JASA Express Letters

DECEMBER 01 2025

Ice-generated sound and its potential masking effects on bearded seal vocalizations in the western Canadian Arctic

Najeem Shajahan; William D. Halliday; Cierra Hart; Ruwan Abeywardhana; Fabio Frazao;
David R. Barclay; Andrea Niemi; Stephen J. Insley

JASA Express Lett. 5, 127701 (2025)
https://doi.org/10.1121/10.0039964

JASA EXPRESS LETTERS ARTICLE asa.scitation.org/journal/jel

Ice-generated sound and its potential masking effects on bearded seal vocalizations in the western Canadian Arctic

Najeem Shajahan,[1,2,a)] William D. Halliday,[1,2] Cierra Hart,[1,2] Ruwan Abeywardhana,[3] Fabio Frazao,[3] David R. Barclay,[4] Andrea Niemi,[5] and Stephen J. Insley[1,6]
[1]Wildlife Conservation Society Canada, 169 Titanium Way, Whitehorse, Yukon Territory Y1A 0E9, Canada
[2]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia V8P 3E6, Canada
[3]Faculty of Computer Science, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada
[4]Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada
[5]Freshwater Institute, Fisheries and Oceans Canada, Winnipeg, Manitoba R3T 2N6, Canada
[6]Department of Biology, University of Victoria, Victoria, British Columbia V8P 3E6, Canada

Note: This article is part of a Special Issue on Climate Change: How the Sound of the Planet Reflects the Health of the Planet.

Abstract: Quantifying acoustic masking due to noise sources is an important part of marine mammal conservation. This study examines the relative masking of bearded seal vocalizations by ice-generated sounds, using passive acoustic data collected from the western Canadian Arctic. Broadband ice sound events and bearded seal calls were extracted from acoustic recordings, and masking potential was estimated using the listening space reduction (LSR) metric, based on the bearded seal audiogram and propagation loss in an ice-covered environment. Results indicate that bearded seal vocal activity decreased with increasing LSR and ambient sound exposure levels, suggesting a potential behavioural adjustment to elevated ice sound levels that warrants further investigation.

[Editor: Charles C. Church] https://doi.org/10.1121/10.0039964

Received: 21 August 2025 **Accepted:** 11 November 2025 **Published Online:** 1 December 2025

1. Introduction

Ocean ambient noise (also called ambient sound) is the resultant complex sound field from natural, biological, geological, and anthropogenic sources. In a seasonally ice-covered ocean, such as the Arctic, natural, and biological sources, contribute the most to ambient sound levels.[1] Wind-driven processes at the ocean's surface (e.g., waves, bubble formation) are a major natural source of sound in the Arctic, with wind speed and sound level showing a positive correlation ($r^2 = 0.28$) when ice concentrations are high (75%–100%).[2–4] Low ice concentrations (0%–25%) increase ambient sound levels substantially (≈ 10 **dB**) in the Arctic, showing a high positive correlation ($r^2 = 0.6$) between wind speed and sound level.[2] Endemic Arctic marine mammals (bowhead whales, beluga whales, narwhals, bearded seals, walruses, and ringed seals), which rely on both acoustic cues and ice cover for navigation, foraging, and resting, are the major biological sources of sound in the Arctic.[5] Another prominent source of ambient sound in the Arctic during winter is ice-generated sound, which is generally discrete in nature.[6] Environmental factors, such as air temperature, water currents, wind, and ice concentration and draft affect sea ice dynamics, resulting in ice cracking, ridging, melting and ice floe collisions that generate transient acoustic signals.[7] The duration of these events typically lasts a few seconds (short-term) to several minutes (long-term) and can exhibit both broadband and narrowband characteristics. The short-term and long-term broadband events indicate cracking and intensive fracturing of ice, while the long-term narrow band events indicate the interaction (rubbing, grinding) between ice floes due to wind, wave, and current forces.[8]

The Arctic has warmed faster than the rest of the world oceans in the last few decades due to climate change.[9] Sea ice extent has decreased by around 4.2% per decade in the summer (September), and by 0.7% in the winter (March).[10] Climate change has also accelerated the transition from multiyear ice to first-year ice.[11] Cracking and ridging resulting from the increased mobility and deformation of thinner first-year ice occur more frequently. Consequently, the ambient soundscape shows a strong correlation ($r = 0.7$) with distant cryogenic events, indicating a substantial contribution from ice-generated sounds.[12]

Broadband ice-generated sound events may overlap (both spectrally and temporally) and mask marine mammal vocalizations, particularly those of bearded seals due to the frequency characteristics of their vocalizations.[13] Masking occurs when the detection of a sound of interest is reduced by the presence of another sound that overlaps in time and frequency.[14] Bearded seals

a)Corresponding author: najeemtkm@gmail.com

are endemic Arctic marine mammals with stereotypical vocalizations, including trills, ascents, sweeps, and moans, used for breeding and holding territory.[13,15] These calls usually range in frequency from 0.1 to 6.5 kHz and last from 1 s to >1 min, with certain call type (trills) reaching frequencies as high as 10 kHz.[13,16,17] Vocalizations are believed to be used in advertising reproductive status, attracting mates, and defending underwater territories. Male bearded seals use their vocalizations to attract mates,[18] and masking could interfere with the ability of males to successfully reproduce. Bearded seals can also be a dominant contributor to the soundscape during late winter (March) and the spring breeding season (April–May), when they can call 24 h/day.[13,15] The shift in ice conditions being caused by climate change has the potential to alter the soundscape during late winter and spring—a period that is critical to the reproduction for bearded seals.

Passive acoustic data can be used to investigate whether ice-generated sounds reduce the available listening space of bearded seals. The listening space of an animal represents the area or volume of the surrounding environment within which a sound of interest is detectable by the animal's auditory system. The listening space reduction (LSR) can be understood as the spatial indication of auditory masking, quantifying how increases in ambient noise due to an external source reduce the area over which a signal is detectable.[19,20] To understand the impact of climate change and the associated shifts in sea ice dynamics on the acoustic habitat of Arctic marine mammals, the LSR metric provides an easily calculable approach, as it requires only minimal inputs, such as passive acoustic data, an estimated propagation loss (PL) slope, and the animal's audiogram. In this study, passive acoustic data collected during late winter from Cape Bathurst, a marine mammal hotspot in the western Canadian Arctic, were used to investigate the reduction in listening space of bearded seals due to ice-generated sound.

2. Methods

2.1 Acoustic data collection and processing

Passive acoustic data collected in the Amundsen Gulf from September 29, 2023 to October 3, 2024 near Cape Bathurst, Northwest Territories, Canada were used for the analysis. Figure 1(a) shows the location of the moored acoustic recorder, at 70.6811° N, 126.87° W. A bottom-mounted acoustic recorder positioned at 300 m depth in a 303 m water column was used to record data. The recorder used was an Ocean Instruments NZ Limited SoundTrap ST600 STD (Auckland, New Zealand) and data were recorded for 5 min every half hour at a sampling rate of 48 kHz using the high gain setting, which adds 12.5 dB. Even though year-round recordings of ambient sound covering both summer and winter were available, only 2 months of acoustic data, specifically March and April, were analyzed. These 2 months include the overlap of increased bearded seal call activity due to the early mating season and increased ice sound events due to motion of late winter ice.[13] Satellite-derived data of ice concentrations of this region (100 km radius around the recording site) indicated > 90% ice cover during this period.[21]

During late winter in the western Canadian Arctic, the ocean is generally covered with first-year ice with intermittent ice motion in the region, with modal ice thicknesses of around 2 m representing typical level ice conditions.[22] Obtaining sound speed profiles and acoustic data simultaneously during winter can be challenging in the Arctic. Figure 1(b) shows a sound speed profile from 15/04/2008 measured as part of the circumpolar flaw lead (CFL) project at a location near the current Cape Bathurst acoustic rcordings.[23] There is evidence of a surface duct (<50 m) above a Beaufort duct, centered at a depth of 90 m, typical of other winter sound speed profiles of the region.[24]

The sound spectral level was calculated for every second with a 1 Hz frequency resolution using a fast Fourier transform (FFT) and a Hanning window with 50% overlap. Spectrograms were created for each 5 min acoustic file by concatenating these segments to identify ice-generated sound. For further analysis, we focused primarily on broadband ice cracking and breaking events present in the acoustic time series because this is most likely to have the greatest masking effect since the calls of bearded seals typically have peak frequencies between 0.1 and 3.9 kHz, with a mean around 0.76 kHz[13] [Fig. 1(c)]. A broadband ice sound event is shown in Fig. 1(d) that lasts for the entire 5 min recording period.

2.2 Detection of ice-generated sound

We used a spectrogram-based method to identify and extract broadband ice-generated sound events using the following steps:

- Step 1: The spectrogram of each acoustic recording (5 min–long file) was calculated at 1 Hz frequency resolution and 1 s time resolution.
- Step 2: The mean spectral level of the recording was calculated within the 0.1–0.8 kHz frequency band, since transient ice-generated sound events generally exhibit peak energy at low frequencies.
- Step 3: A detection threshold was fixed by adding a sensitivity offset of 3 dB to the mean spectral level of each acoustic file in the specific frequency band.
- Step 4: A binary mask was created by comparing the spectral level of each time segment to the detection threshold, where frequency bins exceeding the threshold were considered as true.
- Step 5: A broadband ice sound event was identified when, within a time segment, more than 50% of the frequency bins in the selected band (0.1–0.8 kHz) were true (exceeded the detection threshold).
- Step 6: The total duration and corresponding acoustic metrics [power spectral density, sound pressure level (SPL), and sound exposure level (SEL)] of ice-generated sound in the recording were extracted and the same process was repeated for each subsequent acoustic file.

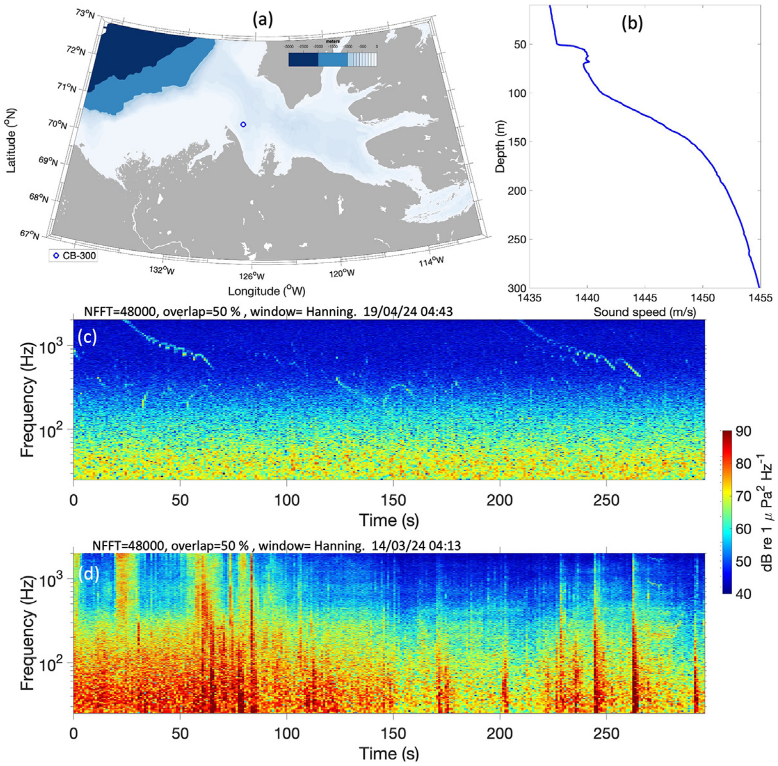

Fig. 1. (a) Map of the western Canadian Arctic study region with the location of the passive acoustic mooring near Cape Bathurst indicated by the blue circle, (b) the measured sound speed profile near the mooring site, (c) a spectrogram showing multiple bearded seal calls, (d) another spectrogram showing ice-generated sound.

An input spectrogram with a few ice cracking events is shown in Fig. 2(a). The extracted broadband transient events after applying the detection algorithm are shown in Fig. 2(b). Ice cracking events from the spectrogram-based detector were manually verified to assess the performance of the detection algorithm. A total of 120 acoustic files (4.1%) were randomly selected from the full dataset (2921), and each file was divided into 30 s segments for annotation of ice sound events. Precision, recall, and $F1$ score for the detector were 0.87, 0.88, and 0.87, respectively. These performance metrics indicate that the detector has a low false positive rate and a good sensitivity to identify true ice sound events. Since the detection threshold is based on the mean spectral level, if ice cracking/fracturing persists over the entire recording, only the loudest events may be detected, while weaker ones may be missed. Moreover, the detector may occasionally misidentify other low-frequency transient sources (anthropogenic or system noise) as ice cracking events if their energy peaks in the same frequency band. However, manual examination of the spectrograms revealed only the presence of natural, biological, and ice-generated sound events and no anthropogenic sources were identified. This lack of anthropogenic noise is expected since the data were collected during the winter when ship traffic is absent and far away from any communities where people would be driving snow mobiles.

2.3 Listening space reduction

We used LSR to assess the effect of masking by ice sound events on bearded seal vocalizations. LSR represents the percentage difference between the listening space available under a given noise condition and the maximum listening space under natural ambient sound conditions.[19,20] LSR can be effectively used to obtain a relative estimate of masking based on the difference between baseline and masked condition (ice-generated sound). LSR was calculated assuming shallow water propagation (horizontal range $\gg$ water depth), which means cylindrical spreading. Under this assumption, LSR can be calculated as

$$LSR = 100\left(1 - 10^{-2\Delta/N}\right), \tag{1}$$

where Δ is the difference (in decibels) between masking noise (NL_2) and perceived ambient noise level (NL_1), and N is the slope [$dB/log_{10}(Range_m)$] of the PL between the noise source and the receiver. NL_1 is defined as the maximum of the receivers hearing threshold (audiogram) and the ambient noise level within a critical bandwidth (1/3 octave bands).[14] An LSR of 0 indicates no reduction in listening space, while an LSR of 100 implies complete loss of detectable listening space under the modelled conditions. The biological relevance of LSR is less direct than the communication range estimation method, which quantifies how far animals can communicate under natural or anthropogenic noise and requires knowledge of the source levels and ranges

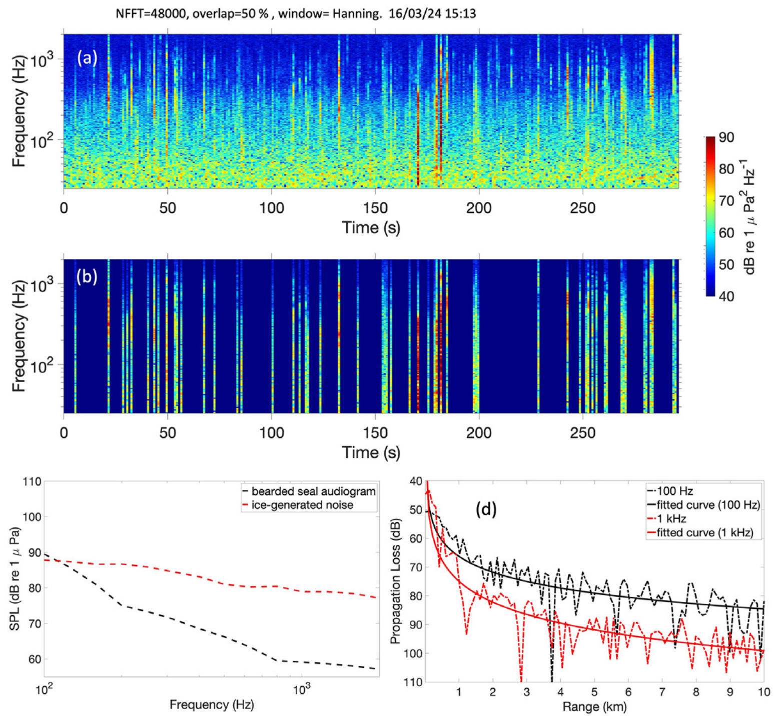

Fig. 2. (a) An example of a measured spectrogram, with (b) extracted broadband ice-generated sound events automatically isolated, (c) third octave band SPL of ice-generated sound (red dashed line) and audiogram of bearded seal (black dashed line), and (d) estimated PL at 100 Hz (black) and 1 kHz (red) and corresponding fitted curves (solid).

of both conspecifics and masking noise. LSR is a relative estimate, which quantifies the impact of external noise source from the listener's perspective, and does not require information on either the SL or ranges of the animal. If the bearded seal is assumed to occupy the position of the hydrophone, then information on the source level of the masking noise is not required for calculating LSR, as the measured ambient noise level already represents the received noise at that location. Based on passive acoustic data, knowledge of the PL slope of the environment, and the species' audiogram, the LSR can be used to estimate the relative change in detection range caused by transient ice sound events. Moreover, this approach provides a first-order approximation of masking effects comparable with the detection-range models validated in other marine mammal studies.[14,17]

Figure 2(c) compares the mean SPL of an ice sound event with the measured audiogram of bearded seal based on psychoacoustic experiments.[25] At frequencies above 150 Hz, ice sound levels substantially exceed the audiogram, indicating a high probability for masking. The range-independent full-wave model in the ocean acoustics and seismic exploration synthesis (OASES) modeling package was used to calculate PL in an ice-covered environment.[26] The model input parameters required are the sea ice acoustic properties, the water column sound speed profile, and the acoustic properties of the seabed. The model can also incorporate under ice roughness to account for scattering loss based on the method of small perturbation. The sound speed profile given in Fig. 1(b) was used as the input for the water column.[23] The thickness of the ice layer was set to 2 m and the input acoustic properties of the ice layer are given in Table 1.[22,27,28] Acoustic properties of fine silt were used for seabed parameters based on a recent study of sedimentary processes in the Canadian Arctic Archipelago.[29,30]

Based on the bearded seal's audiogram, the dominant vocal energy in bearded seal calls and the dominance of ice sound level at lower frequencies, the band 100 Hz to 2 kHz was selected for further analysis. PL was calculated at the central frequencies of each 1/3 octave band between 100 Hz and 2 kHz, over a horizontal range of 10 km at 100 m intervals by keeping an acoustic source at the hydrophone's depth (300 m) and the receivers at a point just below the ice layer (2.3 m). To estimate the PL between ice sound event and the receiver at specific frequencies, the positions of the receiver and source were swapped based on the principle of reciprocity.[30] The value of N at each frequency can be calculated by fitting a straight line to the PL curve, with the logarithm of range on the x axis. Figure 2(d) shows the estimated PL and the best-fit curve for 100 Hz and 1 kHz with range on the x axis in linear scale.

2.4 Influence of masking on bearded seal vocalizations

To investigate whether ice sound events influence the calling activity of bearded seals, we examined the relationship between the vocal activity of seals and two masking-related acoustic metrics: the CLSR and the SEL. CLSR was used to account for the duration of masking and was calculated by multiplying the frequency averaged mean LSR (0.1–1 kHz) of each acoustic recording by the total duration of detected ice sound events, followed by normalization.

We used a deep learning detector employing a convolutional neural network architecture to identify bearded seal calls in each acoustic recording. The network architecture was based on a Residual Networks configuration, with an initial two-dimensional (2D) convolutional layer followed by three block sets, each with two residual blocks adding up to 15 2D convolutional layers.[31] The network input consists of 4 s–long spectrograms, computed using a 0.03 s FFT window with a 0.018 s step size (60% overlap) and a Hamming window function. The detector was trained on manually annotated bearded seal calls by experienced bioacousticians using a large passive acoustic dataset (118 000 training sets and 17 000 test sets) collected by the Wildlife Conservation Society (WCS) Canada from multiple locations in the western Canadian Arctic. Training was performed using the ADAM optimizer.[32] The network was trained in the binary classification task of distinguishing clips that contained bearded seal calls from background noise.

The detector performed well (precision = 0.91 and recall = 0.92) when evaluated using test sets from the same locations used for training. However, when applied to data from other sites, the detector could achieve a recall of 0.9 but the precision was 0.54. Thus, the identified calls in each recording were manually verified by a trained analyst. We then used the total time within each file with bearded seal calls present as a metric of bearded seal calling activity, measured in seconds. We did not count individual calls because the detector splits the acoustic data into 4 s bins and assesses whether bearded seal calls are present within each bin; therefore, there may be multiple calls present within a single bin or the same call in multiple bins. Moreover, bearded seals have been shown to have at least 18 call types in this region, and these different calls can vary quite widely in duration,[13] so counts of calls do not necessarily represent the total calling activity.

3. Results and discussion

Based on the method described in Sec. 2.2, ice-generated sound events were extracted from the acoustic recordings. Out of 2921 5 min recordings, 1529 files were identified to contain ice sound events. The duration of these events ranged from 1 s to a maximum of 140 s per file. The extracted broadband ice sound events were compiled, and the general trend of these events is shown as spectral probability density in Fig. 3(a). An increase in energy above 100 Hz indicates the broadband nature of transient ice cracking events.

Using the extracted ice sound events, bearded seal audiogram and estimated PL in an ice-covered ocean, we calculated the LSR for bearded seals at the measurement site. Figures 3(b) and 3(c) show the measured SPL and the corresponding estimated LSR for an ice sound event at the receiver depth (300 m). A direct correlation between SPL and LSR is evident for louder ice sound events where no effective listening space remains above 150 Hz. Minimal reduction in listening space occurs at frequencies below 150 Hz because of the lower hearing sensitivity of bearded seals in this frequency range. A decrease in LSR can also be observed in the mid-frequency range in certain periods. The main limiting assumption of this LSR estimate is the position of the hydrophone. Even though the adult bearded seals can dive up to 400 m, most of their dives are typically shallower than 70 m.[33,34] Therefore, the estimated LSR based on a bottom-mounted hydrophone is likely lower than the actual effect if the seals were at shallower depths. Presence of two acoustic ducts (surface and Beaufort duct) within the upper 100 m likely facilitate long range propagation of low-frequency signals from distant ice sound events. This can decrease the value of N and consequently increase the LSR at shallower depths. Additionally, the received levels from local ice sound events would be higher closer to the upper ocean layer than measured at a bottom-mounted sensor, further increasing Δ and LSR. Thus, the presence of high-intensity ice sound events can potentially constrain the communication of bearded seals on certain occasions.

The long-term LSR was generated using the extracted ice sound metrics for each acoustic recording and is shown in Fig. 4(a). A notable increase in masking, spanning most of the frequency range, can be observed during mid-March. During other periods, occasional increases in masking can be observed reflecting the random nature of ice sound events. Long-term LSR is a useful metric to understand the influence of environmental forcing leading to ice sound events and corresponding reduction in listening space. Figure 4(b) shows the time series of SEL from ice-generated sound. SEL represents the total acoustic energy of ice sound events over their duration, providing a measure of the cumulative noise exposure that can contribute to masking.

Figures 4(c) and 4(d) shows the relationship between bearded seal vocal activity and SEL and CLSR, respectively. Acoustic recordings. containing both ice-generated sounds and bearded seal calls, were used to investigate this relationship. Vocal activity tends to be higher during periods of low SEL [Fig. 4(c)], followed by a gradual decrease, and then remains relatively stable above 110 dB. This pattern suggests that seals reduce their calling activity during periods of intense ice sound events, possibly due to acoustic masking effects. Vocal activity remained high when CLSR was low [Fig. 4(d)] and

Table 1. Ice-layer properties used as input to the OASES.

Compressional speed (m/s)	Shear speed (m/s)	Density (kg/m^3)	Compressional attenuation (dB/λ)	Shear attenuation (dB/λ)	Root-mean-square roughness (m)	Correlation length (m)
3600	1800	900	0.21	0.65	0.2	20

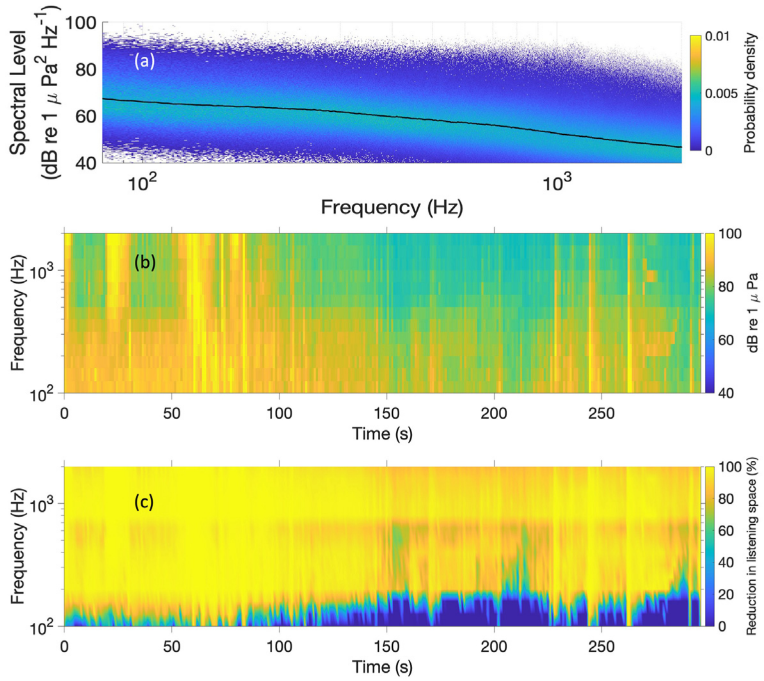

Fig. 3. (a) The spectral probability density of all extracted ice-generated sound events from the March–April dataset (black solid line is the median spectrum), (b) the measured SPL of an ice sound event along with the audiogram. PL and Eq. (1) were applied to compute (c) the corresponding LSR.

declined noticeably at moderate to high CLSR values, indicating that seals vocalized more when the reduction in listening space was minimal. The absence of data between 0.3 and 0.9 resulted from a few high-intensity, long-duration ice sound events dominating the CLSR distribution. A previous study reported a compensatory response in bearded seals, where call source levels increased with rising ambient noise up to a threshold level, beyond which they remained constant.[35] In contrast, the observed decrease in vocal activity during periods of intense ice sound events suggests a behavioural response to high masking. A reduction in listening space indicates a smaller region over which the signals can be perceived by conspecifics, potentially decreasing the effectiveness of acoustic communication. When elevated noise levels lower the probability of successful signal detection, bearded seals may suppress calling activity to conserve energy during acoustically unfavorable conditions. The limited number of data points at higher CLSR values warrants further analysis incorporating the frequency characteristics of seal calls to better understand this behaviour in calling activity.

Increase in vocal activity of bearded seals was observed when ice cover was higher than 70% and under dynamic ice conditions.[36] Based on global climate models data, the Arctic sea ice area is projected to decrease substantially in the coming decades, with some models predicting ice-free summers by 2050.[37,38] Ambient sound measured in the Arctic during winter generally correlates with ice deformation rate and ice drift driven by environmental factors and oceanographic features.[8,12] Model simulations also forecast an increase in sea ice area fluxes in the Canadian Arctic Archipelago including the southern Amundsen Gulf area.[37] This combined with a decrease in sea ice thickness, and altered oceanographic features from ice melting may lead to frequent ice–ice interactions. As a result, ice-generated acoustic activity in the region could increase under future climate change scenarios.

Bearded seals prefer drifting sea ice and unstable ice packs, typically avoiding areas with very high ice concentration.[34] Therefore, ice-generated sound could be a consistent component of their acoustic habitat and these seals might be using typical vocalizations to overcome potential masking from ice-generated sound. Projections of earlier ice breakup and a shorter ice season in the southern Amundsen Gulf due to climate change may not only affect the timing and location of the bearded seal mating season, but also increase the ambient sound levels from both ice- and wave-generated sources during this period.[38] Thus, under changing ice characteristics in the Arctic driven by climate change, the extent of masking introduced by ice-generated sound and its effect on the vocal behaviour of bearded seals remains unclear and needs to be investigated. Studies focusing on the masking effect of ice-generated sound on bearded seals communication have not been conducted previously. This work explored the applicability of LSR to obtain relative information on the effect of ice noise using minimal available data. Future studies should focus on fine scale variations in call characteristics in relation to masking effects caused by ice-generated sound.

4. Conclusion

This study presents the applicability of LSR as a rapid and easily estimable metric that relies on minimal inputs, such as ambient noise data, PL slope, and species audiograms. LSR provides a practical method to assess potential masking effects

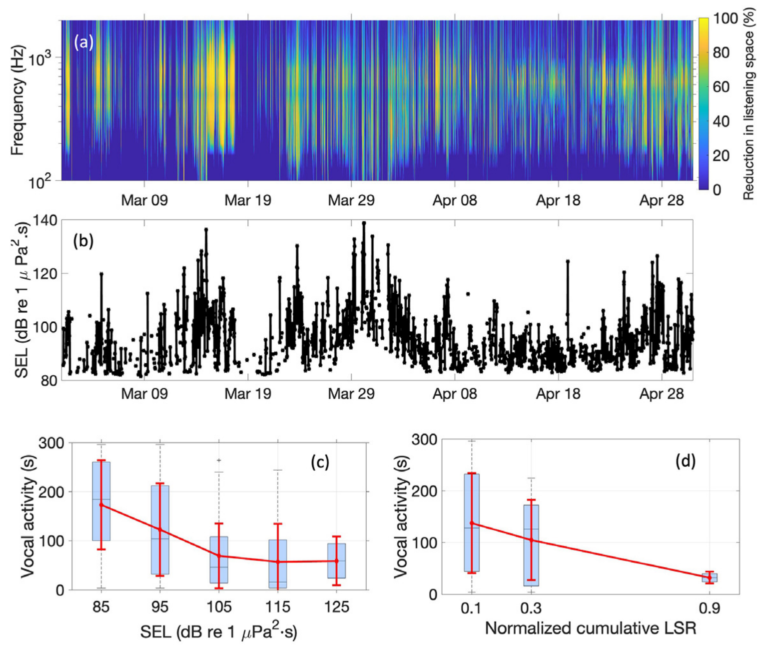

Fig. 4. Time series of (a) LSR, (b) SEL, and the relationship between bearded seal vocal activity and (c) SEL and (d) CLSR. The ends of the box in (c) and (d) show the upper and lower quartiles and the line inside the box shows the median. The redline and error bars indicate the mean ± standard deviation.

when information, such as source levels, spatial distribution, and the positions of animals, is not available. Ice-generated sound is a dominant component of Arctic soundscapes during winter. LSR is used to assess the influence of broadband ice sound events on bearded seal vocalizations during early mating season using ambient sound data collected over 2 months from the western Canadian Arctic. Results showed that vocal activity per acoustic file decreased as the contribution of ice-generated sounds increased, suggesting a behavioural response. The observed trend between seal vocal activity and CLSR indicates acoustic masking due to ice-generated sound and demands further investigation on sea ice deformation due to climate change and its effect on the acoustic habitat of bearded seals.

Acknowledgments

All acoustic data used in this study were collected by Wildlife Conservation Society Canada with assistance from Fisheries and Oceans Canada and the captain and crew of the CCGS Sir Wilfrid Laurier and CCGS Louis S. St. Laurent. We are particularly grateful to N. Diogou, A. Hare, and M. Dempsey for assistance with equipment deployment and recovery. Funding for this work was provided by Fisheries and Oceans Canada (Oceans Management Contribution Program), the Fisheries Joint Management Committee of the Inuvialuit Joint Secretariat, and the Weston Family Foundation.

Author Declarations

Conflict of Interest

The authors have no conflicts to disclose.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1]E. Cook, D. R. Barclay, and C. Richards, "Ambient noise in the Canadian arctic," in *Governance of Arctic Shipping*, Springer Polar Sciences, edited by A. Chircop, F. Goerlandt, C. Aporta, and R. Pelot (Springer, Cham, Switzerland, 2020).

[2]E. H. Roth, J. A. Hildebrand, S. M. Wiggins, and D. Ross, "Underwater ambient noise on the Chukchi Sea continental slope from 2006-2009," J. Acoust. Soc. Am. **131**, 104–110 (2012).

[3]W. D. Halliday, M. K. Pine, X. Mouy, P. Kortsalo, R. C. Hilliard, and S. J. Insley, "The coastal Arctic marine soundscape near Ulukhaktok, Northwest Territories, Canada," Polar Biol. **43**, 623–636 (2020).

[4]J. Dingwall, W. D. Halliday, N. Diogou, A. Neimi, N. Steiner, and S. J. Insley, "The Arctic marine soundscape of the Amundsen Gulf, Western Canadian Arctic," Mar. Pollut. Bull. **204**, 116510 (2024).

[5]W. D. Halliday, D. Barclay, A. N. Barkley, E. Cook, J. Dawson, R. C. Hilliard, N. Hussey, J. Jones, F. Juanes, M. Marcoux, A. Niemi, S. Nudds, M. K. Pine, C. Richards, K. Scharffenberg, K. Westdal, and S. J. Insley, "Underwater sound levels in the Canadian Arctic, 2014-2019," Mar. Pollut. Bull. **168**, 112437 (2021).
[6]G. B. Kinda, Y. Simard, C. Gervise, J. I. Mars, and L. Fortier, "Under-ice ambient noise in Eastern Beaufort Sea, Canadian Arctic, and its relation to environmental forcing," J. Acoust. Soc. Am. **134**, 77–87 (2013).
[7]R. S. Pritchard, "Sea ice noise-generating processes," J. Acoust. Soc. Am. **88**, 2830–2842 (1990).
[8]G. Bazile Kinda, Y. Simard, C. Gervise, J. I. Mars, and L. Fortier, "Arctic underwater noise transients from sea ice deformation: Characteristics, annual time series, and forcing in Beaufort," J. Acoust. Soc. Am. **138**, 2034–2045 (2015).
[9]J. Overland, E. Dunlea, J. E. Box, R. Corell, M. Forsius, V. Kattsov, M. S. Olsen, J. Pawlak, L.-O. Reiersen, and M. Wang, "The urgency of Arctic change," Polar Sci. **21**, 6–13 (2019).
[10]W. N. Meier, A. Petty, S. Hendricks, A. Bliss, L. Kaleschke, D. Devine, S. Farrell, S. Gerland, D. Perovich, R. Ricker, X. Tian-Kunze, and M. Webster, "Sea ice," NOAA Technical Report OAR ARC; 24-06 (Arctic Report Card, 2024).
[11]D. G. Babb, R. J. Galley, S. Kirillov, J. C. Landy, S. E. Howell, J. C. Stroeve, W. Meier, J. K. Ehn, and D. G. Barber, "The stepwise reduction of multiyear sea ice area in the Arctic Ocean since 1980," J. Geophys. Res. Oceans. **128**, e2023JC020157, https://doi.org/10.1029/2023JC020157 (2023).
[12]J. Bonnel, G. B. Kinda, and D. P. Zitterbart, "Low-frequency ocean ambient noise on the Chukchi Shelf in the changing Arctic," J. Acoust. Soc. Am. **149**, 4061–4072 (2021).
[13]A. F. Heimrich, W. D. Halliday, H. Frouin-Mouy, M. K. Pine, F. Juanes, and S. J. Insley, "Vocalizations of bearded seals (*Erignathus barbatus*) and their influence on the soundscape of the western Canadian Arctic," Mar. Mamm. Sci. **37**, 173–192 (2021).
[14]C. Erbe, C. Reichmuth, K. Cunningham, K. Lucke, and R. Dooling, "Communication masking in marine mammals: A review and research strategy," Mar. Pollut. Bull. **103**, 15–38 (2016).
[15]W. D. Halliday, S. J. Insley, T. de Jong, and X. Mouy, "Seasonal patterns in acoustic detections of marine mammals near Sachs Harbour, Northwest Territories," Arctic Sci. **4**, 259–278 (2017).
[16]D. Risch, C. W. Clark, P. J. Corkeron, A. Elepfandt, K. M. Kovavs, C. Lydersen, and S. M. Van Parjis, "Vocalizations of male bearded seals, *Erignathus barbatus*: Classification and geographical variation," Anim. Behav. **73**, 747–762 (2007).
[17]B. L. Southall, J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. P. Nowacek, and P. L. Tyack, "Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects," Aquat. Mamm. **45**, 125–232 (2019).
[18]S. M. Van Parijs, C. Lydersen, and K. M. Kovacs, "Effects of ice cover on the behavioural patterns of aquatic-mating male bearded seals," Anim. Behav. **68**, 89–96 (2004).
[19]M. K. Pine, D. E. Hannay, S. J. Insley, W. D. Halliday, and F. Juanes, "Assessing vessel slowdown for reducing auditory masking for marine mammals and fish of the western Canadian Arctic," Mar. Pollut. Bull. **135**, 290–302 (2018).
[20]M. K. Pine, K. Nikolich, M. Martin, C. Morris, and F. Juanes, "Assessing auditory masking for management of underwater anthropogenic noise," J. Acoust. Soc. Am. **147**, 3408–3417 (2020).
[21]G. Spreen, L. Kaleschke, and G. Heygster, "Sea ice remote sensing using AMSR-E 89-GHz channels," J. Geophys. Res. **113**, C02S03, https://doi.org/10.1029/2005JC003384 (2008).
[22]I. K. Peterson, S. J. Prinsenberg, and J. S. Holladay, "Observations of sea ice thickness, surface roughness and ice motion in Amundsen Gulf," J. Geophy. Res. **113**, C06016, https://doi.org/10.1029/2007JC004456 (2008).
[23]D. G. Barber, M. G. Asplin, Y. Gratton, J. V. Lukovich, R. J. Galley, L. Raddatz, and D. Leitch, "The international polar year (IPY) circumpolar flaw lead (CFL) system study: Overview and the physical system," Atmos.-Ocean. **48**, 225–243 (2010).
[24]M. Kucukosmanoglu, J. A. Colosi, P. F. Worcester, M. A. Dzieciuch, and D. J. Torres, "Eastern Arctic ambient noise on a drifting vertical array," J. Acoust. Soc. Am. **149**, 1536–1548 (2021).
[25]J. M. Sills, C. Reichmuth, B. L. Southall, A. Whiting, and J. Goodwin, "Auditory biology of bearded seals (*Erignathus barbatus*)," Polar Biol. **43**, 1681–1691 (2020).
[26]H. Schmidt, Version 3.1 OASES User Guide and Reference Manual (Department of Ocean Engineering, Massachusetts Institute of Technology, Cambridge, MA, 2020).
[27]H. Liable and S. D. Rajan, "Temporal evolution of under-ice reflectivity," J. Acoust. Soc. Am. **99**, 851–865 (1996).
[28]G. Hope, H. Sagen, E. Storheim, H. Hobaek, and L. Freitag, "Measured and modeled acoustic propagation underneath the rough Arctic sea-ice," J. Acoust. Soc. Am. **142**, 1619–1633 (2017).
[29]S. Lataief, J.-C. Montero-Serrano, and G. St-Onge, "Sedimentary processes within the Canadian Arctic Archipelago: Relationships among sedimentological, geochemical and magnetic sediment properties," Geochem. Geophys. Geosys. **22**, e2021GC009719 (2021).
[30]F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt, *Computational Ocean Acoustics* (Springer, New York, 2011).
[31]K. He, X. Zhang, S. Ren, and J. Sun, "Deep residual learning for image recognition," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* (2025), pp. 770–778.
[32]D. P. Kingma and J. Ba (2014). "ADAM: A method for stochastic optimization," *ICLR 2015-1-15*.
[33]I. Gjertz, K. M. Kovacs, C. Lydersen, and O. Wiig, "Movements and diving of bearded seal (Erignatus barbatus) mothers and pups during lactation and post-weaning," Polar Biol. **23**, 559–566 (2000).
[34]C. D. Hamilton, K. M. Kovacs, and C. Lydersen, "Individual variability in diving, movement and activity patterns of adult bearded seals in Svalbard, Norway," Sci. Rep. **8**, 16988 (2018).
[35]M. E. H. Fournet, M. Silvestri, C. W. Clark, H. Klinck, and A. N. Rice, "Limited vocal compensation for elevated ambient noise in bearded seals: Implications for an industrializing Arctic Ocean," Proc. R. Soc. B **288**, 20202712 (2021).
[36]S. M. Llobet, H. Ahonen, C. Lydersen, J. Berge, R. Ims, and K. M. Kovacs, "Bearded seal (*Erignathus barbatus*) vocalizations across seasons and habitat types in Svalbard, Norway," Polar Biol. **44**, 1273–1287 (2021).
[37]A. Jahn, M. M. Holland, and J. E. Kay, "Projections of an ice-free Arctic Ocean," Nat. Rev. Earth Environ. **5**, 164–176 (2024).
[38]M. Fol, B. Tremblay, S. Pfirman, R. Newton, S. Howell, and J.-F. Lemieux, "Revisiting the last ice area projections from a high resolution global earth system model," Commun. Earth Env. **6**, 46 (2025).