in this region initiate mating concurrently with their fall migration, which would contribute to confirming ES as a key area for this species.

Conclusions and future work

This study presents the results of the first marine mammal acoustic survey in the Southampton Island AOI and informs on species seasonal and diurnal vocal activities. Based on the type of vocalizations recorded, specific use of the area was found to differ among species. It represents a breeding habitat for bearded seals; a summer key area for walruses; a migration corridor for both belugas and bowhead whales, and possibly, an important region for the onset of bowhead whale mating. These results contribute to the current understanding of marine mammal habitat use, acoustic behavior, and breeding periods in this important sub-Arctic region and provide valuable information for the creation of the proposed MPA. Moreover, given the importance of this area to many marine mammal species and the rapid changes that this region is experiencing, our study represents a first acoustic baseline that can be used to study marine mammal reactions to future changes in the underwater soundscape and to inform management plans of anthropogenic activities in the AOI. The pilot-project and opportunistic data collection nature of this study result in some limitations that should be overcome in future work. Among them, the hydrophone malfunctioning and the short overlap in recording time between the 2018 and the 2019 surveys that further inhibit a comparison among sites and years. Future studies in the AOI should consider including consistent and synchronous PAM at different sites and during consecutive years, as well as integrating it with other monitoring methods such as visual observations, data loggers, and acoustic tags that might test many of the hypotheses presented in this study. An underwater sound propagation model specific to the study area would also benefit local PAM studies. Future work should consider expanding the acoustic analyses to include more species and a wider vocal repertoire for each of them. Finally, GLMs of marine mammal vocal behavior may include additional parameters such as bathymetry, oceanographic variables, and prey availability.

Acknowledgements

The authors are thankful to the Aiviit Hunters and Trappers Organization and the Hamlet of Salliq for the support received for the project, which occurred under the Nunavut Research License #03 015 18N-M in 2018 and #03 009 19R-M in 2019. They would like to acknowledge the crew and scientists of the RV William Kennedy for their help with the moorings and acoustic data collection, in particular our sea-going technicians and Sergei Kirillov (University of Manitoba). The authors are thankful to Florian Aulanier (Fisheries and Oceans Canada), Héloïse Frouin-Mouy (University of Miami and NOAA Fisheries), and Yvan Simard (Fisheries and Oceans Canada) for sharing their scientific expertise on marine mammal vocalizations; Courtney Shuert (Fisheries and Oceans Canada) for her help with statistical models; Emma Ausen (University of Manitoba) for her GIS knowledge; and Jody Willis (Fisheries and Oceans) for her support to the project. Special thanks to Giuseppe Suaria (CNR-ISMAR Institute of Marine Sciences) for reviewing the final draft of the manuscript.

Article information

History dates

Received: 10 December 2023
Accepted: 19 April 2024
Accepted manuscript online: 10 May 2024
Version of record online: 29 July 2024

Copyright

Data availability

Data will be made available upon reasonable request.

Author information

Author ORCIDs

Veronica Laura Maria Coppolaro https://orcid.org/0000-0002-8688-8527

Author notes

Lisa Loseto served as Editor-in-Chief at the time of manuscript review and acceptance and did not handle peer review and editorial decisions regarding this manuscript.

Author contributions

Conceptualization: VLMC, LL, CJM, MM
Data curation: VLMC, KG
Formal analysis: VLMC
Funding acquisition: VLMC, CJM
Investigation: VLMC
Methodology: VLMC, MM
Project administration: CJM
Resources: VLMC, CJM, MM
Software: VLMC, KG
Supervision: LL, MM
Validation: VLMC, MM
Visualization: VLMC
Writing – original draft: VLMC
Writing – review & editing: VLMC, KG, LL, CJM, MM

Competing interests

The authors declare that there are no competing interests.

Funding information

This research was funded by the Marine Environmental Observation, Prediction and Response Network of Centres of Excellence (MEOPAR-NCE), the Oceans Management Contribution Program of DFO, and a National Science and Engineering Research Council of Canada (NSERC) ship time grant for the Southampton Island Marine Ecosystem Project (SIMEP). An NSERC-matched grant for the 2017–2018 Belmont Forum and BiodivERsA joint call for research proposals under the BiodivScen ERA-Net CO-FUND programme to the project ACCES: De-icing of Arctic Coasts: Critical or new opportunities for marine biodiversity and Ecosystem Services? Individual NSERC Discovery Grant and Northern Research Supplement were provided to CJM. This study was also supported by the Churchill Marine Observatory (CMO), funded by the Canada Foundation for Innovation and other partners, including the Arctic Research Foundation (ARF). Funding from the Oceans Management Contribution Program of Fisheries and Oceans Canada and the University of Manitoba Graduate Fellowship (UMGF) were provided to VC. This work represents a contribution to the Canada Excellence Research Chair (CERC) unit at the University of Manitoba.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/as-2023-0076.

References

Ahonen, H., Stafford, K.M., de Steur, L., Lydersen, C., Wiig, Ø., and Kovacs, K.M. 2017. The underwater soundscape in western Fram Strait: breeding ground of Spitsbergen's endangered bowhead whales. Marine Pollution Bulletin, **123**(1–2): 97–112. doi:10.1016/j.marpolbul.2017.09.019.

AMAP (Arctic Monitoring and Assessment Programme), CAFF (Conservation of Arctic Flora and Fauna) and SDWG (Sustainable Development Working Group). 2013. Identification of Arctic marine areas of heightened ecological and cultural significance: Arctic Marine Shipping Assessment (AMSA) IIc. 116 p.

Andrews, J., Babb, D., and Barber, D.G. 2018. Climate change and sea ice: shipping in Hudson Bay, Hudson Strait, and Foxe Basin (1980–2016).

Elementa: Science of the Anthropocene, **6**: 19. doi:10.1525/elementa.281.

Au, W.W.L., Carder, D.A., Penner, R.H., and Scronce, B.L. 1985. Demonstration of adaptation in beluga whale echolocation signals. Journal of the Acoustical Society of America, **77**: 726–730. doi:10.1121/1.392341.

Blackwell, S.B., Richardson, W.J., Greene, C.R., and Streever, B. 2007. Bowhead whale (*Balaena mysticetus*) migration and calling behaviour in the Alaskan Beaufort Sea, Autumn 2001–04: an acoustic localization study. Arctic, **60**(3): 255–270.

Booth, C.G., Sinclair, R.R., and Harwood, J. 2020. Methods for monitoring for the population consequences of disturbance in marine mammals: a review. Frontiers in Marine Science, **7**: 115. doi:10.3389/fmars.2020.00115.

Booy, K.V., Mouy, X., Ferguson, S.H., and Marcoux, M. 2021. Spatiotemporal summer distribution of Cumberland Sound beluga whales (*Delphinapterus leucas*) in Clearwater Fiord, Nunavut, Canada. Arctic Science, **7**(2): 394–412. doi:10.1139/as-2019-0031.

Born, E.W. 2003. Reproduction in male Atlantic walruses (*Odobenus rosmarus rosmarus*) from the North Water (N Baffin Bay). Marine Mammal Science, **19**(4): 819–831. doi:10.1111/j.1748-7692.2003.tb01132.x.

Born, E.W., and Knutsen, L.Ø. 1997. Haul-out activity of male Atlantic walruses (*Odobenus rosmarus rosmarus*) in northeastern Greenland. Journal of Zoology, **243**: 381–396. doi:10.1111/j.1469-7998.1997.tb02789.x.

Born, E.W., Gjertz, I., and Reeves, R.R. 1995. Population assessment of Atlantic walrus. Norsk Polarinstituttt Meddelelser 138. pp. 1–100.

Bruno, J.F., Bates, A.E., Cacciapaglia, C., Pike, E.P., Amstrup, S.C., van Hooidonk, R., et al. 2018. Climate change threatens the world's marine protected areas. Natural Climate Change, **8**(6): 499–503. doi:10.1038/s41558-018-0149-2.

Burek, K.A., Gulland, F.M.D., and O'Hara, T.M. 2008. Effects of climate change on Arctic marine mammal health. Ecological Applications, **18**(2): S126–S134. doi:10.1890/06-0553.1.

Burns, J.J. 1981. Bearded seal. *In* Handbook of marine mammals: Vol. 2 Seals. *Edited by* S.H. Ridgway and R.J. Harrison. Academic Press, London. pp 145–170.

CAFF and PAME. 2017. Arctic Protected Areas: Indicator Report, 2017: Conservation of Arctic Flora and Fauna and Protection of the Arctic Marine Environment, Akureyri, Iceland. ISBN 978-9935-431-64-6.

Carter, N.A., Dawson, J., and Weber, M. 2019. Arctic corridors and Northern voices: governing marine transportation in the Canadian Arctic (Salliq, Nunavut community report).

Castellote, M., Leeney, R.H., O'Corry-Crowe, G., Lauhakangas, R., Kovacs, K.M., Lucey, W., et al. 2013. Monitoring white whales (*Delphinapterus leucas*) with echolocation loggers. Polar Biology, **36**: 493–509. doi:10.1007/s00300-012-1276-2.

Castellote, M., Small, R.J., Lammers, M.O., Jenniges, J., Mondragon, J., Garner, C.D., et al. 2020. Seasonal distribution and foraging occurrence of Cook Inlet beluga whales based on passive acoustic monitoring. Endangered Species Research, **41**: 225–243. doi:10.3354/esr01023.

Castellote, M., Mooney, A., Andrews, R., Deruiter, S., Lee, W.-J., Ferguson, M., and Wade, P. 2021. Beluga whale (*Delphinapterus leucas*) acoustic foraging behavior and applications for long term monitoring. PLoS ONE, **16**(11): e0260485. doi:10.1371/journal.pone.0260485. PMID: 34847192.

Cavalieri, D.J., Parkinson, C.L., Gloerson, P., Comiso, J.C., and Zwally, H.J. 1999. Deriving long-term time series of sea-ice cover from satellite passive-microwave multisensory data sets. Journal of Geophysical Research: Oceans, **104**(C7): 15803–15814. doi:10.1029/1999JC900081.

Chape, S., Harrison, J., Spalding, M., and Lysenko, I. 2005. Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philosophical Transactions of the Royal Society B: Biological Sciences, **360**(1454): 443–455. doi:10.1098/rstb.2004.1592.

Chmelnitsky, E.G., and Ferguson, S.H. 2012. Beluga whale, *Delphinapterus leucas*, vocalizations from the Churchill River, Manitoba, Canada. Journal of the Acoustical Society of America, **131**(6): 4821–4835. doi:10.1121/1.4707501.

Chou, E., Antunes, R., Sardelis, S., Stafford, K.M., West, L., Spagnoli, C., et al. 2020. Seasonal variation in Arctic marine mammal acoustic detection in the northern Bering Sea. Marine Mammal Science, **36**: 522–547. doi:10.1111/mms.12658.

Cleator, H.J. 1996. The status of the bearded seal, *Erignathus barbatus* in Canada. The Canadian Field-Naturalist, **110**: 501–510. doi:10.5962/p.357506.

Cleator, H.J., Stirling, I., and Smith, T.G. 1989. Underwater vocalizations of the bearded seal (*Erignathus barbatus*). Canadian Journal of Zoology, **67**: 1900–1910. doi:10.1139/z89-272.

Cobb, D.G. 2011. Identification of ecologically and biologically significant areas (EBSAs) in the Canadian Arctic. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/070. vi + 38p.

Comiso, J.C., and Hall, D.K. 2014. Climate trends in the Arctic as observed from space. WIREs Climate Change, **5**: 389–409. doi:10.1002/wcc.277.

Cosens, S.E., and 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. doi:10.1111/j.1748-7692.2003.tb01109.x.

Cosens, S., and Innes, S. 2000. Distribution and numbers of bowhead whales (*Balaena mysticetus*) in Northwestern Hudson Bay in August 1995. Arctic, **53**(1): 36–41. doi:10.14430/arctic832.

COSEWIC. 2009. COSEWIC assessment and update status report on the bowhead whale *Balaena mysticetus*, Bering–Chukchi–Beaufort population and Eastern Canada–West Greenland population, in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa, ON. vii + 49p.

COSEWIC. 2017. COSEWIC assessment and status report on the Atlantic walrus *Odobenus rosmarus rosmarus*, High Arctic population, Central-Low Arctic population and Nova Scotia–Newfoundland–Gulf of St. Lawrence population in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xxi + 89p.

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. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xxxv + 84pp.

Crawford, A., Stroeve, J., Smith, A., and Jahn, A. 2021. Arctic open-water periods are projected to lengthen dramatically by 2100. Communications Earth & Environment, **2**: 109. doi:10.1038/s43247-021-00183-x.

Cummings, W.C., and Holliday, D.V. 1987. Sounds and source levels from bowhead whales off Pt. Barrow, Alaska. Journal of the Acoustical Society of America, **82**(3): 814–821. doi:10.1121/1.395279.

Davis, G.E., Baumgartner, M.F., Corkeron, P.J., Bell, J., Berchok, C., Bonnell, J.M., et al. 2020. Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. Global Change Biology, 4812–4840, **26**(9). doi:10.1111/gcb.15191.

Dawson, J., Pizzolato, L., Howell, S.E.L., Copland, L., and Johnston, M.E. 2018. Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. Arctic, **71**(1): 15–26. doi:10.14430/arctic4698.

DFO. 1999. Hudson Bay/Foxe Basin bowhead whale. DFO Science Stock Status Report E5-52 1999.

DFO. 2011. Identification of ecologically and biologically significant areas (EBSA) in the Canadian Arctic. Department of Fisheries and Oceans (DFO), Canadian Science Advisory Secretariat, Science Advisory Report 2011/055.

Diachok, O.I., and Winokur, R.S. 1974. Spatial variability of underwater ambient noise at the Arctic ice-water boundary. Journal of the Acoustical Society of America, **55**: 750–753. doi:10.1121/1.1914594.

Diogou, N., Halliday, W.D., Dosso, S.E., Mouy, X., Niemi, A., and 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**: 103004. doi:10.1016/j.pocean.2023.103004.

Escobar-Amado, C.D., Badiey, M., and Pecknold, S. 2022. Automatic detection and classification of bearded seal vocalizations in the northeastern Chukchi Sea using convolutional neural networks. Journal of the Acoustical Society of America, **151**(1): 299–309. doi:10.1121/10.0009256.

ESRI. 2018. Environmental Systems Research Institute, ArcGIS Release 10.6 Redlands, CA.

EUMETSAT. 2019. Ocean and Sea Ice Satellite Application Facility. Global sea ice concentration interim climate data record 2016 onwards (v2.0) Norwegian and Danish Meteorological Institutes. *Edited by* T.

Lavergne, A.M. Sorensen, S. Kern, R. Tonboe, D. Notz, S. Aaboe, L. Bell, G. Dybkjaer, S. Eastwood, C. Gabarro, G. Heygster, M.A. Killie, M. Brandt Kreiner, J. Lavelle, R. Saldo, S. Sandven and L.T. Pedersen. Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, The Cryosphere 13(1). pp. 49–78.

Fay, F.H., Ray, G.C., and Kibal'chich, A.A. 1984. Time and location of mating and associated behavior of the Pacific walrus, *Odobenus rosmarus divergens* Illiger. NOAA Technical Report NMFS 12. pp. 89–99.

Ferguson, S., Dueck, L., Loseto, L., and Luque, S. 2010. Bowhead whale *Balaena mysticetus* seasonal selection of sea ice. Marine Ecology Progress Series, **411**: 285–297. doi:10.3354/meps08652.

Finley, K.J., Miller, G.W., Allard, M., Davis, R.A., and Evans, C.R. 1982. The belugas (*Delphinatperus leucas*) of Northern Quebec: distribution, abundance, stock identity, catch history and management. Can. Tech. Rep. Fish. Aquat. Sci. 1123. v + 57p.

Flanders Marine Institute. 2018. IHO Sea Areas, version 3. Available from https://www.marineregions.org/ [accessed 9 December 2022].

Florko, K.R.N., Bernhardt, W., Breiter, CJ.C., Ferguson, F.H., Hainstock, M., Young, B.G., and Petersen, S.D. 2018. Decreasing sea ice conditions in western Hudson Bay and an increase in abundance of harbour seals (*Phoca vitulina*) in the Churchill River. Polar Biology, **41**: 1187–1195. doi:10.1007/s00300-018-2277-6.

Fossi, M.C., and Panti, C. 2017. Sentinel species of marine ecosystems. Oxford Research Encyclopedia of Environmental Science, Oxford.

Fox, J. 2002. An R and S-plus companion to applied regression. Sage, Thousand Oaks, CA.

Frouin-Mouy, H., Mouy, X., Martin, B., and Hannay, D. 2016. Underwater acoustic behavior of bearded seals (*Erignathus barbatus*) in the northeastern Chukchi Sea, 2007–2010. Marine Mammal Science, **32**: 141–160. doi:10.1111/mms.12246.

Frouin-Mouy, H., Kowarski, K., Martin, B., and Bröker, K. 2017. Seasonal trends in acoustic detection of marine mammals in Baffin Bay and Melville Bay, Northwest Greenland. Arctic, **70**: 59–76. doi:10.14430/arctic4632.

Gagnon, A.S., and Gough, W.A. 2005. Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. Arctic, **58**(4): 370–382.

Gallardo, B., Aldridge, D.C., González-Moreno, P., Pergl, J., Pizarro, M., Pyšek, P., et al. 2017. Protected areas offer refuge from invasive species spreading under climate change. Global Change Biology, **23**(12): 5331–5343. doi:10.1111/gcb.13798.

Garcia-Soto, C., Cheng, L., Caesar, L., Schmidtko, S., Jewett, E.B., Cheripka, A., et al. 2021. An overview of ocean climate change indicators: sea surface temperature, ocean heat content, ocean pH, dissolved oxygen concentration, Arctic sea ice extent, thickness and volume, sea level and strength of the AMOC (Atlantic Meridional Overturning Circulation). Frontiers in Marine Science, **8**: 642372.

Garland, E.C., Castellote, M., and Berchok, C.L. 2015. Beluga whale (*Delphinapterus leucas*) vocalizations and call classification from the eastern Beaufort Sea population. Journal of the Acoustical Society of America, **137**: 3054. doi:10.1121/1.4919338.

Giard, S., Simard, Y., and Roy, N. 2020. Decadal passive acoustics time series of St. Lawrence estuary beluga. Journal of the Acoustical Society of America, **147**(3): 1874–1884. doi:10.1121/10.0000922.

GN. 2012. Nunavut Coastal Resource Inventory: Salliq. Nunavut Department of Environment, Fisheries and Sealing Division, Iqaluit, NU. 152p.

González-Maya, J.F., Víquez-R, L.R., Belant, J.L., and Ceballos, G. 2015. Effectiveness of protected areas for representing species and populations of terrestrial mammals in Costa Rica. PLoS ONE, **10**(5): e0124480. doi:10.1371/journal.pone.0124480.

Green, K., and Burton, H.R. 1988. Annual and diurnal variations in the underwater vocalizations of Weddell seals. Polar Biology, **8**: 161–164. doi:10.1007/BF00443447.

Gupta, K., Mukhopadhyay, A., Babb, D.G., Barber, D.G., and Ehn, J.K. 2022. Landfast sea ice in Hudson Bay and James Bay: Annual cycle, variability and trends, 2000-2019. Elementa: Science of the Anthropocene, **10**: 1. doi:10.1525/elementa.2021.00073.

Halliday, W.D., Insley, S.J., de Jong, T., and Mouy, X. 2017. Seasonal patterns in acoustic detections of marine mammals near Sachs Harbour, Northwest Territories. Arctic Science, **4**(3): 259–278.

Halliday, W.D., Pine, M.K., Insley, S.J., Soares, R.N., Kortsalo, P., and Mouy, X. 2019. Acoustic detections of Arctic marine mammals near Ulukhaktok, Northwest Territories, Canada. Canadian Journal of Zoology, **97**(1): 72–80. doi:10.1139/cjz-2018-0077.

Hannay, D.E., Delarue, J., Mouy, X., Martin, B.S., Leary, D., Oswald, J.N., and Vallarta, J. 2013. Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011. Continental Shelf Research, **67**: 127–146. doi:10.1016/j.csr.2013.07.009.

Hartig, F. 2016. DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. Available from https://cran.r-project.org/web/packages/DHARMa/vignettes/DHARMa.html [accessed 30 May 2023].

Hauser, D.D.W., Laidre, K.L., Stafford, K.M., Stern, H.L., Suydam, R.S., and 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**: 2206–2217. doi:10.1111/gcb.13564.

Hay, K., Aglukark, D., Igutsaq, D., Ikkidluak, J., and Mike, M. 2000. Final report of the Inuit Bowhead Knowledge Study. Nunavut Canada, Nunavut Wildlife Management Board, Nunavut, Canada. 101p.

Hazen, E.L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M.G., Savoca, M.S., et al. 2019. Marine top predators as climate and ecosystem sentinels. Frontiers in Ecology and the Environment, **17**(10): 565–574. doi:10.1002/fee.2125.

Heenehan, H., Stanistreet, J.E., Corkeron, P.J., Bouveret, L., Chalifour, J., Davis, G.E., et al. 2019. Caribbean Sea soundscapes: monitoring humpback whales, biological aounds, geological events, and anthropogenic impacts of vessel noise. Frontiers in Marine Science, **6**: 347. doi:10.3389/fmars.2019.00347.

Heide-Jørgensen, M.P., Laidre, K.L., Borchers, D., Marques, T.A., Stern, H., and Simon, M. 2010. The effect of sea-ice loss on beluga whales (*Delphinapterus leucas*) in West Greenland. Polar Research, **29**: 198–208. doi:10.1111/j.1751-8369.2009.00142.x.

Heide-Jørgensen, M.P., Born, E.W., Laidre, K.L., Fossette, S., Hansen, R.G., Dietz, R., et al. 2014. Abundance and trends in abundance of the Atlantic walrus (*Odobenus rosmarus rosmarus*) in Central West Greenland. NAMMCO Scientific Publications 9. pp. 159–172. doi:10.7557/3.2606.

Henderson, E., Helble, T.A., Ierley, G.R., and Martin, S. 2018. Identifying behavioral states and habitat use of acoustically tracked humpback whales in Hawaii. Marine Mammal Science, **34**(3).

Higdon, J.W. 2017. Mapping critical whale habitat in the Nunavut Settlement Area. A report prepared for Brandon Laforest, Senior Specialist, Arctic Species & Ecosystems, WWF—Canada, Iqaluit, NU. 41 p.

Higdon, J.W., Hauser, D.D.W., and Ferguson, S.H. 2012. Killer whales (*Orcinus orca*) in the Canadian Arctic: distribution, prey items, group sizes, and seasonality. Marine Mammal Science, **28**: E93–E109. doi:10.1111/j.1748-7692.2011.00489.x.

Higdon, J.W., Stewart, D.B., and 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 (Jeff W. Higdon).

Hochheim, K.P., and Barber, D.G. 2010. Atmospheric forcing of sea ice in Hudson Bay during the fall period, 1980–2005. Journal of Geophysical Research: Oceans, **115**: C05009. doi:10.1029/2009JC005334.

Hochheim, K.P., and Barber, D.G. 2014. An update on the ice climatology of the Hudson Bay System, Arctic, Antarctic, and Alpine Research, **46**(1): 66–83.

Hoover, C., Bailey, M.L., Higdon, J., Ferguson, S.H., and Sumaila, R. 2013. Estimating the economic value of narwhal and beluga hunts in Hudson Bay, Nunavut. Arctic, **66**(1): 1–16. doi:10.14430/arctic4261.

Hopkins, R.C., Bailey, D.M., and Potts, T. 2016. Perceptions of practitioners: managing marine protected areas for climate change resilience. Ocean & Coastal Management, **128**: 18–28. doi:10.1016/j.ocecoaman.2016.04.014.

Iacozza, J., and Ferguson, S. 2014. Spatio-temporal variability of snow over sea ice in western Hudson Bay, with reference to ringed seal pup survival. Polar Biology, **37**(37): 817–832. doi:10.1007/s00300-014-1484-z.

IPCC. 2022. Climate change 2022: impacts, adaptation and vulnerability. *In* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Edited by* H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA. 3056pp.

Jay, C.V., and Hills, S. 2005. Movements of walruses radio-tagged in Bristol Bay, Alaska. Arctic, **58**(2): 192–202.

Johnson, H.D. 2013. Diversity and characterization of songs in the Bering–Chukchi–Beaufort population of bowhead whales (*Balaena mysticetus*) during their annual spring migration, 2011. Honors theses. p. 61.

Jones, J.M., Thayre, B.J., Roth, E.H., Mahoney, M., Sia, I., Merculief, K., et al. 2014. Seasonal presence of ringed, ribbon, and bearded seal vocalizations in the Chukchi Sea north of Barrow, Alaska. Arctic, **67**: 203–222. doi:10.14430/arctic4388.

Kingsley, M.C.S., and Stirling, I. 1991. Haul-out behaviour of ringed and bearded seals in relation to defence against surface predators. Canadian Journal of Zoology, **69**(7): 1857–1861. doi:10.1139/z91-257.

Kline, L.R., DeAngelis, A.I., McBride, C., Rodgers, G.G., Rowell, T.J., Smith, J., et al. 2020. Sleuthing with sound: understanding vessel activity in marine protected areas using passive acoustic monitoring. Marine Policy, **120**: 104138. doi:10.1016/j.marpol.2020.104138.

Krafft, B.A., Lydersen, C., Kovacs, K.M., Gjertz, I., and Haug, T. 2000. Diving behaviour of lactating bearded seals (*Erignathus barbatus*) in the Svalbard area. Canadian Journal of Zoology, **78**: 1408–1418. doi:10.1139/z00-088.

Laidre, K.L., Stirling, I., Lowry, L.F., Wiig, Ø., Heide-Jørgensen, M.P., and Ferguson, S.H. 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. Ecological Applications, **18**(S2): S97–S125. doi:10.1890/06-0546.1.

Laidre, K.L., Stern, H., Kovacs, K.M., Lowry, L., Moore, S.E., Regehr, E.V., et al. 2015. Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. Conservation Biology, **29**: 724–737. doi:10.1111/cobi.12474.

Lalonde, S., Abashidze, A., and Solntsev, A. 2022. Marine protected areas and other effective area-based conservation measures. Arctic Review on Law and Politics, **13**: 312–337.

Larsen, O.N., and Reichmuth, C. 2021. Walruses produce intense impulse sounds by clap-induced cavitation during breeding displays. Royal Society Open Science, **8**: 210197. doi:10.1098/rsos.210197.

Llobet, S.M., Ahonen, H., Lydersen, C., Berge, J., Ims, R., and Kovacs, K.M. 2021. Bearded seal (*Erignathus barbatus*) vocalizations across seasons and habitat types in Svalbard, Norway. Polar Biology, **44**(7): 1273–1287. doi:10.1007/s00300-021-02874-9.

Loewen, T.N., Hornby, C.A., Johnson, M., Chambers, C., Dawson, K., MacDonell, D., et al. 2020. Ecological and biophysical overview of the Southampton proposed Area of Interest for the Southampton Island ecologically and biologically significant area. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/032. vi + 96p.

Loughrey, A.G. 1955. Preliminary investigation of the Atlantic walrus, *Odobenus rosmarus rosmarus* (Linnaeus). Dept, N. Affairs and National Resources, Can. Wildlife Service, Ottawa, MS. 175pp.

MacCracken, J., Beatty, W., Garlich-Miller, J., Kissling, M., and Snyder, J. 2017. Final species status assessment for the Pacific walrus (*Odobenus rosmarus divergens*), May 2017 (Version 1.0). Marine Mammals Management, US Fish & Wildlife Service, Anchorage, AK.

MacIntyre, K.Q., Stafford, K.M., Berchok, C.L., and 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, **36**: 1161–1173. doi:10.1007/s00300-013-1337-1.

MacIntyre, K.Q., Stafford, K.M., Conn, P.B., Laidre, K.L., and 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. doi:10.1016/j.pocean.2015.05.008.

Maestro, M., Pérez-Cayeiro, M.L., Chica-Ruiz, J.A., and Reyes, H. 2019. Marine protected areas in the 21st century: current situation and trends. Ocean & Coastal Management, **171**: 28–36. doi:10.1016/j.ocecoaman.2019.01.008.

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, 653. xiii + 146p.

Mansfield, A.W., and St. Aubin, D.J. 1991. Distribution and abundance of the Atlantic Walrus, *Odobenus rosmarus rosmarus*, in the Southampton Island–Coats Island region of northern Hudson Bay. The Canadian Field-Naturalist, **105**: 95–100. doi:10.5962/p.357954.

Marcoux, M., Ferguson, S.H., Roy, N., Bedard, J.M., and Simard, Y. 2017. Seasonal marine mammal occurrence detected from passive acoustic monitoring in Scott Inlet, Nunavut, Canada. Polar Biology, **40**: 1127–1138. doi:10.1007/s00300-016-2040-9.

McDonald, M., Arragutainaq, L., and Novalinga, Z. 1995. Traditional ecological knowledge of environmental changes in Hudson and James bays—Part I. An unpublished report prepared for The Hudson Bay Programme. Canadian Arctic Resources Committee (CARC), Ottawa, ON. vi + 98p.

McLaren, I.A. 1958. Some aspects of growth and reproduction of the Bearded seal, *Erignathus barbatus* (Erxleben). Journal of the Fisheries Board of Canada, **15**: 219–227. doi:10.1139/f58-012.

Miller, E.H., and Boness, D.J. 1982. Summer behavior of Atlantic walruses *Odobenus rosmarus rosmarus* (L.) at Coats Island, N.W.T. (Canada). Zeitschrift Für Säugetierkunde: Im Auftrage Der Deutschen Gesellschaft Für Säugetierkunde e.V, **48**: 298–313.

Miller, L.A., Pristed, J., Møshl, B., and Surlykke, A. 1995. The click-sounds of narwhals (*Monodon monoceros*) in Inglefield Bay, Northwest Greenland. Marine Mammal Science, **11**(4): 491–502. doi:10.1111/j.1748-7692.1995.tb00672.x.

Moore, S.E. 2008. Marine mammals as ecosystem sentinels. Journal of Mammalogy, **89**(3): 534–540. doi:10.1644/07-MAMM-S-312R1.1.

Moore, S.E., Reeves, R.R., Southall, B.L., Ragen, T.J., Suydam, R.S., and 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. doi:10.1525/bio.2012.62.3.10.

Mouy, X., Hannay, D., Zykov, M., and Martin, B. 2012. Tracking of Pacific walruses in the Chukchi Sea using a single hydrophone. Journal of the Acoustical Society of America, **131**: 1349–1358. doi:10.1121/1.3675008.

Mundy, C.J. 2022. Southampton Island Marine Ecosystem Project. CanWIN. doi:10.34992/dc0p-kf56.

Nielsen, N.H., Laidre, K., Larsen, R.S., and Heide-Jørgensen, M.P. 2015. Identification of potential foraging areas for bowhead whales in Baffin Bay and adjacent waters. Arctic, **68**(2): 169–179. doi:10.14430/arctic4488.

NCRI. 2012. Nunavut Coastal Resource Inventory—Salliq 2012.

NRCC. 2022. National Research Council Canada Sunrise/sunset calculator. Available from https://nrc.canada.ca/en/research-development/products-services/software-applications/sun-calculator/ [accessed 13 March 2022].

NWMB. 2013. Integrated Fisheries Management Plan (IFMP) for Narwhal in the Nunavut Settlement Area (*Monodon monoceros*). Nunavut Wildlife Management Board, Iqaluit, NU. 48 p.

Orr, J.R., and Rebizant, T. 1987. A summary of information on the seasonal distribution and abundance of Walrus (*Odobenus rosmarus*) in the area of northern Hudson Bay and western Hudson Strait, NWT, as collected from local hunters. Can. J. Fish. Aquat. 624. pp. iv + 16.

Pacifici, M., Di Marco, M., and Watson, J.E.M. 2020. Protected areas are now the last strongholds for many imperiled mammal species. Conservation Letters, **13**: e12748. doi:10.1111/conl.12748.

Panova, E.M., Belikov, R.A., Agafonov, A.V., and Bel'Kovich, V.M. 2012. The relationship between the behavioral activity and the underwater vocalization of the beluga whale (*Delphinapterus leucas*). Oceanology, **52**: 79–87. doi:10.1134/S000143701201016X.

Parkinson, C.L. 2014. Spatially mapped reductions in the length of the Arctic sea ice season. Geophysical Research Letters, **41**: 4316. doi:10.1002/2014GL060434.

Pirotta, E., Booth, C.G., Costa, D.P., Fleishman, E., Kraus, S.D., Lusseau, D., et al. 2018. Understanding the population consequences of disturbance. Ecology and Evolution, **8**: 9934–9946. doi:10.1002/ece3.4458.

Pizzolato, L., Howell, S.E.L., Dawson, J., Laliberte, F., and Copland, L. 2016. The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophysical Research Letters, 43.

R Core Team. 2022. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from https://www.R-project.org/ [accessed 3 February 2023].

R Studio Team. 2022. RStudio: integrated development environment for R. RStudio, PBC, Boston, MA. Available from http://www.rstudio.com/ [accessed 3 February 2023].

Ranius, T., Widenfalk, L.A., Seedre, M., Lindman, L., Felton, A., Hämäläinen, A., et al. 2023. Protected area designation and management in a world of climate change: a review of recommendations. Ambio, **52**: 68–80. doi:10.1007/s13280-022-01779-z.

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, **3**(1): 168. doi:10.1038/s43247-022-00498-3.

Raven Pro. 2023. Interactive sound analysis software (Version 1.6.4), K. Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology [computer software]. The Cornell Lab of Ornithology, Ithaca, NY. Available from https://ravensoundsoftware.com/ [accessed 3 February 2023].

Ray, G.C., and Watkins, W.A. 1975. Social function of underwater sounds in the walrus *Odobenus rosmarus*. *In* Biology of the seal: Proceedings of a Symposium. *Edited by* K. Ronald and A.W. Mansfield, Guelph, Ont., 14–17 August 1972. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 169. pp. 524–526.

Reese, C., Calvin, J.A., George, J.C., and Tarpley, R.J. 2001. Estimation of fetal growth and gestation in bowhead whales. Journal of the American Statistical Association, **96**: 915–938. doi:10.1198/016214501753208618.

Reeves, R.R., and Mitchell, E. 1989. Status of white whales, *Delphinapterus leucas*, in Ungava Bay and Eastern Hudson Bay. The Canadian Field-Naturalist, **103**(2): 220–239. doi:10.5962/p.356125.

Reeves, R., Mitchell, E., Mansfield, A., and McLaughlin, M. 1983. Distribution and Migration of the Bowhead Whale, *Balaena mysticetus*, in the Eastern North American Arctic. Arctic, **36**(1): 5–64. doi:10.14430/arctic2243.

Richard, P.R. 2010. Stock definition of belugas and narwhals in Nunavut. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/022. iv + 14p.

Rideout, B.P., Dosso, S.E., and Hannay, D.E. 2013. Underwater passive acoustic localization of Pacific walruses in the northeastern Chukchi Sea. Journal of the Acoustical Society of America, **134**: 2534. doi:10.1121/1.4816580.

Roy, N., and Simard, Y. 2015. Bruit ambiant et fréquentation de la région de Cacouna par le béluga du Saint-Laurent à l'été 2014 par monitorage acoustique continu. Rapport Technique Canadien des Sciences Halieutiques et Aquatiques 3141 (Fisheries and Oceans Canada, Ottawa, Canada).

Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., et al. 2021. Protecting the global ocean for biodiversity, food and climate. Nature, **592**(7854): 397–402. doi:10.1038/s41586-021-03371-z.

Salter, R.E. 1979. Site utilization, activity budgets, and disturbance responses of Atlantic walruses during terrestrial haul-out. Canadian Journal of Zoology, **57**(6): 1169–1180. doi:10.1139/z79-149.

Scharffenberg, K., Whalen, D., Marcoux, M., Iacozza, J., Davoren, G., and Loseto, L. 2019. Environmental drivers of beluga whale *Delphinapterus leucas* habitat use in the Mackenzie Estuary, Northwest Territories, Canada. Marine Ecology Progress Series, **626**: 209–226. doi:10.3354/meps13011.

Schevill, W.E., and Lawrence, B. 1949. Underwater listening to the white porpoise (*Delphinapterus leucas*). Science, **109**(2824): 143–144. doi:10.1126/science.109.2824.143.

Schmidt, D.N., Pieraccini, M., and Evans, L. 2022. Marine Protected Areas in the context of climate change: key challenges for coastal social-ecological systems. Philosophical Transactions of the Royal Society B: Biological Sciences, **377**(1854). doi:10.1098/rstb.2021.0131.

Schusterman, R.J., and Reichmuth, C. 2008. Novel sound production through contingency learning in the Pacific walrus (*Odobenus rosmarus divergens*). Animal Cognition, **11**(2): 319–327. doi:10.1007/s10071-007-0120-5.

Sergeant, D.E. 1973. Biology of white whales (*Delphinapterus leucas*) in western Hudson Bay. Journal of the Fisheries Research Board of Canada, **30**: 1065–1090. doi:10.1139/f73-178.

Shannon, C. E. 1949. Communication in the presence of noise. Proceedings of the IRE, **37**(1): 10–21. doi:10.1109/JRPROC.1949.232969.

Simard, F., Laffoley, D., and Baxter, J.M. 2016. Marine protected areas and climate change: adaptation and mitigation synergies, opportunities and challenges. IUCN, Gland, Switzerland. 52p.

Simard, Y., Giard, S., Roy, N., Aulanier, F., and Lesage, V. 2023. Mesoscale habitat use by St. Lawrence estuary beluga over the annual cycle from an acoustic recording network. Journal of the Acoustical Society of America, **154**(2): 635–649. doi:10.1121/10.0020534.

Sjare, B.L., and Smith, T.G. 1986. The vocal repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. Canadian Journal of Zoology, **64**: 407–415. doi:10.1139/z86-063.

Sjare, B., and 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. doi:10.1139/z96-103.

Sjare, B., Stirling, I., and Spencer, C. 2003. Structural variation in the songs of Atlantic walruses breeding in the Canadian High Arctic. Aquatic Mammals, **29**(2): 297–318. doi:10.1578/016754203101024121.

Smith, A.J., Richard, P., Orr, J., and Ferguson, S. 2007. Study of the use of the Nelson Estuary and adjacent waters by beluga whales equipped with satellite-linked radio transmitters:2002–2005. A report prepared for Manitoba Hydro. 45 p.

Sousa-Lima, R.S., Norris, T.F., Oswald, J.N., and Fernandes, D.P. 2013. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. Aquatic Mammals, **39**(1): 23–53. doi:10.1578/AM.39.1.2013.23.

Stafford, K.M., Moore, S.E., Laidre, K.L., and Heide-Jørgensen, M.P. 2008. Bowhead whale springtime song off West Greenland. Journal of the Acoustical Society of America, **124**(5): 3315–3323. doi:10.1121/1.2980443.

Stafford, K.M., Moore, S.E., Berchok, C.L., Wiig, Ø., Lydersen, C., Hansen, E., et al. 2012. Spitsbergen's endangered bowhead whales sing through the polar night. Endangered Species Research, **18**: 95–103. doi:10.3354/esr00444.

Stafford, K.M., Citta, J.J., Okkonen, S.R., and Zhang, J. 2021. Bowhead and beluga whale acoustic detections in the western Beaufort Sea 2008–2018. PLoS ONE, **16**(6): e0253929. doi:10.1371/journal.pone.0253929.

Statistics Canada. 2023. Census Profile. 2021 Census of Population. Statistics Canada Catalogue no. 98-316-X2021001. Ottawa. Released 29 March 2023.

Stevenson, T.C., Davies, J., Huntington, H.P., and Sheard, W. 2019. An examination of trans-Arctic vessel routing in the Central Arctic Ocean. Marine Policy, **100**: 83–89. doi:10.1016/j.marpol.2018.11.031.

Stewart, D.B., and Lockhart, W.L. 2005. An overview of the Hudson Bay marine ecosystem. Can. Tech Rep. Fish. Aquat. Sci. 2586. vi + 487p.

Stirling, I., and Derocher, A.E. 2012. Effects of climate warming on polar bears: a review of the evidence. Global Change Biology, **18**: 2694–2706. doi:10.1111/j.1365-2486.2012.02753.x.

Stirling, I., and Parkinson, C.L. 2006. Possible effects of climate warming on selected species if polar bears (*Ursus maritimus*) in the Canadian Arctic. Arctic, **59**(3): 261–275.

Stirling, I., Calvert, W., and Cleator, H. 1983. Underwater vocalizations as a tool for studying the distribution and relative abundance of wintering pinnipeds in the High Arctic. Arctic, **36**(3): 262–274. doi:10.14430/arctic2275.

Stirling, I., Calvert, W., and Spencer, C. 1987. Evidence of stereotyped underwater vocalizations of male Atlantic walruses, *Odobenus rosmarus rosmarus*. Canadian Journal of Zoology, **65**: 2311–2321. doi:10.1139/z87-348.

Tervo, O.M., Parks, S.E., and Miller, L.A. 2009. Seasonal changes in the vocal behavior of bowhead whales (*Balaena mysticetus*) in Disko Bay, Western-Greenland. Journal of the Acoustical Society of America, **126**(3): 1570. doi:10.1121/1.3158941.

Thomas, J.A., and DeMaster, D.P. 1982. An acoustic technique for determining diurnal activities in leopard (*Hydruga leptonyx*) and crabeater (*Lobodon carcinophagus*) seals. Canadian Journal of Zoology, **60**: 2028–2031. doi:10.1139/z82-260.

Thomisch, K., Hiemer, K., Boebel, O., Burkhardt, E., Spiesecke, S., and Van Opzeeland, I. 2022. Acoustic presence and vocal repertoire of bowhead whales (*Balaena mysticetus*) in eastern and central Fram Strait. Frontiers in Remote Sensing, **3**: 907105. doi:10.3389/frsen.2022.907105.

Tynan, C.T., and DeMaster, D.P. 1997. Observations and predictions of Arctic climatic change: potential effects on marine mammals. Arctic, **50**(4): 308–322. doi:10.14430/arctic1113.

UNEP, CBD and COP. 2022. Decision adopted by the conference of the parties to the convention on biological diversity. CBD/COP/DEC/15/4.

UNEP-WCMC and IUCN. 2023. Marine Protected Planet [online]. UNEP-WCMC and IUCN, Cambridge, UK. Available from www.protectedplanet.net [accessed September 2023].

Van Opzeeland, I.C., Van Parijs, S., Bornemann, H., Frickenhaus, S., Kindermann, L., Klinck, H., et al. 2010. Acoustic ecology of Antarctic pinnipeds. Marine Ecology Progress Series, **414**: 267–291. doi:10.3354/meps08683.

Van Parijs, Hastie, G.D., and Thompson, P.M. 1999. Geographical variation in temporal and spatial vocalization patterns of male harbour seals in the mating season. Animal Behaviour, **58**(6): 1231–1239. doi:10.1006/anbe.1999.1258.

Van Parijs, S.M., Kovacs, K.M., and Lydersen, C. 2001. Spatial and temporal distribution of vocalizing male bearded seals: implications for male mating strategies. Behaviour, **138**: 905–922. doi:10.1163/156853901753172719.

Van Parijs, S.M., Lydersen, C., and Kovacs, K.M. 2003. Vocalizations and movements suggest alternative mating tactics in male bearded seals. Animal Behaviour, **65**: 273–283. doi:10.1006/anbe.2003.2048.

Van Parijs, S.M., Lydersen, C., and Kovacs, K.M. 2004. The effects of ice cover on the behaviour of aquatic-mating male bearded seals. Animal Behaviour, **68**: 89–96. doi:10.1016/j.anbehav.2003.09.013.

Walsh, J.E., Eicken, H., Redilla, K., and Johnson, M. 2022. Sea ice breakup and freeze-up indicators for users of the Arctic coastal environment. The Cryosphere, **16**: 4617–4635. doi:10.5194/tc-16-4617-2022.

Wang, Y., Murphy, O., Turgeon, M., Wang, Z., Bhatnagar, S.R., Schulz, J., and Moodie, E.E. 2015. The perils of quasi-likelihood information criteria. Stat, **4**(1): 246–254. doi:10.1002/sta4.95.

Xavier da Silva, M., Paviolo, A.J., Tambosi, L.R., and Pardini, R. 2018. Effectiveness of protected areas for biodiversity conservation: mammal occupancy patterns in the Iguaçu National Park, Brazil. Journal for Nature Conservation, **41**(2): 51–62. doi:10.1016/j.jnc.2017.11.001.x`

Yurkowski, D.J., Auger-Méthé, M., Mallory, M.L., Wong, S.N.P., Gilchrist, H.G., Derocher, A.E., et al. 2019. Abundance and species diversity hotspots of tracked marine predators across the North American Arctic. Diversity and Distributions, **25**: 328–345. doi:10.1111/ddi.12860.

Zahn, M.J., Rankin, S., McCullough, J.L.K., Koblitz, J.C., Archer, F., Rasmussen., M.H., and Laidre, K.L. 2021. Acoustic differentiation and classification of wild belugas and narwhals using echolocation clicks. Scientific Reports, **11**: 22141. doi:10.1038/s41598-021-01441-w.

Appendix A

Table A1. Resulting coefficients and Akaike's information criterion (AIC) values of the binomial distribution generalized linear models of the effect of quarter of day, hydrophone location, month, and season on the proportion of marine mammal vocalizations.

Species	Model #	Quarter of day	Location	Month	Season	AIC	Dev. expl. (%)	R^2	*p*
Bearded seal	**1**	*	*			**861.48**	**6.7**	**0.10**	**<0.001**
	2		*			886.14	5.5	0.07	<0.001
	3	*				926.26	0.9	0.03	<0.001
Walrus	**1**	*		*	*	**1415**	**11**	**0.16**	**<0.001**
	2	*	*	*	*	1416.7	11.1	0.16	<0.001
	3	*		*		1441.3	9.9	0.14	<0.001
	4	*	*	*		1442.9	9.9	0.14	<0.001
	5			*	*	1454.7	8.9	0.13	<0.001
	6		*	*	*	1456.3	8.9	0.13	<0.001
	7			*		1480.6	7.7	0.12	<0.001
	8		*	*		1482.3	7.8	0.12	<0.001
	9	*	*		*	1604.3	3	0.04	<0.001
	10	*	*			1607.1	2.9	0.04	<0.001
	11	*			*	1616.9	2.4	0.03	<0.001
	12	*				1627.2	2	0.03	<0.001
	13		*		*	1641.9	1	0.02	<0.001
	14		*			1644.7	0.9	0.01	<0.001
	15				*	1654.4	0.4	0.01	<0.001
Beluga	**1**	*	*	*	*	**1225.2**	**20**	**0.29**	**<0.001**
	2		*	*	*	1233.2	19.8	0.28	<0.001
	3	*	*	*		1281.4	17.7	0.26	<0.001
	4		*	*		1289.4	17.5	0.25	<0.001
	5	*		*	*	1359.1	11.5	0.21	<0.001
	6			*	*	1367.5	11.4	0.20	<0.001
	7	*	*		*	1407	10.2	0.18	<0.001
	8		*		*	1415.1	10.1	0.17	<0.001
	9	*		*		1430.1	8.6	0.17	<0.001
	10			*		1438.4	8.5	0.16	<0.001
	11	*			*	1495.7	6.2	0.13	<0.001
	12	*	*			1498.9	8.8	0.13	<0.001
	13				*	1503.7	6.1	0.12	<0.001
	14		*			1506.4	8.8	0.12	<0.001
	15	*				1695.1	0	0.01	<0.01
Bowhead whale	**1**		*	*		**706.1**	**25.6**	**0.15**	**<0.001**
	2	*	*	*		710.42	25.1	0.15	<0.001
	3		*			807.75	3.1	0.02	<0.001
	4	*	*			812.49	2.3	0.02	<0.001
	5			*		815.24	0	0.01	<0.01
	6	*		*		819.51	0	0.01	<0.05
	7	*				827.91	0	0.00	ns

Note: for each species, models are presented in order of increasing aic with the best model shown in bold. "dev. expl." indicates deviance explained; "ns" indicates a nonsignificant *p* value at the 5% level.

Table A2. Resulting coefficients and Akaike's information criterion (AIC) values of the binomial distribution generalized linear models of the effect of light level, hydrophone location, month, and season on the proportion of marine mammal vocalizations.

Species	Model #	Light level	Location	Month	Season	AIC	Dev. expl. (%)	R^2	*p*
Bearded seal	**1**	*	*			**734.61**	**5.3**	**0.10**	**<0.001**
	2		*			744.48	2.8	0.08	<0.001
	3	*				799.77	1.1	0.01	<0.001
Walrus	**1**	*		*	*	**1219.1**	**7.6**	**0.18**	**<0.001**
	2	*	*	*	*	1220.9	7.6	0.18	<0.001
	3	*		*		1242.9	7.6	0.16	<0.001
	4	*	*	*		1244.7	7.6	0.16	<0.001
	5			*	*	1251.9	6.4	0.15	<0.001
	6		*	*	*	1253.5	6.5	0.15	<0.001
	7			*		1277.9	6.0	0.13	<0.001
	8		*	*		1279.5	6.1	0.13	<0.001
	9	*	*			1393.4	1.7	0.05	<0.001
	10	*	*		*	1393.7	1.5	0.05	<0.001
	11	*			*	1397.4	0.8	0.05	<0.001
	12	*				1399.5	0.8	0.05	<0.001
	13		*		*	1438.8	0.6	0.02	<0.001
	14		*			1441.6	0.8	0.01	<0.001
	15				*	1451.2	0.0	0.01	<0.001
Beluga	**1**	*	*	*	*	**922.64**	**21.7**	**0.36**	**<0.001**
	2		*	*	*	938.47	20.7	0.34	<0.001
	3	*	*	*		977.93	19.1	0.32	<0.001
	4		*	*		994.67	18.0	0.30	<0.001
	5	*		*	*	1054.8	7.8	0.26	<0.001
	6			*	*	1072.1	6.2	0.25	<0.001
	7	*	*		*	1109.8	7.2	0.22	<0.001
	8		*		*	1121.8	7.0	0.21	<0.001
	9	*		*		1124.4	4.6	0.21	<0.001
	10			*		1143	2.8	0.20	<0.001
	11	*	*			1192.6	10.4	0.16	<0.001
	12	*			*	1202.9	3.0	0.15	<0.001
	13				*	1210.4	2.2	0.14	<0.001
	14		*			1214.4	9.7	0.14	<0.001
	15	*				1347.8	1.0	0.05	<0.001
Bowhead whale	**1**		*	*		**654.83**	**25.4**	**0.16**	**<0.001**
	2	*	*	*		653.35	24.1	0.16	<0.001
	3	*	*			753.37	0.0	0.03	<0.001
	4		*			754.67	2.2	0.02	<0.001
	5			*		761.65	0.0	0.01	<0.01
	6	*		*		763.45	0.0	0.02	<0.01
	7	*				770.86	0.0	0.00	ns

Note: For each species, models are presented in order of increasing AIC with the best model shown in bold. "Dev. expl." indicates deviance explained; "ns" indicates a nonsignificant *p* value at the 5% level.

Table A3. Resulting coefficients and Akaike's information criterion (AIC) values of the generalized linear models of the effect of sea ice concentration (SIC) class, week, and season on the proportion of beluga vocalizations recorded at hydrophone ES.

Model #	SIC class	Week	Season	AIC	Deviance explained (%)	R^2	p
1	*****	*****	*****	**196.36**	**13.5**	**0.73**	**< 0.001**
2	*		*	242.70	0.0	0.66	< 0.001
3	*			272.92	5.6	0.62	< 0.001
4	*	*		274.61	2.8	0.62	< 0.001
5		*	*	356.13	0.0	0.50	< 0.001
6			*	362.65	0.0	0.49	< 0.001
7		*		399.12	0.0	0.44	< 0.001

Note: Models are presented in order of increasing AIC with the best model shown in bold.

Fig. A1. Schematic of mooring Evans Strait (ES). The ellipse shows the hydrophone position.

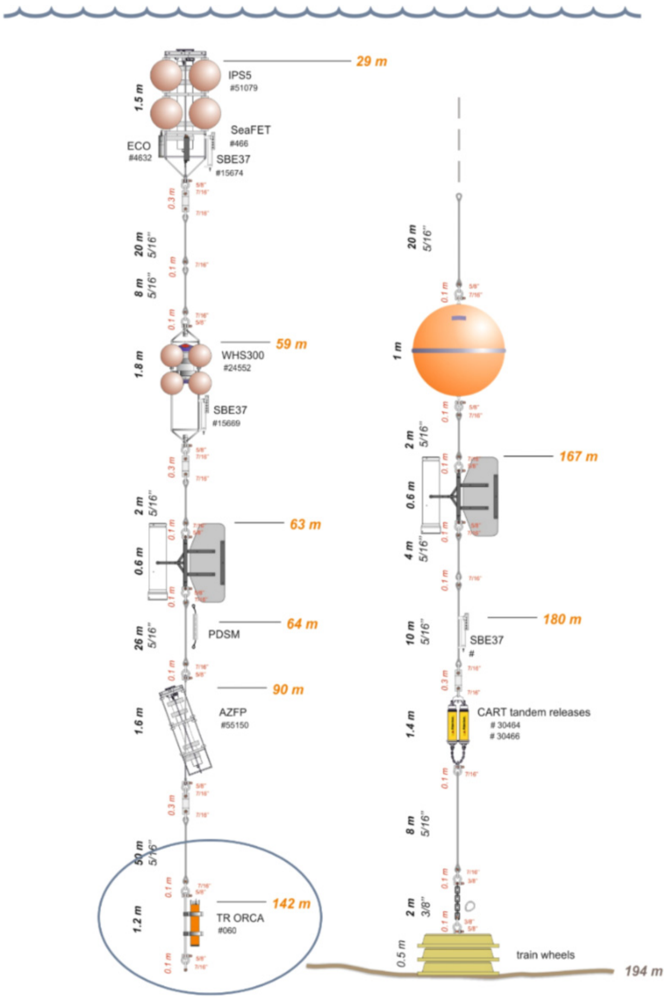


Fig. A2. Seasonal trend of individual species vocal activity (color bars) and local sea ice concentration (SIC) (black line) at hydrophone Coats Island (CI). Each recorded species is presented in a separate plot. The *X* axis shows the date; the left *Y* axis shows the percentage of vocal activity for each species; and the right *Y* axis shows the percentage SIC.

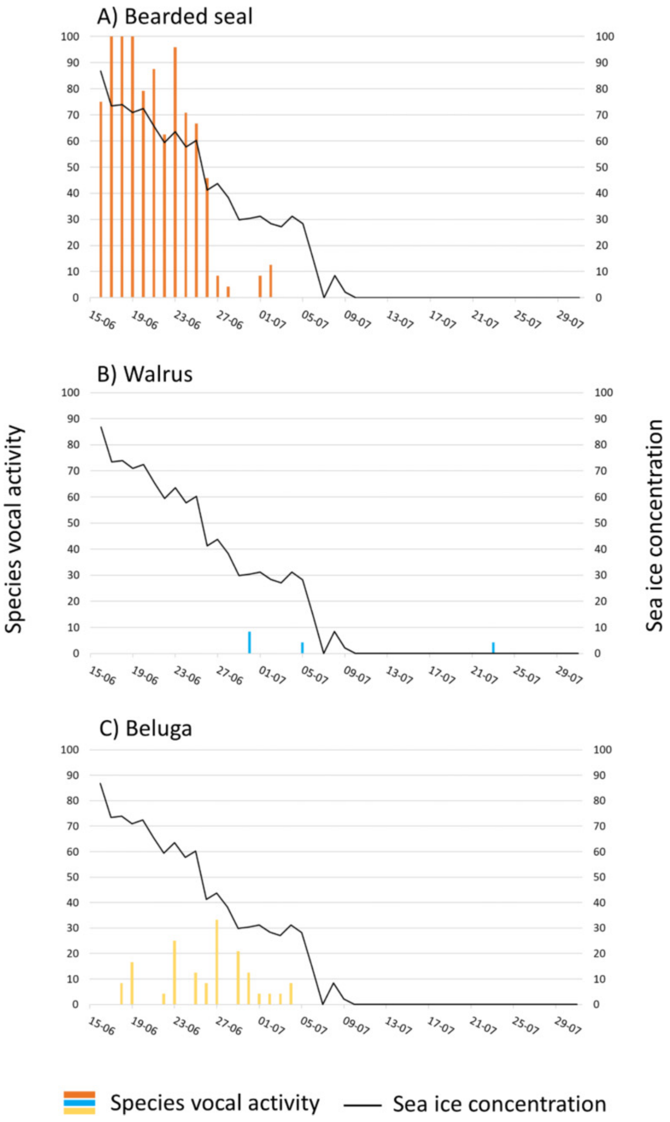


Fig. A3. Seasonal trend of individual species vocal activity (color bars) and local sea ice concentration (SIC) (black line) at hydrophone South Bay (SB). Each recorded species is presented in a separate plot. The *X* axis shows the date; the left *Y* axis shows the percentage of vocal activity for each species; and the right *Y* axis shows the percentage SIC.