Received: 9 January 2020 | Accepted: 19 July 2020

DOI: 10.1111/mms.12732

**ARTICLE**

Marine Mammal Science

# Vocalizations of bearded seals (*Erignathus barbatus*) and their influence on the soundscape of the western Canadian Arctic

**Annika F. Heimrich**[1,2] | **William D. Halliday**[2,3] | **Héloïse Frouin-Mouy**[2,4] | **Matthew K. Pine**[2] | **Francis Juanes**[2] | **Stephen J. Insley**[2,3]

[1]Department of Biology, University of Ghent, Ghent, Belgium

[2]Department of Biology, University of Victoria, Victoria, British Columbia, Canada

[3]Wildlife Conservation Society Canada, Whitehorse, Yukon, Canada

[4]JASCO Applied Science Ltd., Victoria, British Columbia, Canada

**Correspondence**

William D. Halliday, 169 Titanium Way, Whitehorse, Yukon Y1A 0E9, Canada.
Email: whalliday@wcs.org

**Funding information**

Liber Ero Foundation; Marine Environmental Observation Prediction and Response Network; W. Garfield Weston Foundation; World Wildlife Fund

## Abstract

The soundscape is a crucial habitat feature for marine mammals. This study investigates the contribution of bearded seal vocalizations to the soundscape in the western Canadian Arctic, and also the vocal characteristics of bearded seals relative to sea ice conditions. Passive acoustic data were recorded near Sachs Harbour between August 2015 and July 2016. Sound pressure levels (SPL) in the 50–1,000 Hz and 1–10 kHz bands increased as the total duration of all bearded seal vocalizations increased, and this relationship was moderated by sea ice concentration. Bearded seals in this region had an overlapping vocal repertoire with bearded seals in other areas of the Arctic, and had seven additional vocalizations that have not been previously documented for this region. This study is the first detailed assessment of the influence of bearded seal calls on SPL, which shows the high potential of bearded seals to influence underwater sound levels during the mating season. Bearded seals live in a changing Arctic seascape, and their influence on the soundscape may shift as sea ice continues to diminish. It is imperative that acoustic monitoring continues within the Arctic, and this study provides a baseline for future monitoring as the Arctic continues to change.

**KEYWORDS**

Arctic Ocean, bearded seals, Canadian Arctic, sea ice, soundscape

## 1 | INTRODUCTION

The marine soundscape is a steadily changing sonic environment shaped by several sound sources. The soundscape is usually divided into three different components: geophony (e.g., wind, ice, and earthquakes), biophony (e.g., sound produced by marine animals), and anthrophony (e.g., dredging, shipping, and seismic surveys) (Pijanowski et al., 2011); all three components vary spatially and temporally (Cotter, 2008). The soundscape is considered a crucial habitat feature for marine animals because it impacts the ability of these animals to use sound for a variety of sensory functions, including communication, predator detection, foraging, and navigation (Stafford, Castellote, Guerra, & Berchok, 2018). Therefore, alterations to the soundscape become of utmost concern because increased sound levels can lead to changes in the behavior of marine animals in various ways (Ellison, Southall, Clark, & Frankel, 2011; Gomez et al., 2016; Nowacek, Thorne, Johnston, & Tyack, 2007; Southall et al., 2007). Previous studies have shown both modified vocal behavior (Holt, Noren, Veirs, Emmons, & Veirs, 2009), changes in calling rates (Melcón et al., 2012), increased stress levels (Rolland et al., 2012), and acoustic masking of biological sounds emitted by other marine animals (Clark et al., 2015; Erbe, Reichmuth, Cunningham, Lucke & Dooling, 2016).

The Arctic Ocean usually has lower ambient sound levels, on average, than other marine environments due to thick sea ice layers, short ice-free seasons, and less anthropogenic activities compared to non-Arctic seas (Insley, Halliday, & de Jong, 2017; Protection of the Arctic Marine Environment, 2019; Roth, Hildebrand, Wiggins, & Ross, 2012); however, the Arctic is changing rapidly, including through increased access for ship traffic (Dawson, Pizzolato, Howell, Copland, & Johnston, 2017), which will likely influence the soundscape. Arctic waters are known to be extremely important for several marine mammals as both feeding and birthing grounds (Heide-Jørgensen et al., 2013; Laidre et al., 2010; Moore & Huntington, 2008), and yet little is known about seasonal variation in marine mammal vocalizations and their contribution to the soundscape. Some biophony sound sources, such as bearded seals (Frouin-Mouy, Mouy, Berchokm Blackwell, & Stafford, 2016; MacIntyre, Stafford, Berchok, & Boveng, 2013; Marcoux, Auger-Methe, & Humphries, 2012), seem to shape the soundscape more than others within the Arctic Ocean (Protection of the Arctic Marine Environment, 2019). Since sea ice is considered a crucial habitat feature influencing most facets of Arctic marine life (Laidre et al., 2008), the loss of sea ice in the future is likely to affect both resident and migratory species within the Arctic, which will then influence their contribution to the soundscape.

Since bearded seals are characterized by their readily identifiable vocalizations (Risch et al., 2007), numerous studies have investigated their vocal behavior (Davies, Kovacs, Lydersen, & Van Parijs, 2006; Frouin-Mouy et al., 2016; MacIntyre et al., 2013; Risch et al., 2007; Van Parijs, Kovacs, & Lydersen, 2001; Van Parijs, Lydersen, & Kovacs, 2003). Males produce long trilling vocalizations in order to advertise their breeding conditions and/or mark their territories (Burns, 1981; Cleator, Stirling, & Smith, 1989; Frouin-Mouy, Mouy, Martin, & Hannay, 2016; Van Parijs, Kovacs, & Lydersen, 2001). Vocalizations usually cover frequencies from 130 Hz to 6 kHz and can last from 10 s up to 3 min (Cleator et al., 1989). According to Cleator et al. (1989) and Cleator and Stirling (1990), male bearded seals are thought to be in breeding condition between April and June, while previous studies showed that call activity can start earlier and increases significantly throughout the mating season (Frouin-Mouy et al., 2016; Hannay et al., 2013; MacIntyre et al., 2013). Bearded seal vocalizations can be detected 24 hr per day during the peak mating season at some sites (Halliday, Insley, de Jong, & Mouy, 2018; MacIntyre et al., 2013), and may therefore be a main contributor to the soundscape during the mating season. In this study, we document the vocal characteristics of bearded seals at one location in the western Canadian Arctic. We also assess how bearded seal vocalizations contribute to the soundscape by specifically examining their influence on sound pressure levels. To the best of our knowledge, this is the first study examining how bearded seal vocalizations impact sound pressure levels. The influence of bearded seal vocalizations on the soundscape is an important component of the current Arctic soundscape, especially in areas with high densities of bearded seals, and is one aspect of the soundscape that other marine life has evolved to deal with when using the soundscape. Results from this study will be a useful comparison for future soundscape studies, where sea ice loss may change the relative distribution of bearded seals and the contribution of their vocalizations to the soundscape.

## 2 | MATERIAL AND METHODS

### 2.1 | Data collection

Acoustic data were collected using a factory-calibrated Wildlife Acoustics (Maynard, MD) SM3M acoustic recorder with a low-noise HTI 92-WB hydrophone (High Tech, Inc., Gulfport, MS). The sensitivity of these hydrophones is relatively flat between 200 Hz and 6 kHz, but drops rapidly below 50 Hz. Sensitivity drops 2–3 dB above 6 kHz, but remains relatively constant. The noise floor of the hydrophone and recorder is quite low, starting around 63 dB re 1 $\mu Pa^2$/Hz at 25 Hz, and decreases continuously down to ~40 dB between 25 and 200 Hz. Furthermore, the noise floor level drops down to ~35 dB between 1 and 5 kHz. The recorder was set to a duty cycle with 5 min on followed by 30 min off. The sampling rate was set to 48 kHz, the bit-depth to 16-bit, and amplification gain to 18 dB. The acoustic recorder was anchored at a depth of 23.5 m (28.5 m actual water depth) 8 km southwest of Sachs Harbour, Northwest Territories, Canada (71°55.621'N, 125°23.447'W) from August 20, 2015 until July 8, 2016. The positively buoyant recorder floated 5 m above an anchor (sandbag), attached by 9 mm rope. In total, a data set containing 13,339 5 min files was recorded during the deployment. This data set was chosen for a focused analysis of bearded seal vocalizations because it has by far the most bearded seal vocalizations of any data set that we had collected to date when we started this project (Halliday et al. 2018, 2019).

### 2.2 | Data processing

To quantify the underwater soundscape, all data were processed in Matlab version R2017b (MathWorks, Natick, MA) using the PAMGuide package (Merchant et al., 2015). Sound pressure levels (SPL) were calculated for three frequency bands (50–1,000 Hz, 1–10 kHz, 10–16 kHz) based on 5 min averages (one SPL value for each frequency band per file) calculated using a Hann window with 1 s window length and 50% overlap. The hydrophone had low sensitivity below 50 Hz, therefore we did not examine data below 50 Hz. We also did not examine data above 16 kHz to maintain comparability of measurements with another data set collected at this site that had a 32 kHz sampling rate; this other data set was not included in this study, but has been previously examined along with this current one (Halliday et al., 2018; Insley et al., 2017).

### 2.3 | Bioacoustic analyses

Files were first processed using an automated detector and classifier (Spectro Detector; JASCO Applied Science Ltd., Victoria, British Columbia, Canada) (Mouy et al., 2013), which enabled automatic classification for beluga whales (*Delphinapterus leucas*), bowhead whales (*Balaena mysticetus*), and bearded seals. All files with at least one automated detection for one of these species, as well as 5% of files with no detections, were then manually inspected for the presence of vocalizations from these three species, as well as by ringed seals (*Pusa hispida*). Methods and results from this analysis are fully described and analyzed in Halliday et al. (2018). In this study, we specifically worked with files that included bearded seal calls ($N$ = 5,321), as determined in the analysis by Halliday et al. (2018). We sampled 10% of all files with bearded seal calls in this analysis, and selected files by creating groups of ten (files put into groups of 10 systematically with the data ordered from highest to lowest call counts, as counted by the automated detector/classifier), and then randomly picking one of the 10 files in each group by applying a random calculator in R (version

1.0.153; R Core Team, 2016). The final data set of 532 files included recordings from November 2015 until June 2016, and was further analyzed using Raven Pro (Bioacoustics Research Program, 2017).

Within Raven Pro, we set brightness, contrast, and spectrogram window size to 50, 50, and 4,000, respectively, while frequency (*y*-axis) and time (*x*-axis) range initially set to 6 kHz and 30 s, but both were adjusted as required when selecting vocalizations. The selection table measured "Begin File," "Begin Time," "End Time," "Delta Time," "Low Frequency," "High Frequency," "Delta Frequency," "Peak Frequency," "Leq," "Peak Power Density," and "File offset," and all selections were manually annotated with "Call Category," "Call Type," and "Diel Period." Both Leq and Peak Power Density are measurements of uncalibrated decibel (dB) levels. Peak Power Density is the maximum dB for any pixel within the selected signal, whereas Leq is the sound pressure level within the frequency range of the selected call, averaged across the length of the call. Peak Power Density is calculated from the spectrogram, whereas Leq is calculated from the waveform. Both Leq and Peak Power Density can be converted to calibrated levels based on the calibrated sensitivity of the recording system. All selected files were manually examined based on both auditory as well as visual analyses by a single analyst to avoid observer bias. The analyst drew selection boxes around the fundamental frequency of the signal (i.e., not selecting harmonics) of each bearded seal vocalization in a file. In order to avoid bias caused by including incomplete calls, only calls with clear limits (i.e., not masked by background noise (high signal-to-noise ratio), not up against the limits of the time or frequency axes) and call duration longer than 0.9 s were evaluated. Calls shorter than 0.9 s tend to become easily confused with background noise (A.F.H., personal observation). Furthermore, no calls at the beginning or end of a file were selected to account for potentially missing call parts.

To further characterize the selection of calls used in our analysis, we calculated signal-to-noise ratio (SNR) of each call using custom code in Matlab (Version 2019b; Mathworks Inc., Natick, MA). We loaded the selection table from Raven into Matlab, and then used Matlab to calculate the signal level of each call and the ambient sound levels at the same time as the call. The signal level in dB was based on the RMS sound pressure within the frequency band limits of each specific call, while the corresponding ambient sound level was the noise floor of the recording that contained the signal, represented by the 5th percentile noise level within the same frequency limits as the signal. The use of the 5th percentile within each recording that contained a bearded seal's call ensured a more accurate measurement of the SNR for each specific call, as it did not contain any signal energy (due to their highly transient presence) and was based on the noise level at the time of the call, which is what a conspecific listener would be experiencing.

All calls were primarily classified into four different call categories including trills, ascents, moans, and sweeps based on previous studies of bearded seal vocalizations (Cleator et al., 1989; Risch et al., 2007), and then further classified into subcategories following the call catalogue in Risch et al. (2007) based on frequency range, call duration, minimum and maximum frequency, peak frequency, as well as shape of call. Any calls that did not match the catalog in Risch et al. (2007) were assigned to new subcategories. Similar to Risch et al. (2007) we used further descriptive parameters such as presence of ascents, plumes and mid-call ascents to characterize the new call types. All statistical analyses were performed in RStudio (Version 1.0.153), including the usage of package "tibble" to label each call before further analyses, by month and season of recording. Seasons were determined as suggested by Clark et al. (2015) and slightly modified due to low calling rates before November and an absence of vocal activity in July. Seasons were split as follows: winter season (November 1 until March 31) and mating season (April 1 until June 30).

## 2.4 | Call repertoire analyses

Monthly patterns in bearded seal call parameters were evaluated by applying a Kruskal-Wallis test, accounting for a varying monthly sample size, followed by a Wilcoxon rank test examining statistical significance between months. The Wilcoxon test included a Bonferroni correction for multiple testing with $p < .05$ for statistical significance. The call parameters that were examined included minimum and maximum frequency, frequency range, received level (RL), and duration.

Variation in the abundance of call types was examined by computing total call counts per months for each of the 18 call types. Months where single call types were absent were excluded for type-specific analyses. Examination of potential significance between the different months was performed by applying a generalized linear model and post hoc test based on a Poisson distribution. Further pairwise comparison was conducted using Tukey's test from the "multcomp" package in R, with $p < .05$ indicating statistical significance.

## 2.5 | Soundscape analyses

To investigate the effect of sea ice, season, peak power density and received level on the soundscape, multiple linear regressions were fitted to the data, with SPL in one of three frequency bands (50–1,000 Hz, 1–10 kHz, 10–16 kHz) as the dependent variable. Further parameters such as call counts, call duration and minimum and maximum frequencies were also included in the models. Call duration was calculated as the sum of the duration of all calls per each 5 min file so that this variable quantified the total time that bearded seals spent calling within each file. Variables describing frequency, received level, and peak power density were averages for each file. Initially, two sets of models containing either sea ice concentration or season as the main predictor were created for each frequency band, since these two variables have strong multicollinearity. Ice concentrations were based on daily measurements of remote sensing data, obtained from the Advanced Microwave Scanning Radiometer 2 (AMSR2) instrument onboard the Japan Aerospace Exploration Agency's GCOM-W satellite, provided by the Physical Analysis of Remote Sensing Images group at the University of Bremen (Spreen, Kaleschke, & Heygster, 2008). Sea ice resolution was set to 106.25 km because this was the best scale identified in Halliday et al. (2018) for predicting the presence of bearded seal vocalizations at this site, likely because this spatial resolution best captured seasonal patterns in ice concentration. Sea ice concentration was transformed into a categorical variable, indicating low (<50%) and high (>50%) ice concentrations. Further analysis examined the suitability of received level (i.e., peak power density) as a second independent variable. Since the parameters "call counts" and "call duration" displayed high correlation, competing sets of models were included to evaluate the impact of these two predictor variables. Predictors such as frequency range and peak frequency were excluded from the analyses based on previous testing for correlation, where they were highly correlated with minimum and maximum frequency, and would therefore introduce multicollinearity into the model. A low correlation was detected between received level and call duration ($r = 0.30$, $p < .0001$), while a very low correlation was found between received level and maximum frequency ($r = 0.21$, $p < .0001$). To evaluate the potential effect of bearded seals on SPL, each set of frequency band models was tested again including call categories as an additional factor. Models were compared by using Akaike's information criterion (AIC). Assumptions were met for all models.

## 2.6 | Manual vs. automated call counts in the soundscape analysis

Following the initial analysis of the soundscape based on 10% of the data with bearded seal calls, the full data set was analyzed based on counts of bearded seal calls from the automated detector and classifier. First, linear regression was used to examine the relationship between manual call counts and automated call counts, including sea ice concentration, wind speed, and broadband (50 Hz–16 kHz) SPL as independent variables to control for background ambient sound level and assess their influence on the auto detector. Following this, linear regression was used to examine the relationship between SPL in each frequency band and automated call counts, excluding any files where no calls were counted. An additional analysis was also performed, which adjusted the automated call counts by the relationship between manual and auto call counts and adjusted for ambient sound levels in order to have comparable slopes with the analysis of SPL based on manual call counts.

## 3 | RESULTS

### 3.1 | Call repertoire

A total of 44 hr and 20 min of recording were manually analyzed, revealing 6,849 bearded seal calls within 513 5 min files. Nineteen files were excluded because although bearded seal calls were present, the individual calls were either significantly masked by background noise or were lacking parts at the end or beginning of a recording. The number of calls within each 5 min file showed strong fluctuation throughout the different months. Progressively increasing counts were found within the mating season, peaking in May (*N* = 2,238; Figure 1). Lowest call numbers were obtained during November (*N* = 80). Calls were entirely absent from early July until the end of September. The calls used in our analysis had a minimum SNR of 2.15 dB, maximum of 46.47 dB, mean of 13.46 dB, and median of 12.83 dB.

An initial visual examination revealed four basic call categories, including trills (T), ascents (A), sweeps (S), and moans (M). All call categories are labeled based on previous studies (Cleator et al., 1989; Risch et al., 2007; Van Parijs et al., 2001). While trills represented 63.5% of all recorded vocalizations, moans accounted for 14.8%, and ascents and sweeps accounted for the least with 11.3% and 10.4% of all calls, respectively. Further call classification revealed 18 different call types including 11 call types defined and modified by Risch et al. (2007) within the western Canadian Arctic. Seven new call types were identified, including a mix of five trills, one ascent, and one sweep. These previously undocumented calls that we identified for the western Canadian Arctic did not overlap with the calls identified by Risch et al. (2007) for any other study regions (Alaska, Canadian High Arctic, or Svalbard), except for two call types. First, the sweep we found in our data set showed similarities with the sweep detected within the Svalbard region by Risch et al. (2007). However, the sweep newly classified in this study displayed much higher levels in high frequencies than the one detected in Svalbard. Thus, we labelled this call as a new area-specific sweep for the western Canadian Arctic. Second, a small number of trills (*n* = 21) showed a similarity to the AL1 trill defined by

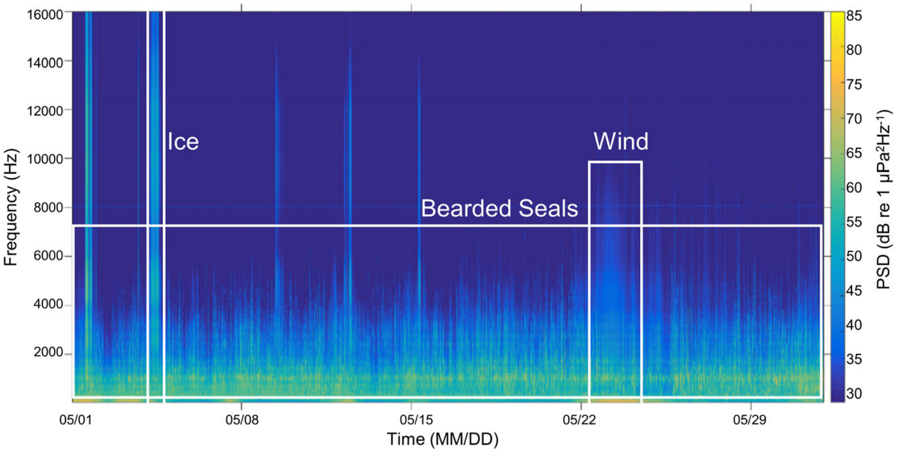

**FIGURE 1** Long-term spectrogram for the month of May 2016 at Sachs Harbour, Northwest Territories, Canada, showing the large contribution of bearded seal (*Erignathus barbatus*) vocalizations to the soundscape. Bearded seal vocalizations dominate frequencies below 4 kHz for the entire month. Other important contributors to the acoustic environment are ice sounds and wind sounds.

Risch et al. (2007), containing plumes and ascents, but the calls found in this study containing these two features showed overall longer durations of the ascents. We therefore decided to group these trills into the WCA1 category. We defined all new calls based on their shape, frequency range, minimum and maximum frequency, peak frequency, presence of ascents/plumes, and call duration (Figure 2). In total, we found 13 distinct trills, three distinguishable types of ascents (see characteristics in Table 1), and one each of moans and sweeps (WCA5 and WCA14, respectively). Some of the analyzed calls showed the presence of ascents and plumes, whereby ascents had longer durations than described in the previous study by Risch et al. (2007). Two call types contained a rounded mid-call ascent (WCA15 and WCA17), lasting up to ~11 s (see call characteristics in Table 1).

Bearded seal call parameters (all call types pooled) revealed monthly differences in call duration ($\chi^2_{7,6849} = 880.7$, $p < .0001$), frequency range of calls ($\chi^2_{7,6849} = 917.5$, $p < .0001$), minimum ($\chi^2_{7,6849} = 375.7$, $p < .0001$) and maximum frequency ($\chi^2_{7,6849} = 784.1$, $p < .0001$) (Figure 3), as well as the received level of the call ($\chi^2_{7,6846} = 4{,}932.7$, $p < .0001$). Note that three calls were removed from the analysis of received levels due to a

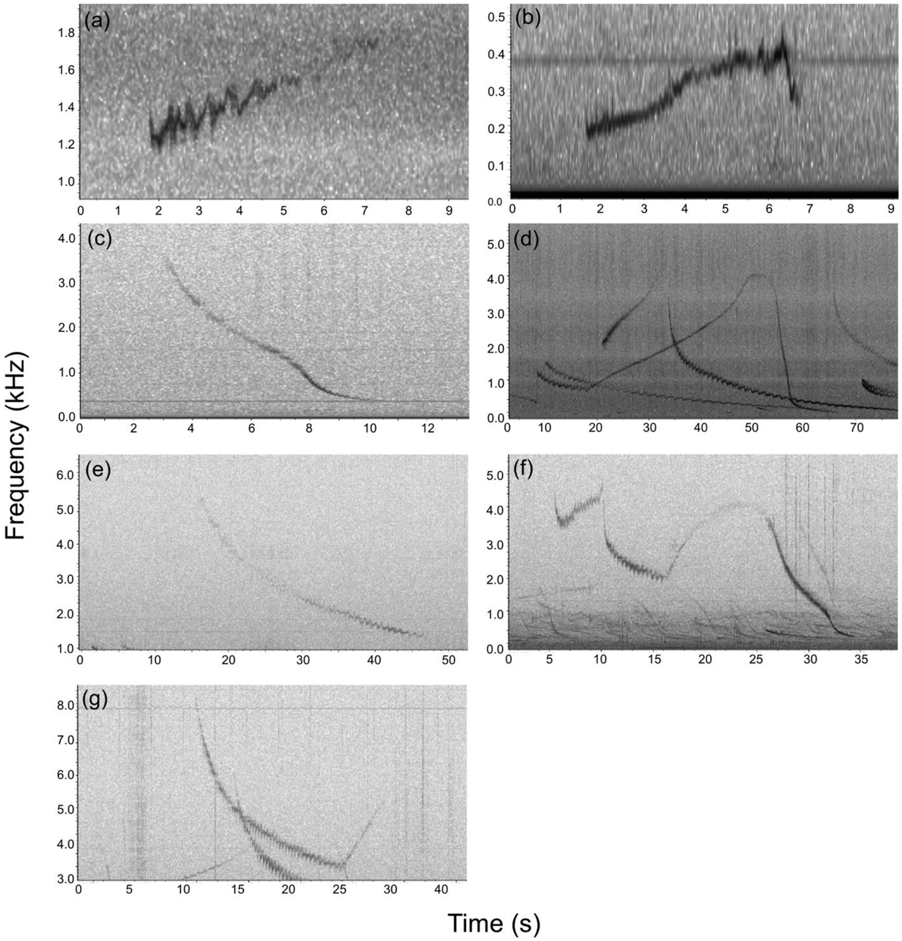

**FIGURE 2** Newly classified bearded seal (*Erignathus barbatus*) call types with A = WCA12 Ascent, B = WCA13 Trill, C = WCA14 Sweep, D = WCA15 Trill, E = WCA16 Trill, F = WCA17 Trill, and G = WCA18 Trill. Note that the limits and ranges of the y-axes and x-axes vary between panels. Sampling rate was at 48 kHz. Spectrogram window size was set to 4,000 with a 50% overlap, calculated using a Hann window.

**TABLE 1** Descriptive statistics for bearded seal calls within the western Canadian Arctic (*N* = 6,849). Mean and ± SD and range are displayed for minimum and maximum frequency and frequency range (FR) as well as call duration for each call type. The presence of an ascents, plumes, and mid-call ascents is also denoted.

| Call type | Minimum frequency (kHz) | Maximum frequency (kHz) | Frequency range (kHz) | Peak frequency (kHz) | Call duration | Ascent | Plume | Mid-call ascent | *N* |
|---|---|---|---|---|---|---|---|---|---|
| WCA1 (T) | 0.36 ± 0.14 | 5.00 ± 2.57 | 4.64 ± 2.53 | 1.53 ± 2.47 | 54.61 ± 12.06 | 1 | 1 | 0 | 447 |
| | 0.15–0.71 | 1.61–13.06 | 1.24–12.60 | 0.19–9.56 | 28.60–87.83 | | | | |
| WCA2 (T) | 0.43 ± 0.18 | 1.53 ± 0.62 | 1.10 ± 0.60 | 0.63 ± 0.28 | 3.73 ± 2.94 | 0 | 0 | 0 | 391 |
| | 0.15–1.61 | 0.71–3.82 | 0.30–3.58 | 0.19–3.09 | 1.02–20.02 | | | | |
| WCA3 (T) | 0.53 ± 0.20 | 1.05 ± 0.28 | 0.52 ± 0.20 | 0.69 ± 0.26 | 7.31 ± 4.95 | 0 | 1 | 0 | 2,048 |
| | 0.17–1.52 | 0.43–2.39 | 0.23–1.80 | 0.19–1.88 | 0.91–33.72 | | | | |
| WCA4 (T) | 0.80 ± 0.15 | 2.72 ± 1.00 | 1.92 ± 1.00 | 1.21 ± 0.36 | 29.18 ± 10.45 | 0 | 0 | 0 | 142 |
| | 0.49–2.20 | 1.17–4.84 | 0.39–4.07 | 0.66–4.03 | 6.70–56.44 | | | | |
| WCA5(M) | 0.30 ± 0.12 | 0.44 ± 0.14 | 0.14 ± 0.05 | 0.35 ± 0.14 | 2.69 ± 1.14 | 0 | 0 | 0 | 1,010 |
| | 0.12–1.22 | 0.19–1.39 | 0.05–0.23 | 0.19–1.22 | 0.93–9.00 | | | | |
| WCA6 (T) | 0.45 ± 0.74 | 4.03 ± 1.14 | 3.58 ± 1.12 | 0.76 ± 0.81 | 36.88 ± 6.32 | 0 | 0 | 0 | 334 |
| | 0.12–0.65 | 0.85–8.40 | 0.70–7.96 | 0.19–7.22 | 4.58–48.55 | | | | |
| WCA7 (A) | 0.17 ± 0.16 | 1.25 ± 0.33 | 1.08 ± 0.35 | 0.24 ± 0.18 | 10.24 ± 3.22 | 0 | 0 | 0 | 504 |
| | 0.07–1.33 | 0.29–2.54 | 0.14–1.83 | 0.094–1.41 | 1.71–21.88 | | | | |
| WCA8 (A) | 0.17 ± 0.074 | 2.57 ± 0.62 | 2.40 ± 0.63 | 0.23 ± 0.13 | 46.47 ± 7.18 | 0 | 0 | 0 | 228 |
| | 0.10–0.63 | 0.55–3.27 | 0.40–3.14 | 0.19–0.66 | 12.13–59.60 | | | | |
| WCA9 (T) | 0.79 ± 0.36 | 3.85 ± 0.88 | 3.06 ± 1.03 | 1.22 ± 0.74 | 27.68 ± 13.76 | 0 | 0 | 0 | 370 |
| | 0.17–2.55 | 2.94–6.17 | 1.77–5.83 | 0.19–5.25 | 6.17–64.81 | | | | |
| WCA10 (T) | 0.26 ± 0.092 | 4.87 ± 0.19 | 4.62 ± 0.22 | 0.40 ± 0.25 | 50.41 ± 4.29 | 0 | 0 | 0 | 269 |
| | 0.15–0.85 | 4.43–5.59 | 4.01–5.41 | 0.19–2.91 | 26.57–70.53 | | | | |
| WCA11 (T) | 0.66 ± 0.53 | 6.56 ± 0.23 | 5.90 ± 2.49 | 1.97 ± 2.70 | 18.82 ± 8.24 | 0 | 0 | 0 | 4 |
| | 0.26–1.45 | 5.13–9.89 | 4.62–9.63 | 0.28–6.00 | 11.96–30.63 | | | | |
| WCA12 (A) | 1.85 ± 0.57 | 2.91 ± 0.80 | 1.06 ± 0.46 | 2.39 ± 0.93 | 6.61 ± 3.21 | 0 | 0 | 0 | 40 |
| | 1.00–3.61 | 1.56–4.64 | 0.30–2.40 | 1.22–3.84 | 2.04–14.09 | | | | |
| WCA13 (T) | 0.34 ± 0.35 | 0.78 ± 0.50 | 0.45 ± 0.25 | 0.43 ± 0.40 | 6.45 ± 5.23 | 0 | 0 | 0 | 43 |

**TABLE 1** (Continued)

| Call type | Minimum frequency (kHz) | Maximum frequency (kHz) | Frequency range (kHz) | Peak frequency (kHz) | Call duration | Ascent | Plume | Mid-call ascent | *N* |
|---|---|---|---|---|---|---|---|---|---|
| | 0.12–1.61 | 0.30–2.32 | 0.17–1.42 | 0.19–1.97 | 1.07–21.57 | | | | |
| WCA14 (S) | 0.42 ± 0.073 | 2.71 ± 0.87 | 2.29 ± 0.88 | 0.63 ± 0.17 | 5.04 ± 2.95 | 0 | 0 | 0 | 715 |
| | 0.18–1.09 | 0.70–7.04 | 0.49–5.95 | 0.19–2.81 | 1.11–29.77 | | | | |
| WCA15 (T) | 0.27 ± 0.10 | 4.52 ± 0.23 | 4.25 ± 0.22 | 0.42 ± 0.23 | 55.65 ± 10.52 | 0 | 0 | 1 | 73 |
| | 0.11–0.82 | 4.25–5.73 | 3.91–5.33 | 0.19–1.22 | 22.66–74.00 | | | | |
| WCA16 (T) | 2.07 ± 0.57 | 4.85 ± 1.57 | 2.78 ± 1.27 | 3.80 ± 1.58 | 9.50 ± 6.11 | 0 | 0 | 0 | 45 |
| | 1.06–3.38 | 2.73–9.80 | 1.06–6.82 | 1.22–7.22 | 2.28–30.79 | | | | |
| WCA17 (T) | 0.35 ± 0.051 | 6.11 ± 1.00 | 5.75 ± 1.02 | 1.39 ± 2.07 | 24.40 ± 2.11 | 1 | 0 | 1 | 163 |
| | 0.25–0.61 | 4.02–9.53 | 3.63–9.23 | 0.28–7.31 | 15.87–29.26 | | | | |
| WCA18 (T) | 2.58 ± 0.32 | 5.35 ± 1.25 | 2.77 ± 1.11 | 3.99 ± 1.61 | 8.64 ± 3.88 | 0 | 1 | 0 | 23 |
| | 1.66–3.33 | 3.48–8.37 | 1.42–5.32 | 0.28–7.31 | 1.57–17.85 | | | | |

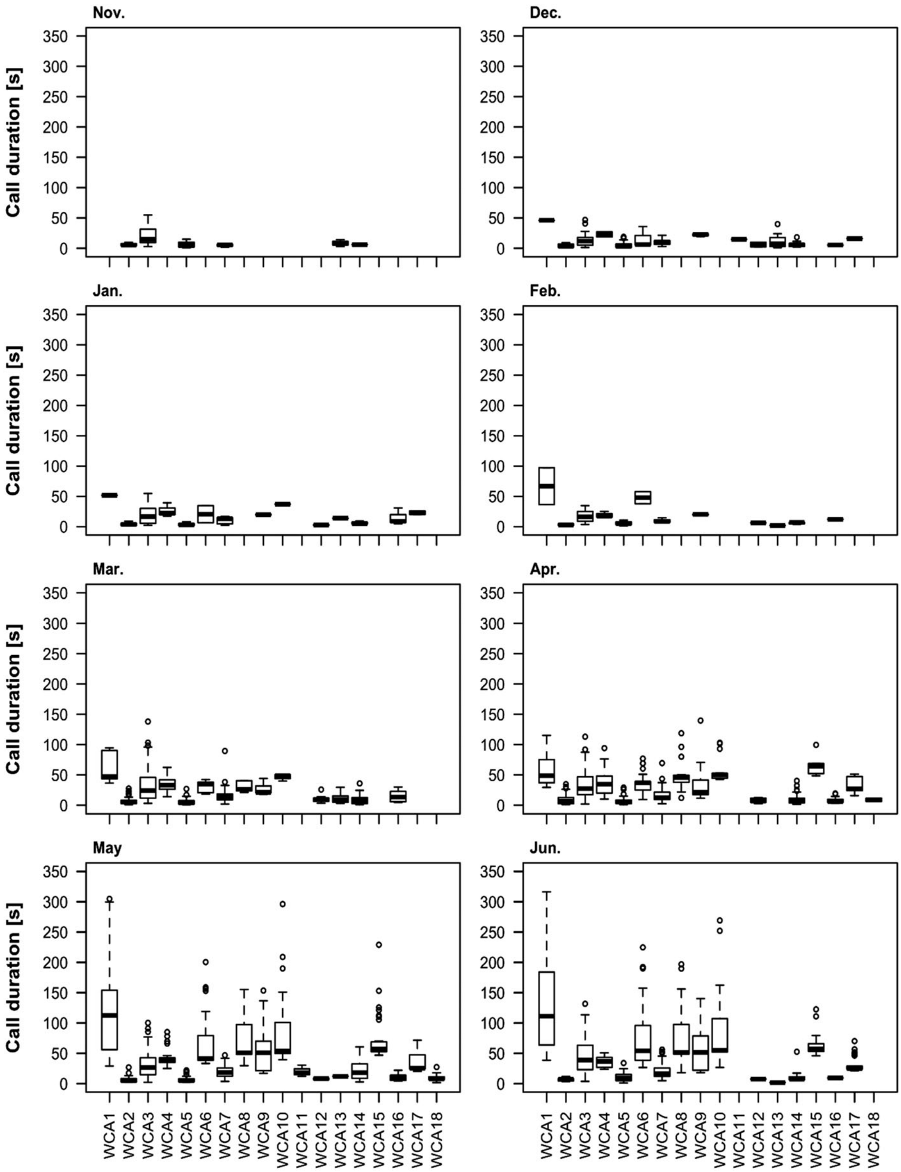

**FIGURE 3** Box plots for the total duration of each bearded seal (*Erignathus barbatus*) call type during each 300 s file in each month. The boxes represent the interquartile range, lines within the box are the mean, whiskers are 1.5 times the interquartile range, and outliers are indicated by dots.

technical issue when calculating received levels in Matlab. Signal-to-noise ratio generally increased throughout time, leading to the highest levels within the mating season ($\chi^2_{7,6846} = 1,349.3$, $p < .0001$).

Call duration was significantly higher ($p < .05$) during May and June, while there was no difference between February, March, and April. December and November showed shorter call durations compared to all other months ($p < .05$) except January. The longest individual call detected lasted 87.83 s. Overall, calls detected during May and June showed a wider range in frequencies in comparison to the other months, whereas calls in May covered a broader range than calls throughout June ($p < .0001$). Nearly no differences within monthly frequency ranges were observed between November, December, January, and February, except the comparison between November and

January ($p$ = .016), indicating a slightly broader range in January. March and April were significantly different from each other and differed from all other months except January and February. Both call duration and frequency range started to increase in March and April, indicating a transitional phase towards the most vocally active months (May and June).

Comparisons of minimum and maximum frequency showed significantly lower measurements in June. No significant differences could be detected between December, January, February, March, and April for the minimum frequency. November showed only significant differences compared to January ($p$ = .036). Minimum frequency was significantly higher in May compared to January, March, April, or June ($p$ < .0001). Maximum frequency displayed a different pattern. While calls in May reached a much higher maximum frequency compared to the other months ($p$ < .0001), calls in November showed a significantly lower maximum frequency compared with all months except December ($p$ = .48). Similar to the results for frequency range, no significant differences in maximum frequency values were found among December, January, and February.

No significant differences within received level were detected for November and February ($p$ = 1.00), whereas variation was similar to the parameter call duration for May and June, displaying significantly higher values for both months ($p$ < .0001). April displayed no differences compared to November and February ($p$ = 1.00 for both comparisons), however, significant differences were obtained between April and March ($p$ < .0001). March showed overall significantly lower values compared to the other months, except February ($p$ = .12). Although no significant differences were found between December and January ($p$ = .44), both months differed significantly from all other months ($p$ < .0001 and $p$ < .05, respectively). Signal-to-noise ratio was highest in June, showing significant differences to all other months ($p$ < .05). The lowest values were detected in both March and April ($p$ < .05), while May showed similar values compared to January and December ($p$ = 1.00) but was significantly different to all other months ($p$ < .05).

Seasonal examination of call type occurrence showed fluctuating call counts and presence between the distinct months (Figure 4). The most common call detected belonged to the category of trills, defined as WCA3 ($N$ = 2,048), followed by WCA5 moans ($N$ = 1,010), and sweeps of the call type WCA14 ($N$ = 715). Results of generalized linear models indicated variation for all four call categories between the different months. Presence of WCA3 trills was significantly higher during all mating months, as well as throughout December and March. WCA14 occurrence was significantly higher throughout April and May, whereas the cross-comparison between the months November, January, and February showed no significant differences. Lowest call rates for both calls were found in November, January, and February. Moans were significantly higher in June than in all other months, nevertheless significant variation was also detected between April and all other months except May.

The second most common trill, WCA1, was also significantly lower from November until March, and a significant increase of calls was detected from April on. Highest call numbers were present in May and June. Pairwise comparison demonstrated that WCA7 ascent was most common in May and June but lower throughout November until the end of February.

All remaining call types showed either no presence or very low numbers from November until the end of February, while highest counts were found in May and June, except for call types WCA2, WCA4, and WCA12, which showed significantly higher numbers throughout April. WCA8 ascents were only detected between March and June, with significantly higher counts in May and June. WCA15 trills were only recorded during the mating season, with the highest call counts in May, followed by June and April.

## 3.2 | Soundscape analysis

All models showed lower AIC values and higher adjusted $R^2$ values for multiple linear regressions including received level and sea ice as main predictors (Tables S1 and S2). In general, multiple linear regressions including call counts instead of call duration as an independent variable showed slightly lower AIC values (Table S3). SPL in both the 50–1,000 Hz and 1–10 kHz bands increased as received level increased (Figure 5). Additionally, the interaction

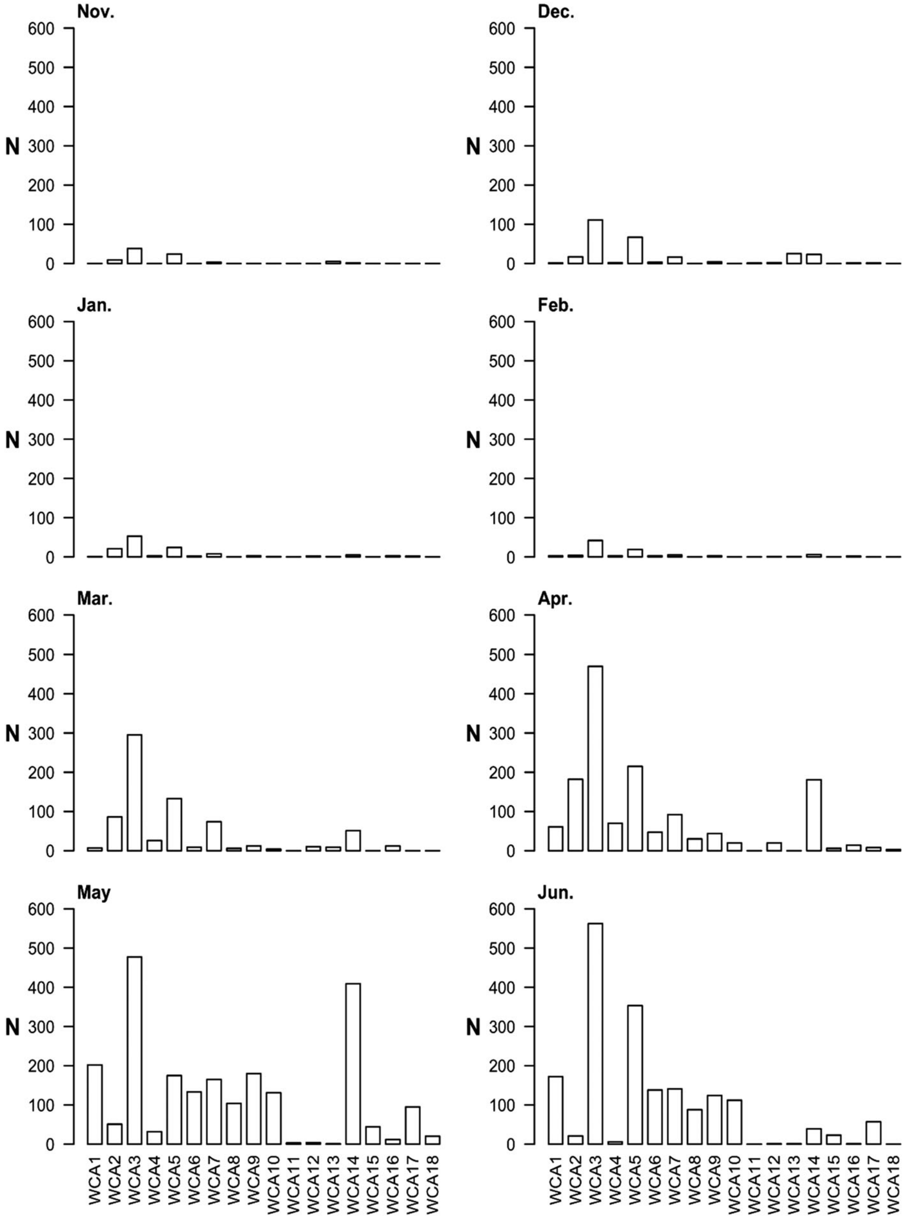

**FIGURE 4** Counts (*N*) of different bearded seal (*Erignathus barbatus*) call types in each month.

between either call count or call duration with received level was positive for both the 50–1,000 Hz and 1–10 kHz bands, but the models including call counts had a stronger effect (Figure 6; Tables S6 and S7). The main effects were slightly negative for both call duration (50–1,000 Hz slope = –0.072 ± 0.016, *p* < .0001; 1–10 kHz slope = –0.041 ±).017, *p* < .05) and call counts (50–1,000 Hz slope = –1.51 ± 0.30, *p* < .0001; 1–10 kHz slope = –1.55 ± 0.30, *p* < .0001, respectively), but this negative main effect was overshadowed by the positive interaction between received level and both call duration and call count (Figure 6). Depending on the inclusion of call duration or call counts into the linear regressions, varying effects on SPLs were detected. While a negative effect on SPL within the 1–10 kHz band was detected as the minimum frequency increased for linear regressions including either call

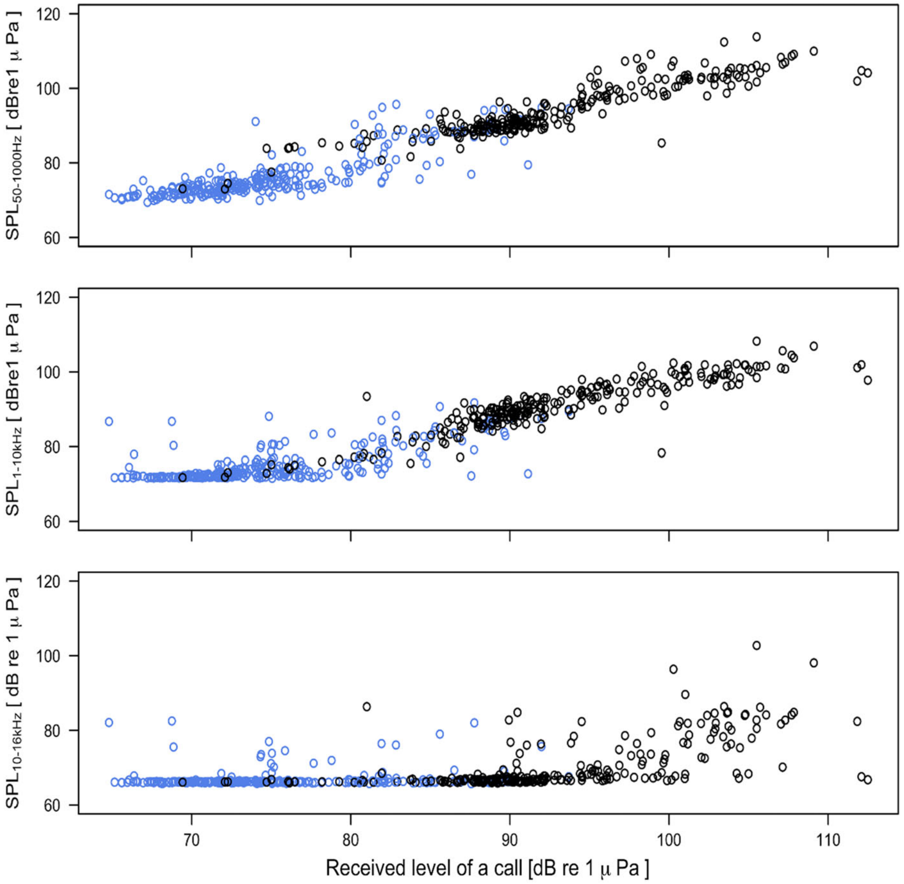

**FIGURE 5** The influence of bearded seal (*Erignathus barbatus*) call received level on sound pressure level (SPL) within three different frequency bands (50–1,000 Hz, 1–10 kHz, 10–16 kHz) relative to sea ice concentration.

duration (slope = –0.016, $p < .05$) or call counts (slope = –0.012, $p < .05$) as the independent variable, no effect could be detected for the 50–1,000 Hz band. Further, an increase in the maximum frequency also led to a negative effect on SPL in both bands, 50–1,000 Hz and 1–10 kHz, for linear regressions, including call counts (50–1,000 Hz slope = –0.00049, $p < .001$; 1–10 kHz slope = –0.0036, $p < .05$). Ice concentration had a negative interaction with both call duration and call count in the 1–10 kHz bands (ice concentration × call duration = –10.66 ± 2.51, $p < .0001$; ice concentration × call count = –15.34 ± 2.50, $p < .0001$). An increase in sweeps during low ice periods led to an increase in SPL for both the 50–1,000 Hz and 1–10 kHz bands with call duration included in the model, but only in the 50–1,000 Hz band when call counts was included as a predictor (Tables S6 and S7).

SPL in the 10–16 kHz band was best predicted by ice concentration, and bearded seal call characteristics were not positively related to SPL in this band. When examining all call types pooled together, SPL increased in the 50–1,000 Hz and 1–10 kHz bands as the number and duration of bearded seal calls increased, but not in the 10–16 kHz band (Figures 6 and 7).

Sea ice concentration as single predictor of SPL had a strong impact in the 50–1,000 Hz and 1–10 kHz bands, but a much weaker influence in the 10–16 kHz band ($R^2$ = 0.74 at 50–1,000 Hz, $R^2$ = 0.75 at 1–10 kHz, and $R^2$ = 0.12 at 10–16 kHz). In all three bands, increased sea ice concentration coincided with lower SPL (SPL at 50–1,000 Hz: slope = –0.25 ± 0.003, $p < .0001$; SPL at 1–10 kHz: slope = –0.22 ± 0.003, $p < .0001$; SPL at 10–16 kHz: slope = –0.05 ± 0.003, $p < .0001$).

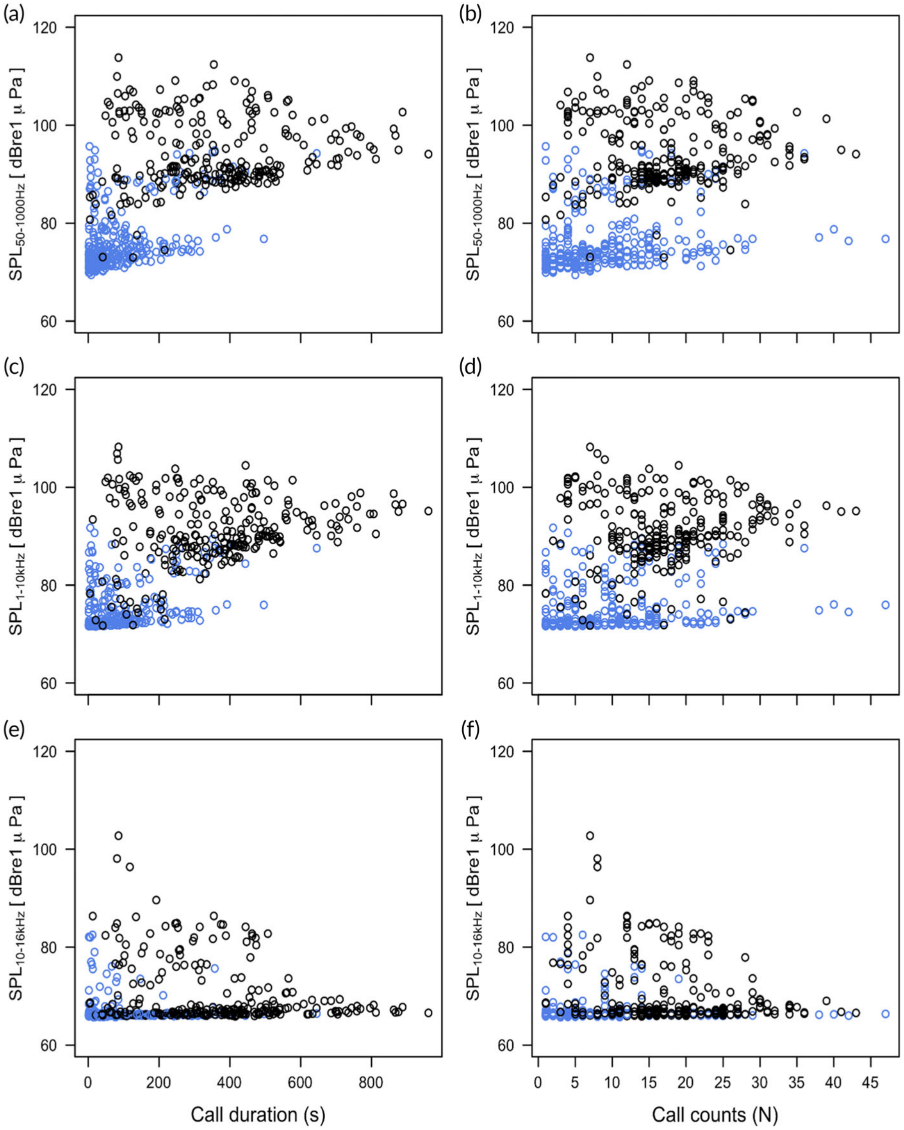

**FIGURE 6** Influence of bearded seal (*Erignathus barbatus*) call duration (a, c, e) and call count (b, d, f) on sound pressure level (SPL) within three different frequency bands (50–1,000 Hz, 1–10 kHz, 10–16 kHz) relative to sea ice concentration.

### 3.3 | Manual vs. automated call counts in the soundscape analysis

Comparison between manually detected call counts and automated call counts showed a positive relationship ($R^2$ = 0.48, intercept = 4.03 ± 0.51 calls, $t_{511}$ = 7.87, $p < .0001$; auto calls slope = 0.99 ± .05 calls, $t_{511}$ = 21.70, $p < .0001$). Including wind speed and ice concentration in the model added more strength to the relationship ($R^2$ = 0.51, intercept = 8.48 ± 0.96 calls, $t_{509}$ = 8.80, $p < .0001$; auto calls slope = 0.91 ± .05 calls, $t_{509}$ = 17.73, $p < .0001$; wind speed slope = –0.09 ± 0.03 calls/km/hr, $t_{509}$ = 3.41, $p < .001$; ice concentration slope = –0.04 ± 0.001 calls/percent, $t_{509}$ = 4.35, $p < .0001$). Broadband SPL also predicted changes in manual call counts, but was not significant when included in models with wind speed and ice concentration. Overall, this analysis shows that the

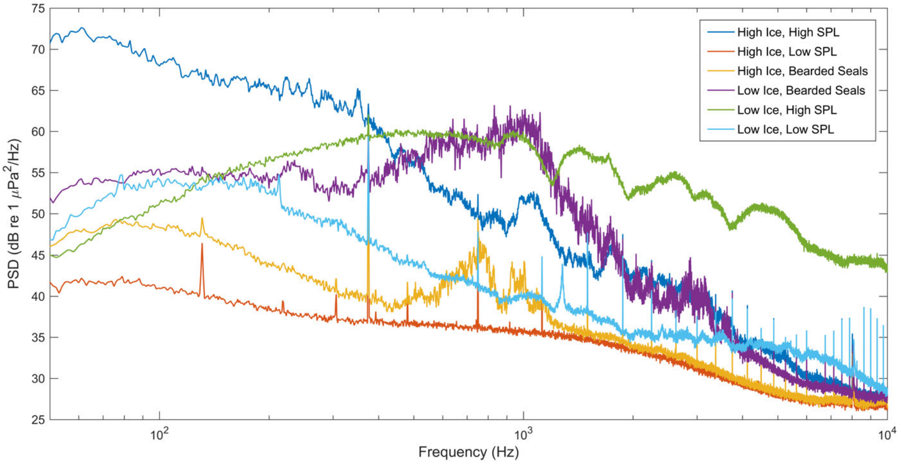

**FIGURE 7** Median power spectral densities (PSD) between 50 Hz and 10 kHz for five-minute acoustic recordings under high ice and low ice concentration in the absence of bearded seals (*Erignathus barbatus*) (low and high sound pressure levels, SPL) and in the presence of many bearded seal vocalizations. Note that the file with bearded seals present and high ice concentration had 40 calls that lasted a total of 312 s, and the low ice concentration file had 43 calls that lasted a total of 846 s.

automated call counts account for nearly 50% of the variance in manual call counts, but wind speed and ice concentration both account for significant variation in the relationship.

Sound pressure levels in the 50–1,000 Hz band increased as the number of automated call counts increased ($R^2$ = 0.18, intercept = 78.16 ± 0.25 dB, $t_{5,295}$ = 313.66, $p < .0001$; slope = 0.77 ± 0.02 dB, $t_{5,295}$ = 34.19, $p < .0001$) and similarly increased in the 1–10 kHz band as call counts increased ($R^2$ = 0.12, intercept = 77.71 ± .24 dB, $t_{5,295}$ = 328.97, $p < .0001$; slope = 0.58 ± 0.02 dB, $t_{5,295}$ = 27.34, $p < .0001$); however, call counts had no meaningful influence on SPL in the 10–16 kHz band, despite a slight statistically significant relationship ($R^2 < .01$, intercept = 68.53 ± .14 dB, $t_{5,295}$ = 494.94, $p < .0001$; slope = 0.03 ± .01 dB, $t_{5,295}$ = 2.05, $p = .04$). When automated call counts were adjusted by their relationship with manual call counts, wind speed, and ice concentration, the relationship strengthened and shifted slightly in both the 50–1,000 Hz band (intercept = 80.87 ± .16 dB, $t_{5,295}$ = 503.87, $p < .0001$; slope = 0.94 ± 0.02 dB, $t_{5,295}$ = 45.71, $p < .0001$, $R^2$ = 0.28) and the 1–10 kHz band (intercept = 79.59 ± 0.15 dB, $t_{5,295}$ = 516.92, $p < .0001$; slope = 0.75 ± 0.02 dB, $t_{5,295}$ = 38.02, $p < .0001$, $R^2$ = 0.21), and had the same relationship in the 10–16 kHz band.

## 4 | DISCUSSION

This study represents a detailed examination of the vocal repertoire of bearded seals at one site in the western Canadian Arctic, as well as their influence on sound pressure levels and the soundscape. Bearded seals showed a clear seasonal pattern in call types, where some call types were only used during the mating season, whereas others were used in every month. According to MacIntyre et al. (2013) vocal bearded seals inhabiting the Beaufort Sea are present nearly year-round. This coincided largely with call occurrence examined in this study. While low call rates were found during November until February/March (with lowest detections in November), call presence increased significantly throughout the following months. Similar results were obtained by MacIntyre et al. (2013) for bearded seals recorded at another site within the Beaufort Sea, showing lowest call rates during November followed by an increase mid-December and a peak of vocal activity in May. Contradictory, to MacIntyre's study, no calls were detected in this study after a sudden stop at the end of June until end of September, when seals re-established their vocal activity. However, without additional years of data, we do not know how common this pattern is at this particular site.

Bearded seals are known to be ice-obligate (Moore & Huntington, 2008). Greatest call counts were found when ice concentration was <50%. Mid-March and the beginning of April showed ice concentrations >95%, while a rapid decline in ice coverage was measured around April 20, 2016, leading to a minimum ice cover of 7% by June 21. This observation was somewhat contradictory to observations made by MacIntyre et al. (2013), who correlated highest call rates with ice cover of 100%, but is directly in line with observations by Van Parijs, Lydersen, and Kovacs (2004) showing an increased number of vocalizing males and increased vocalizations during lower ice concentrations. Although ice break-up occurred earlier in the year during this study, interannual variation is not uncommon in the Arctic and seals are likely to adapt to these fluctuations (Laidre et al., 2008; Moore & Huntington, 2008; Van Parijs et al., 2004). The phenology of peak vocalizations may not even be linked to ice cover, but rather to reproductive cycles of females (i.e., when females are receptive to mating). Moreover, a recent study showed that bearded seals prefer habitats characterized by sea ice cover even as low as 25% (Ver Hoef, Cameron, Boveng, London, & Moreland, 2014). Low levels and rapid decline of ice cover caused by global warming pose a greater threat to ice obligate species in terms of adaptation, than to seasonally migrating species (Moore & Huntington, 2008). Warming is further thought to result in an accelerated ice breakup in spring and postponed freeze-up later in the year, that will consequently limit available habitats used by bearded seals for breeding, molting, or simply as a haul-out site (Moore & Huntington, 2008).

Increased call activity, which was observed throughout spring months (mid-March until late May/mid-June), coincides with the mating season (Frouin-Mouy et al., 2016; Hannay et al., 2013; MacIntyre et al., 2013) and has been demonstrated in many other aquatic pinnipeds, e.g., ribbon seals, *Histriophoca fasciata*; Frouin-Mouy et al. (2019); leopard seals, *Hydrurga leptonyx*, and crabeater seals, *Lobodon carcinophaga*; Van Opzeeland et al. (2010), and for Weddell seals, *Leptonychotes weddellii*; Rouget, Terhune, & Burton (2007). Published evidence to date suggests that vocalizations are most likely only produced by male bearded seals (Burns, 1981; Van Parijs et al., 2001, 2004) after they reach sexual maturity (Davies et al., 2006), although no evidence has been found so far to rule out potential female vocalizations. According to previous studies, increased levels of vocalization can be caused by two events. First, as demonstrated within other aquatic species (Tripovich, Rogers, & Dutton, 2009), males increase their calling rates due to changing hormone levels during the mating period. Second, Van Parijs, Lydersen, & Kovacs, (2003) showed an overlap of territory occupancy by male individuals, meaning increased call activity is caused by a higher number of males. These two hypotheses are not mutually exclusive and could both be occurring.

Similar to previous studies in the western Canadian Arctic (Risch et al., 2007) and Chukchi Sea (Frouin-Mouy et al., 2016; Jones et al., 2014), the most common calls detected were trills (63.5%). Additionally, as in Risch et al. (2007), moans were the second most detected calls with 14.8%. Contrary to Risch et al. (2007), sweeps (classified as WCA14) were mainly detected throughout the mating season, with a peak in May, and showed only 10.4% occurrence. An enlarged composition of call types during the mating season was also observed, and this result was similar to one study of bearded seals in the Chukchi Sea (Frouin-Mouy et al., 2016), and also in harp seals (*Pagophilus groenlandicus*; Serrano & Miller, 2000), which introduced new call types during the mating period. While trills occurred throughout the entire period of recordings in this study, sweeps, moans, and ascents showed higher temporal fluctuation, and were most common during the mating period.

This study revealed monthly variation in call parameters. Both frequency-related parameters as well as call duration showed a broader range from April until June. Longer call durations were also documented for male calls in the Chukchi Sea (Frouin-Mouy et al., 2016) and around Svalbard (Van Parijs et al., 2001), suggesting that trill duration may be used as a proxy for male breeding quality in bearded seals (Van Parijs et al., 2003). Males likely increased their call duration and frequency range during the mating season to attract females from a farther distance, especially under the influence of limiting ambient sound levels (Frouin-Mouy et al., 2016). Typical propagation range for trills is reported as 5–10 km, but can reach distances over 20–45 km under perfect conditions (Cleator et al., 1989; Stirling, Calvert, & Cleator, 1983). Similar observations were made for received level of calls in our study, with the highest levels within the period of low sea ice (May and June). This pattern of increased received levels during the mating season could be caused by a number of factors, including: increased source levels of vocalizations as males are actively competing for mates during the breeding season; males coincidentally located closer to the acoustic recorder during the mating season; or even frequency-dependent attenuation of acoustic signals (especially for high frequency signals) interacting with the sea during the winter (LePage and Schmidt, 1994; Thode, Kim, Greene, & Roth, 2010), thereby reducing received levels of calls. For this latter pattern, however, we might expect a stronger correlation between received level and maximum frequency during periods of reduced ice compared with periods of solid ice as high frequency sounds have greater levels of attenuation when reflecting against sea ice (Au & Hastings, 2008), yet instead we found a very low correlation between received level and maximum frequency in the full data set ($r = 0.21$), under solid sea ice in March ($r = 0.16$), or under low sea ice in May ($r = -0.09$). Increased attenuation of high frequency signals may similarly affect estimates of call duration, which could explain the seasonal patterns that we found in these variables, but we also found low correlations between call duration and received level ($r = 0.30$). The increase in the signal-to-noise-ratio within this breeding period also provides evidence that bearded seals are either increasing the source levels of their vocalizations or were located closer to the acoustic recorder during the breeding period.

Overall, bearded seal vocalizations had a variety of impacts on SPL in the 50–1,000 Hz and 1–10 kHz frequency bands, but not in the 10–16 kHz band. This result was not surprising as bearded seal vocalizations are known to mainly range between 130 Hz and 6 kHz (Cleator et al., 1989). The contribution of bearded seal vocalizations to the soundscape was much stronger during periods of low ice concentration. The observed variation in SPL from all months of this study is likely mainly driven by changes in wind speed and ice concentration (Southall et al., 2020), but seals did have some influence on SPL, particularly during the breeding season when the signal-to-noise ratio and received levels of their vocalizations increased the most (Figures 5–7). Because bearded seal calls range mainly within these two frequency bands, displaying a positive relationship between SPL and both call duration and maximum frequency was expected, and was demonstrated in this study. Additionally, the observed lack of positive interaction between call duration or call counts and sound level at 10–16 kHz further supported these expectations. This same trend was found when using the automated call counts, which showed that bearded seal vocalizations explained 18% and 12% of the variance in SPL in the 50–1,000 Hz and 1–10 kHz bands throughout this study.

## 4.1 | Conclusions

By evaluating a large number of acoustic recordings, this study demonstrated both a seasonal and monthly dynamic in bearded seal vocalizations as well as their impact on the soundscape in the Canadian Beaufort Sea. Even though most findings of bearded seal vocal behavior were consistent with previous studies at other sites, new insights were found for this particular area, including new vocalizations and how vocalizations influence local sound pressure levels. Future studies should closely monitor bearded seal vocal behavior relative to sea ice dynamics as an important aspect of how the soundscape may change in response to climate change.

## ACKNOWLEDGMENTS

We are grateful to the people of Sachs Harbour, specifically the Sachs Harbour Hunters and Trappers Committee, W. Gully, B. Hoagak, T. Lennie, J. Kudak, and J. Kuptana, as well as the Captain and crew of the HMCS *Saskatoon* and the Royal Canadian Navy Fleet Dive Unit Pacific, for their assistance with the deployment and recovery of the acoustic recorder. We also thank the Associate Editor, V. Lesage, and two reviewers, J. Jones and an anonymous reviewer, for providing constructive feedback that improved the quality of this study. This project was funded by The W. Garfield Weston Foundation, the MEOPAR (Marine Environmental Observation, Prediction, and Response) Network of Centres of Excellence, the Liber Ero Foundation, and the World Wildlife Fund.

## AUTHOR CONTRIBUTIONS

**Annika Heimrich:** Conceptualization; formal analysis; investigation; methodology; visualization; writing-original draft; writing-review and editing. **William Halliday:** Conceptualization; formal analysis; investigation; methodology; project administration; supervision; validation; visualization; writing-original draft; writing-review and editing. **Heloise Frouin-Mouy:** Methodology; validation; writing-review and editing. **Matthew Pine:** Formal analysis; writing-review and editing. **Francis Juanes:** Supervision; writing-review and editing. **Steve Insley:** Data curation; funding acquisition; project administration; writing-review and editing.

## ORCID

*Annika F. Heimrich* https://orcid.org/0000-0001-5512-1107
*William D. Halliday* https://orcid.org/0000-0001-7135-076X
*Héloïse Frouin-Mouy* https://orcid.org/0000-0003-2693-1105
*Matthew K. Pine* https://orcid.org/0000-0002-7289-7115
*Francis Juanes* https://orcid.org/0000-0001-7397-0014
*Stephen J. Insley* https://orcid.org/0000-0003-3402-8418

## REFERENCES

Au, W. W. L., & Hastings, M. C. (2008). *Principles of marine bioacoustics*. New York, NY: Springer Science+Business Media.

Bioacoustics Research Program. (2017). *Raven Pro: Interactive sound analysis software (Version 1.5)*. Ithaca, NY: Cornell Lab of Ornithology.

Burns, J. J. (1981). Bearded seal *Erignathus barbatus* (Erxleben, 1777). In S. H. Ridgway & R. J. Harrison (Eds.), *Handbook of marine mammals* (Vol. 2, pp. 145–170). London, UK: Academic Press.

Clark, C. W., Berchok, C. L., Blackwell, S. B., Hannay, D. E., Jones, J., Ponirakis, D., & Stafford, K. M. (2015). A year in the acoustic world of bowhead whales in the Bering, Chukchi and Beaufort seas. *Progress in Oceanography*, *136*, 223–240.

Cleator, H. J., & Stirling, I. (1990). Winter distribution of bearded seals (*Erignathus barbatus*) in the Penny Strait area, Northwest Territories, as determined by underwater vocalizations. *Canadian Journal of Fisheries and Aquatic Sciences*, *47*, 1071–1076.

Cleator, H. J., Stirling, I., & Smith, T. G. (1989). Underwater vocalizations of the bearded seal (*Erignathus barbatus*). *Canadian Journal of Zoology*, *67*, 1900–1910.

Cotter, A. J. R. (2008). The "soundscape" of the sea, underwater navigation, and why we should be listening more. In A. I. L. Payne, A. J. R. Cotter, & E. C. E. Potter (Eds.), *Advances in fisheries science: 50 years on from Beverton and Holt* (pp. 451–471). Oxford, UK: Blackwell Publishing.

Davies, C. E., Kovacs, K. M., Lydersen, C., & Van Parijs, S. M. (2006). Development of display behavior in young captive bearded seals. *Marine Mammal Science*, *22*, 952–965.

Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., & Johnston, M. E. (2017). Temporal and spatial patterns of ship traffic in the Canadian arctic from 1990 to 2015. *Arctic*, *71*(1), S1–S7.

Ellison, W. T., Southall, B. L., Clark, C. W., & Frankel, A. S. (2011). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology*, *26*(December), 21–28.

Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., & Dooling, R. (2016). Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin*, *103*(1–2), 15–38.

Frouin-Mouy, H., Mouy, X., Berchok, C. L., Blackwell, S. B., & Stafford, K. M. (2019). Acoustic occurrence and behavior of ribbon seals (*Histriophoca fasciata*) in the Bering, Chukchi, and Beaufort seas. *Polar Biology*, *42*, 657–674.

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

Gomez, C., Lawson, J. W., Wright, A. J., Buren, A. D., Tollit, D., & Lesage, V. (2016). A systematic review on the behavioural responses of wild marine mammals to noise: The disparity between science and policy. *Canadian Journal of Zoology*, *94*, 801–819.

Halliday, W. D., Insley, S. J., de Jong, T., & Mouy, X. (2018). Seasonal patterns in acoustic detections of marine mammals near Sachs Harbour, Northwest Territories. *Arctic Science*, *4*, 259–278.

Halliday, W. D., Pine, M. K., Insley, S. J., Soares, R. N., Kortsalo, P., & Mouy, X. (2019). Acoustic detections of Arctic marine mammals near Ulukhaktok, Northwest Territories. *Canadian Journal of Zoology*, *97*, 72–80.

Hannay, D. E., Delarue, J., Mouy, X., Martin, B. S., Leary, D., Oswald, J. N., & Vallarta, J. (2013). Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011. *Continental Shelf Research*, *67*, 127–146.

Heide-Jørgensen, M. P., Burt, L. M., Hansen, R. G., Nielsen, N. H., Rasmussen, M., Fossette, S., & Stern, H. (2013). The significance of the North Water polynya to Arctic top predators. *Ambio*, *42*, 596–610.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., & Veirs, S. (2009). Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *Journal of the Acoustical Society of America*, *125*, EL27–EL32.

Insley, S. J., Halliday, W. D., & de Jong, T. (2017). Seasonal patterns in ocean ambient noise near Sachs Harbour, Northwest Territories. *Arctic*, *70*, 239–248.

Jones, J. M., Thayre, B. J., Roth, E. H., Mahoney, M., Sia, I., Merculief, K., … Hildebrand, J. A. (2014). Ringed, bearded, and ribbon seal vocalizations north of Barrow, Alaska: Seasonal presence and relationship with sea ice. *Arctic*, *67*, 203–222.

Laidre, K. L., Heide-Jørgensen, M. P., Heagerty, P., Cossio, A., Bergström, B., & Simon, M. (2010). Spatial associations between large baleen whales and their prey in West Greenland. *Marine Ecology Progress Series*, *402*, 269–284.

Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, Ø., Heide-Jørgensen, M. P., & Ferguson, S. H. (2008). Quantifying the sensitivity of arctic marine mammals to climate-induced habitat change. *Ecological Applications*, *18*(sp2), 97–125.

LePage, K., & Schmidt, H. (1994). Modeling of low frequency transmission loss in the central Arctic. *Journal of the Acoustical Society of America*, *96*, 1783–1795.

MacIntyre, K. Q., Stafford, K. M., Berchok, C. L., & Boveng, P. L. (2013). Year-round acoustic detection of bearded seals (*Erignathus barbatus*) in the Beaufort Sea relative to changing environmental conditions, 2008–2010. *Polar Biology*, *36*, 1161–1173.

Marcoux, M., Auger-Methe, M., & Humphries, M. M. (2012). Variability and context specificity of narwhal (*Monodon monoceros*) whistles and pulsed calls. *Marine Mammal Science*, *28*, 649–665.

Melcón, M. L., Cummins, A. J., Kerosky, S. M., Roche, L. K., Wiggins, S. M., & Hildebrand, J. A. (2012). Blue whales respond to anthropogenic noise. *PLoS ONE*, *7*(2), e32681.

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E. (2015). Measuring acoustic habitats. *Methods in Ecology and Evolution*, *6*, 257–265.

Moore, S. E., & Huntington, H. P. (2008). Arctic marine mammals and climate change: Impacts and resilience. *Ecological Applications*, *18*(sp2), 157–165.

Mouy, X., Oswald, J. N., Leary, D., Delarue, J., Vallarta, J., Rideout, B., … Martin, B. (2013). Passive acoustic monitoring of marine mammals in the Arctic. In O. Adam & F. Samaran (Eds.), *Detection, classification, localization of marine mammals using passive acoustics* (pp. 185–224). Paris, France: Dirac NGO.

Nowacek, D. P., Thorne, L. H., Johnston, D. W., & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammal Review*, *37*(2), 81–115.

Pijanowski, B. C., Villanueva-Rivera, L. J., Dumyahn, S. L., Farina, A., Krause, B. L., Napoletano, B. M., … Pieretti, N. (2011). Soundscape ecology: The science of sound in the landscape. *BioScience*, *61*, 203–216.

Protection of the Arctic Marine Environment. (2019). *Underwater noise in the Arctic: A state of knowledge report*. Akureyri, Iceland: Protection of the Arctic Marine Environment (PAME) Secretariat.

R Core Team. (2016). *R: A language and environment for statistical computing (Version 3.3.0)*. Vienna, Austria: R Foundation for Statistical Computing.

Risch, D., Clark, C. W., Corkeron, P. J., Elepfandt, A., Kovacs, K. M., Lydersen, C., … Van Parijs, S. M. (2007). Vocalizations of male bearded seals, *Erignathus barbatus*: classification and geographical variation. *Animal Behaviour*, *73*, 747–762.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., … Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1737), 2363–2368.

Roth, E. H., Hildebrand, J. A., Wiggins, S. M., & Ross, D. (2012). Underwater ambient noise on the Chukchi Sea continental slope from 2006–2009. *Journal of the Acoustical Society of America*, *131*, 104–110.

Rouget, P. A., Terhune, J. M., & Burton, H. R. (2007). Weddell seal underwater calling rates during the winter and spring near Mawson Station, Antarctica. *Marine Mammal Science*, *23*, 508–523.

Serrano, A., & Miller, E. H. (2000). How vocal are harp seals (*Pagophilus groenlandicus*)? A captive study of seasonal and diel patterns. *Aquatic Mammals*, *26*, 253–259.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., … Tyack, P. L. (2007). Marine mammal noise-exposure criteria: Initial scientific recommendations. *Aquatic Mammals*, *33*, 411–522.

Southall, B. L., Southall, H., Antunes, R., Nichols, R., Rouse, A., Stafford, K. M., … Rosenbaum, H. C. (2020). Seasonal trends in underwater ambient noise near St. Lawrence Island and the Bering Strait. *Marine Pollution Bulletin*, *157*, 111283.

Spreen, G., Kaleschke, L., & Heygster, G. (2008). Sea ice remote sensing using AMSR-E 89-GHz channels. *Journal of Geophysical Research: Oceans*, *113*, C02S03.

Stafford, K. M., Castellote, M., Guerra, M., & Berchok, C. L. (2018). Seasonal acoustic environments of beluga and bowhead whale core-use regions in the Pacific Arctic. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *152*, 108–120.

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

Thode, A., Kim, K. H., Greene, C. R., & Roth, E. (2010). Long range transmission loss of broadband seismic pulses in the Arctic under ice-free conditions. *Journal of the Acoustical Society of America*, *128*, EL181–EL187.

Tripovich, J. S., Rogers, T. L., & Dutton, G. (2009). Faecal testosterone concentrations and the acoustic behaviour of two captive male Australian fur seals. *Australian Mammalogy*, *31*, 117–122.

Van Opzeeland, I., Van Parijs, S., Bornemann, H., Frickenhaus, S., Kindermann, L., Klinck, H., … Boebel, O. (2010). Acoustic ecology of Antarctic pinnipeds. *Marine Ecology Progress Series*, *414*, 267–291.

Van Parijs, S. M., Kovacs, K. M., & Lydersen, C. (2001). Spatial and temporal distribution of vocalising male bearded seals: Implications for male mating strategies. *Behaviour*, *138*, 905–922.

Van Parijs, S. M., Lydersen, C., & Kovacs, K. M. (2003). Vocalizations and movements suggest alternative mating tactics in male bearded seals. *Animal Behaviour*, *65*, 273–283.

Van Parijs, S. M., Lydersen, C., & Kovacs, K. M. (2004). Effects of ice cover on the behavioural patterns of aquatic-mating male bearded seals. *Animal Behaviour*, *68*, 89–96.

Ver Hoef, J. M., Cameron, M. F., Boveng, P. L., London, J. M., & Moreland, E. E. (2014). A spatial hierarchical model for abundance of three ice-associated seal species in the eastern Bering Sea. *Statistical Methodology*, *17*, 46–66.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Heimrich AF, Halliday WD, Frouin-Mouy H, Pine MK, Juanes F, Insley SJ. Vocalizations of bearded seals (*Erignathus barbatus*) and their influence on the soundscape of the western Canadian Arctic. *Mar Mam Sci*. 2021;37:173–192. https://doi.org/10.1111/mms.12732