Underwater noise from ship traffic near Cambridge Bay, Nunavut in 2017 and 2018

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Report Prepared for

Transport Canada

5 February 2021

Abstract

Underwater noise from ship traffic is an increasing concern in the Arctic as ship traffic continues to increase throughout the region. In this report, we analyzed ship noise from passive acoustic data that was recorded near Cambridge Bay, Nunavut, in 2017 and 2018. We estimated the influence of the presence and number of ships, distance to the nearest ship, and speed of the nearest ship on sound pressure levels. We also estimated the source levels of eight individual ships, including multiple estimates for some ships, for a total of 14 source level estimates. Finally, we examined marine mammal and fish vocalizations between August and October (i.e. the shipping season) within the datasets to estimate the exposure to underwater noise for different species. 15 unique ships with AIS transponders (or a GPS track) came within 10 km of the acoustic recorder in 2017, and 12 unique ships in 2018. Of these, there were a total of 14 passages by eight unique ships within 2.5 km of the acoustic recorder, which were used to measure the source levels of individual ships. The number of ships within 10 km of the recorder, as well as the distance to the nearest ship, were both important predictors of underwater noise levels. Estimated ship source levels ranged from 163.3 to 185.6 dB re 1 μPa at 1 m (bandwidth: 20 Hz to 48 kHz), with the higher source levels belonging to large ships like tankers and bulk carriers, and the lower levels for smaller ships like tugs and research ships. Both ringed seal and fish vocalizations were common in August-October, and typically occurred on the same days that ship noise was present. Bearded seal vocalizations were also common in early August 2018, and similarly occurred in close proximity to ship noise. These species therefore are likely exposed to all of the ship noise occurring at this site. Beluga whales were present on a single day in this study period, and are not frequently encountered in this area. Overall, these results provide the first measurements of ship noise in this region, provide estimates of the exposure of marine animals to ship noise, and provide context for future work on underwater noise in this region.

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Glossary of Terms

Ambient sound: All sound in the ocean that is not the desired signal that a receiver is trying to hear. Anthropogenic sounds do contribute to ambient sound levels. “Ambient noise in the ocean is the sound field against which signals must be detected” (Hildebrand, 2009, p. 5). Also known as background noise and ocean ambient noise. Typically measured as power spectral densities in 1 Hz frequency bands, but can also be measured as sound pressure levels in various frequency bands.

Bandwidth: Frequency range (measured in Hz [Hertz] or kHz [kilo Hertz]). Often in context of hearing capabilities (an animal can hear within a specific frequency range), or in context of a measurement of sound, such as sound pressure level.

Cavitation: The rapid formation and collapse of bubbles. In reference to noise from shipping, cavitation is caused by a spinning propeller, which rapidly creates small bubbles as it rotates, which then collapse and make noise.

Decibel (dB): A measure of the relative loudness of acoustic signals, measured on a logarithmic scale. Underwater, the reference level is always 1 μPa (micro Pascal). For comparison, sound measured in air has a reference level of 20 μPa.

Frequency: Physical definition: the rate of oscillation or vibration, measured in hertz (Hz) or kilohertz (kHz). Psychoacoustic definition: the tone or pitch of an acoustic signal.

Power spectral density (PSD): The distribution of power across a range of frequencies, measured at a single Hz. Measured in dB re 1 $\mu Pa^2/Hz$.

Received level: The sound pressure experienced by a receiver (i.e. animal or recording device). Measured as both power spectral density across a range of frequencies (in dB re 1 $\mu Pa^2/Hz$) and sound pressure level across some range of frequencies (in dB re 1 μPa).

Source level: The sound pressure of some noise-emitting activity, measured (or estimated) at 1 m distance from the source. Initially measured as a power spectral density across a range of frequencies (in dB re 1 $\mu Pa^2/Hz$ at 1 m), and often summarized into a broadband sound pressure level across some range of frequencies (in dB re 1 μPa at 1 m).

Sound pressure level (SPL): The sum of sound pressure within some band of frequencies. Measured in dB re 1 μPa in water.

1. Introduction

Ship traffic in the Canadian Arctic is increasing as the region becomes more consistently ice-free during the summer (Dawson et al., 2018; Halliday et al., 2018b). Increased ship traffic will also cause rising levels of underwater noise, which can have negative impacts on marine animals, particularly for marine mammals that Inuit hunt for subsistence (Halliday et al., 2020a; PAME, 2019). In a previous project, we modeled the underwater noise from ships in the Kitikmeot region of Nunavut based on satellite automatic identification system (AIS) ship tracks, and found that underwater noise from ships is mostly along the shipping route, but ship noise is unevenly distributed throughout the region. Cambridge Bay and Dease Strait, in particular, were areas receiving among the highest levels of ship traffic and consequently the highest levels of modeled underwater noise from ships in the entire Kitikmeot region. These findings were expected because Cambridge Bay is a destination for many of the ships transiting through the region, and the southern part of the Northwest Passage is restricted into a relatively narrow path through Dease Strait as ships transit the Northwest Passage.

Although these modeling results certainly highlight important spatial and temporal patterns in underwater noise within the Kitikmeot region, information is missing that would improve the accuracy of the model outputs. Most notably, a large number of vessels do not carry AIS, and the AIS data also have inherent inaccuracies due to poor satellite coverage in the region. The modeling also assumes that all vessels within a particular category have the same source level (i.e. loudness), regardless of ship size, speed, behaviour, or position related to the receiver which we know is not correct. Direct measurements of underwater noise from ships are required to understand real levels of underwater noise in this region, including more accurate measurements of the variability in underwater noise from different types of ships. Information is also needed on the extent to which marine animals are exposed to these noise levels.

Passive acoustic monitoring (PAM), deploying acoustic recorders with calibrated hydrophones, is the most widely used tool for measuring underwater noise, and has been effectively used around the world, including in the Canadian Arctic (Halliday et al., 2020c, 2020b; Insley et al., 2017; PAME, 2019). PAM not only allows for the measurement of underwater noise levels, but also the identification of a variety of acoustic signals, including ship noise and vocalizations by marine mammals (Halliday et al., 2020b, 2019a, 2019b, 2018a). The presence of marine mammals can therefore be examined using PAM, and any overlap and exposure to underwater noise by these marine mammals can be estimated. In this study, we used passive acoustic data collected near Cambridge Bay, Nunavut in 2017 and 2018 to measure underwater sound levels, assess underwater noise from vessel traffic, and examine the overlap between ship noise and the presence of marine animals based on vocalizations detected in the acoustic data.

2. Methods

2.1 Acoustic Dataset

Passive acoustic data were collected by Fisheries and Oceans Canada (DFO). An acoustic recorder (Model SM3M, Wildlife Acoustics, Maynard, Massachusetts, USA) was attached to an oceanographic mooring, which was anchored to the sea floor to the east of the Finlayson Islands in Dease Strait, which is just over 30 km west of Cambridge Bay, Nunavut (Figure 1). This mooring was deployed from August 2017 to August 2018, and then reset from August 2018 to August 2019. The acoustic recorder was set to record 2 minutes of acoustic data every 12 minutes in 2017-2018, and to record 4 minutes and 22 seconds every hour in 2018-2019. The recorder in 2017-2018 collected data through the entire calendar year, whereas the recorder in 2018-2019 stopped recording in March 2019. Recorders were set at a 96 kHz sample rate, and did not use any gain. The depth for the recorders was 85 and 84 m in 2017-2018 and 2018-2019, respectively.

Although the 2017-2018 dataset continued to record until 15 August 2018, the first vessels identified in the AIS data in 2018 did not pass the mooring site until after the recorder was recovered, so the 2017-2018 dataset only recorded underwater noise from AIS ships in 2017. Similarly, the 2018-2019 dataset only recorded noise from ships in 2018 because it stopped recording in March 2019 long before any ships started transiting in the region in 2019.

2.2 Analysis 1: Presence of ship noise in acoustic data

We processed acoustic data using the PAMGuide package (Merchant et al., 2015) in Matlab (version 2017a, Mathworks Inc, Natick, Massachusetts, USA), and measured sound pressure levels (SPL) in three bandwidths: 50-1000 Hz (low), 1-10 kHz (medium), and 10-48 kHz (high). SPL was measured in 1 second bins using a Hanning window with 50% overlap. 50 Hz represents the minimum effective frequency of these acoustic recorders before the sensitivity of the hydrophone rapidly drops, whereas 48 kHz is the maximum usable frequency with the 96 kHz sample rate. The SPLs were corrected for the factory calibration of the hydrophone, which is -164.7 dB re 1 V/μPa. A single average SPL value was calculated for each file.

Satellite automatic identification system (AIS) data from exactEarth (Cambridge, Ontario, Canada) were used to obtain different metrics of ship traffic around the acoustic recorders. All AIS records within a 10 km buffer around the acoustic recorders were extracted, and the distance between the ship and the acoustic recorder was measured in ArcMap (version 10.4, ESRI, Redlands, California, USA). AIS data were then extracted within the times that the acoustic recorder was actually recording data. For the 2017-2018 data, which recorded 2 minutes of data every 12 minutes, we used AIS records within the 2 minutes that the recorder was active whenever possible; however, satellite AIS records, particularly in the Arctic, are sometime received by satellites at a coarser temporal resolution than 2 minutes, so we also collected data within 5 minutes on either side of the 2 minutes when the recorder was on in order to account for

AIS records outside of that 2 minute window. For the 2018-2019 data, we used AIS records within the 4 minutes that the recorder was active every hour, as well as 5 minutes on either side of the four minute period. We specifically counted the number of AIS vessels within 10 km of the acoustic recorder, the minimum distance to the nearest vessel, the mean speed of the nearest vessel, and the name and category of the nearest vessel within each time window that matched with the acoustic data. While processing the AIS data, we also assessed the number of ships that were either entirely missed, or their closest point of approach was missed, based on the duty cycle and location of the acoustic recorders.

The research/fishing vessel called the F/V Martin Bergmann, which is run by Arctic Research Foundation and was used for the deployments and recoveries of the acoustic recorders from this study, does not have an AIS transponder. However, we obtained GPS tracks for this vessel when our DFO colleagues were on board the vessel, and used the same methodology for the AIS data to extract distance information for this vessel and relate it to the acoustic information. Vessel speed was not available for this vessel. Further reference to AIS data includes the GPS data for the Martin Bergmann.

We also accounted for acoustic signals from ships in the acoustic data by noting the presence of ship noise within each acoustic file (see methods in section 2.3). If ship noise was present when no AIS ships were within 10 km of the recorder, we examined vessel report records from the NORDREG system to determine which ship was plausibly within 10 km of the acoustic recorder when ship noise was detected.

Weather data were obtained from Environment and Climate Change Canada for the Cambridge Bay Airport weather station, which were accessed through the ECCC database: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. Air temperature and wind speed data were then paired with the acoustic and AIS data. Wind speed in particular is an important driver of natural underwater sound levels through wave generation, and as such, must be accounted for in any analysis of underwater noise levels.

Statistical analyses of the influence of ship traffic on SPL were carried out in R statistical software (R Core Team, 2019). More specifically, linear models (package: stats; function: lm) were used to examine variation in SPL in each frequency band, and three separate models were tested. In the first model, we included the number of AIS ships within 10 km of the acoustic recorder as the main independent variable, but also included wind speed and air temperature as additional independent variables to control for variation in natural underwater sound levels. In the second model, we included the distance to the nearest vessel ($\log_{10}$-transformed), speed of the nearest vessel, and vessel class of the nearest vessel as the main independent variables, while also including wind speed and air temperature. In the final model, we included the presence of acoustic signals of ship noise, wind speed, and air temperature. Three separate models were necessary because models including data about the nearest vessel only focus on vessels within 10 km of the acoustic recorder, and therefore do not include data when no ships were within 10 km of the acoustic recorder. The first model that only assesses the number of ships within 10 km of the acoustic recorder includes all acoustic data from when the recorder was deployed to October 31st, and therefore compares SPL data when ships are present to the full natural variability in SPL when ships are absent. Data on the presence of ship noise and the number of AIS ships within 10 km of the recorder are strongly multi-collinear, and cannot be included in the same model. For these models, we assessed data collected by the 2017-2018 recorder and 2018-2019 recorder separately due to their different recording times (2 minutes vs 4:22 minutes) and duty cycles (one file every 12 minutes vs one file every hour).

2.3 Analysis 2: Source level estimates of ships in acoustic data

Once the acoustic data were paired with the AIS data, we identified any acoustic files that had a ship within 2.5 km of the acoustic recorder, and used these files for an analysis of the source levels of ships traveling through the region. The 2.5 km radius is used to maximize sample size for source level measurements, while also ensuring that the ship noise signals cover a broad frequency range (typically 20 to 3,000 Hz or more; Halliday *personal observation*). For the identified acoustic files, we used the PAMGuide package in Matlab to calculate power spectral densities (PSD) and 1/3-octave SPLs. As with the previous analysis, PAMGuide was set to calculate each metric in 1 second bins using a Hanning window with 50% overlap, and then calculate a single mean value for each acoustic file.

We then used the following equation to convert the received level (*RL*) values (i.e. the recorded PSDs and SPLS) into source levels (*SL*) based on the distance (*R*) between the ship and the acoustic recorder which was measured via the AIS data, as well as the frequency-dependent attenuation (α) (Au and Hastings, 2008):

$$SL = RL + 17.1 \log_{10} R + \propto$$

The value of geometric spreading, $17.1\ log_{10}\,R$, was the result from modeling underwater noise from ships within this specific area of the Kitikmeot Region (Halliday *unpublished data*). Briefly, in the modeling study, the software dBSea 2.0 (Irwin Carr Consulting, Northern Ireland) was used to model frequency-dependent propagation of sound using a combination of normal models (low frequency) and ray tracing (high frequency).

2.4 Analysis 3: Presence of marine mammal and fish vocalizations in acoustic data, and overlap with ships

We used Raven Pro (version 1.6; Bioacoustics Research Program, 2017) to manually analyze every audio file between August and October in both datasets. We were specifically looking for known vocalizations by marine animals, including ringed seals (*Pusa hispida*), bearded seals (*Erignathus barbatus*), bowhead whales (*Balaena mysticetus*), beluga whales (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), and sound made by fish, such as those made by Arctic cod (*Boreogadus saida*). Within Raven, we set the spectrogram window size to 7000 samples, the frequency resolution to 3000 Hz, and the time resolution to 15 seconds, although we adjusted these frequency and time settings as necessary to further examine different signals. The only signals expected to be above 3000 Hz are whistles, pulsed calls, and echolocation clicks of beluga and narwhal, but both whistles and pulsed calls do frequently come below 3000 Hz, especially when the whale is close to the acoustic recorder. Given that it is unlikely for either belugas or narwhals to be at this site, it was not necessary to consistently examine data above 3000 Hz. The most likely biological signals to be found in the data are vocalizations of bearded seals, ringed seals, and various fish such as Arctic cod. The typical distribution for the two aforementioned whales and bowhead whales are hundreds of kilometers away from this recording site, although all three species are known to occasionally travel through Dease Strait. A second analyst assisted with the bioacoustic analysis, but all detections made by this analyst were verified by the lead analyst (WH). The presence of ship noise was also noted in all acoustic files, which is an important variable for analyses of sound pressure levels (section 2.1) and identifying the presence of ships not carrying AIS transponders.

3. Results and Discussion

3.1 Trends in AIS vessel traffic while acoustic recorders were active

15 unique AIS vessels (including the F/V Martin Bergmann) came within 10 km of the 2017-2018 recorder while it was actively recording (Figure 1). Of these 15 ships, 5 ships came within 2.5 km of the recorder while it was recording, and the closest ship was 3 m away from the acoustic recorder, although this was the Bergmann while the recorder was being deployed; the next closest vessel was 970 m away from the recorder while it was recording. 12 unique AIS ships came within 10 km of the 2018-2019 recorder while it was recording, 4 of these came within 2.5 km, and the closest ship was 688 m away from the recorder while it was recording. 2018 had reduced ship traffic compared with 2017, particularly in September (Figure 1), and this was caused by 2018 being a heavy ice year, which caused many ships to cancel voyages into the region.

The 2017-2018 acoustic recorder was set to record 2 minutes of acoustic data every 12 minutes, and this duty cycle was not a huge hindrance to recording noise from ships. Although this duty cycle always missed the closest point of approach for vessels traveling within 2.5 km of the acoustic recorder, the difference between the actual closest point of approach versus the minimum distance when the recorder was recording was 225 m, which is not a large difference. However, recording the actual closest point of approach would be better for measurements of source level.

The 2018-2019 recorder had a much more restrictive duty cycle, recording 4 minutes and 22 seconds of data every hour. Ships transiting this region travel an average of 8.3 knots (15.4 km/h), so in the roughly 55 minutes when the recorder was off, the ship could travel 14.1 km.

Many ships could therefore travel through the 10 km radius around the acoustic recorder while it was not recording, and could certainly travel within 2.5 km of the recorder in that time. For periods when the recorder was on and a vessel was within 10 km of the recorder, the recorder missed the closest point of approach by 1774 m, on average. One ship that came within 1829 m of the acoustic recorder was entirely missed, and overall, two vessels and four transits (i.e. two vessels went by the recorder more than once) were entirely missed by the acoustic recorder. For ships that came within 2.5 km of the acoustic recorder, the recorder was off for eight of the 12 one hour periods when source level estimates could have been made, and in the remaining four periods when source level estimates could be made, the closest point of approach was missed by an average of 859 m (maximum difference = 2212 m). In 2018-2019, 10 ships came within 1 km of the acoustic recorder (minimum distance = 116 m), yet when the acoustic recorder was on, only one ship came within 1 km (688 m).

AIS data often does not include all vessels within a region, as many vessels, especially recreational vessels, do not carry AIS transponders (Halliday et al., 2018b). In 2017, according to the NORDREG data, the only non-AIS vessel around the recorders when they were deployed was the Martin Bergmann. In 2018, the Martin Bergmann was again around the recorder, and one other non-AIS vessel was also around the recorder, the sailing vessel Infinity. All other vessels near the acoustic recorder appear to be accounted for by the AIS data. However, caution is required when extrapolating this trend to other years. First, the recorder in 2017 was not active before 31 August, so non-AIS vessels before this period were not accounted for. There were seven sailing vessels in the region in 2017, but they all passed by the mooring location before the recorder was deployed, and all seven of these vessels likely had no AIS transponder. Conversely, 2018 was a year with heavy ice, and all cruise ships were cancelled and most recreation vessels did not enter the Northwest Passage. It can therefore be expected that in other years when the recorder is deployed early in the season, these non-AIS vessels will likely show up in the acoustic data.

For the Martin Bergmann specifically, we were fortunate to have a GPS track of the Bergmann's position while DFO collaborators were on board, which accounts for three of the periods when ship noise was present in the data in 2017 and two of the periods when ship noise was present in 2018. However, according to the NORDREG data, the Bergmann was active in the waters around Cambridge Bay and Dease Strait for six days in 2017 and 37 days in 2018 when the recorder was active, so it was likely responsible for other instances of ship noise in the acoustic recordings.

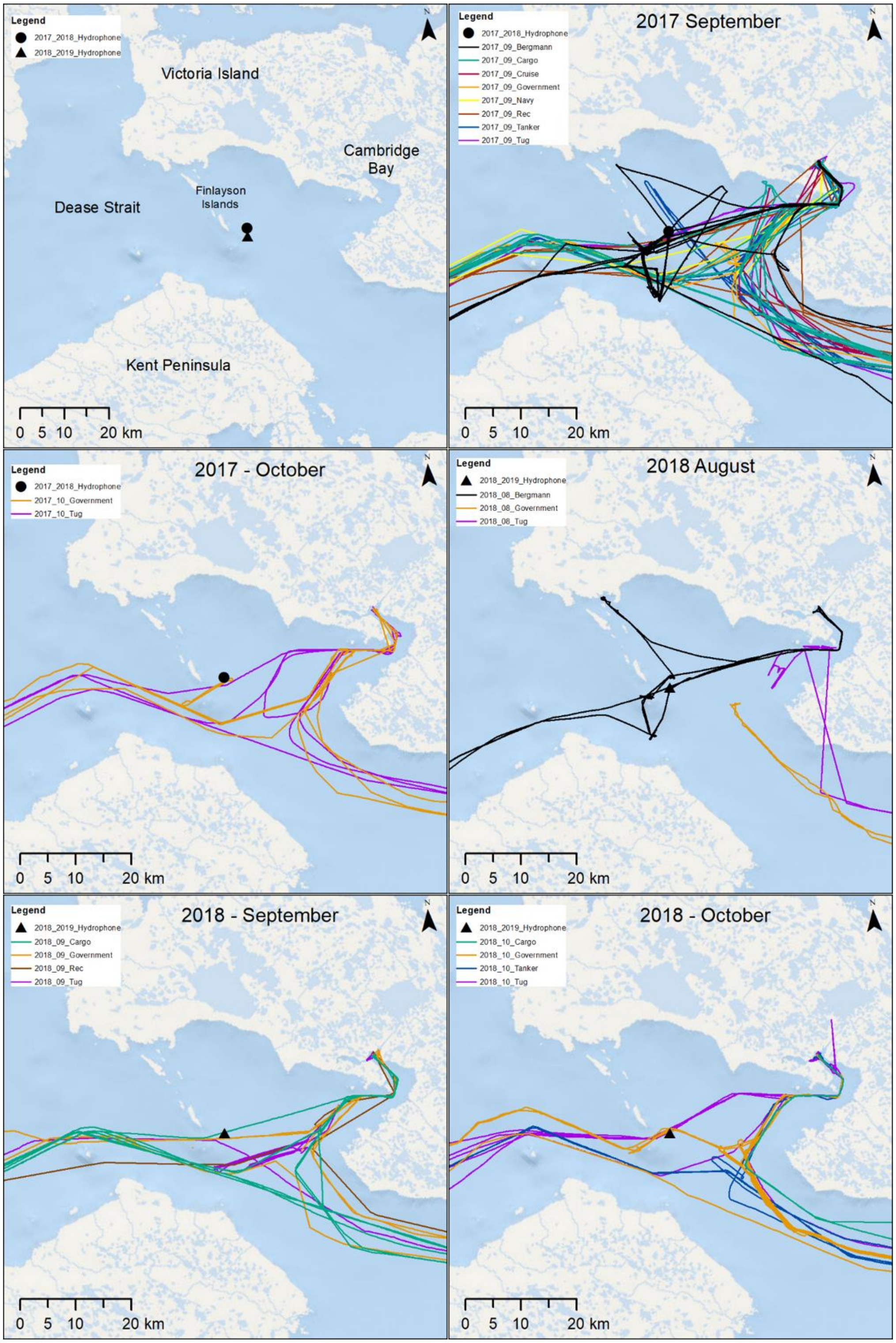

Figure 1. Map of acoustic recorder locations, as well as raw monthly AIS ship tracks.

3.2 Analysis 1: Presence of ship noise in acoustic data

Ships present within 10 km of the acoustic recorder influenced SPL in the 2017-2018 deployment for the low frequency band (50-1000 Hz) and the low and medium (1-10 kHz) frequency bands for the 2018-2019 deployment (Figure 2, Table 1). SPL in the high frequency band (10-48 kHz) was not influenced by the number of ships within 10 km for either deployment, and neither was the medium band for the 2017-2018 deployment. The distance to the nearest ship was consistently a good predictor of SPL in both the low and medium frequency bands in both datasets (Figure 3), with SPL increasing when ships were closer to the acoustic recorder, and this relationship was stronger in the low frequency band than in the medium frequency band (Table 1). Speed of the nearest ship was never an important predictor of SPL (Table 1), likely because most ships were traveling consistent and low speeds, and any differences in ship speed was explained by vessel category (Table 2). SPL in 2017 was highest when bulk carriers were close to the recorder, followed closely by tankers, government vessels and research vessels, whereas cruise ships, navy vessels, and recreational vessels all had smaller influences on SPL. Vessel class had very little influence on SPL in 2018, likely because the vessels were not as close to the recorder when it was on.

Signals of ship noise present in the acoustic data only had a positive effect on SPL in the low frequency band in 2018, whereas it had a negative effect on SPL in both the medium and high frequency bands in 2018 (Table 1). This weak effect is generally related to low ship noise signals being detectable at relatively far distances (> 10 km), but only having large impacts on SPL at closer distances. The negative effect, in particularly, is linked to acoustic masking by ambient sound levels (Halliday et al., 2020b), such that distant, weak signals from ship noise can only be detected when ambient sound levels are low. The presence of ship noise therefore only correlates with higher SPL when ships are close to the hydrophone.

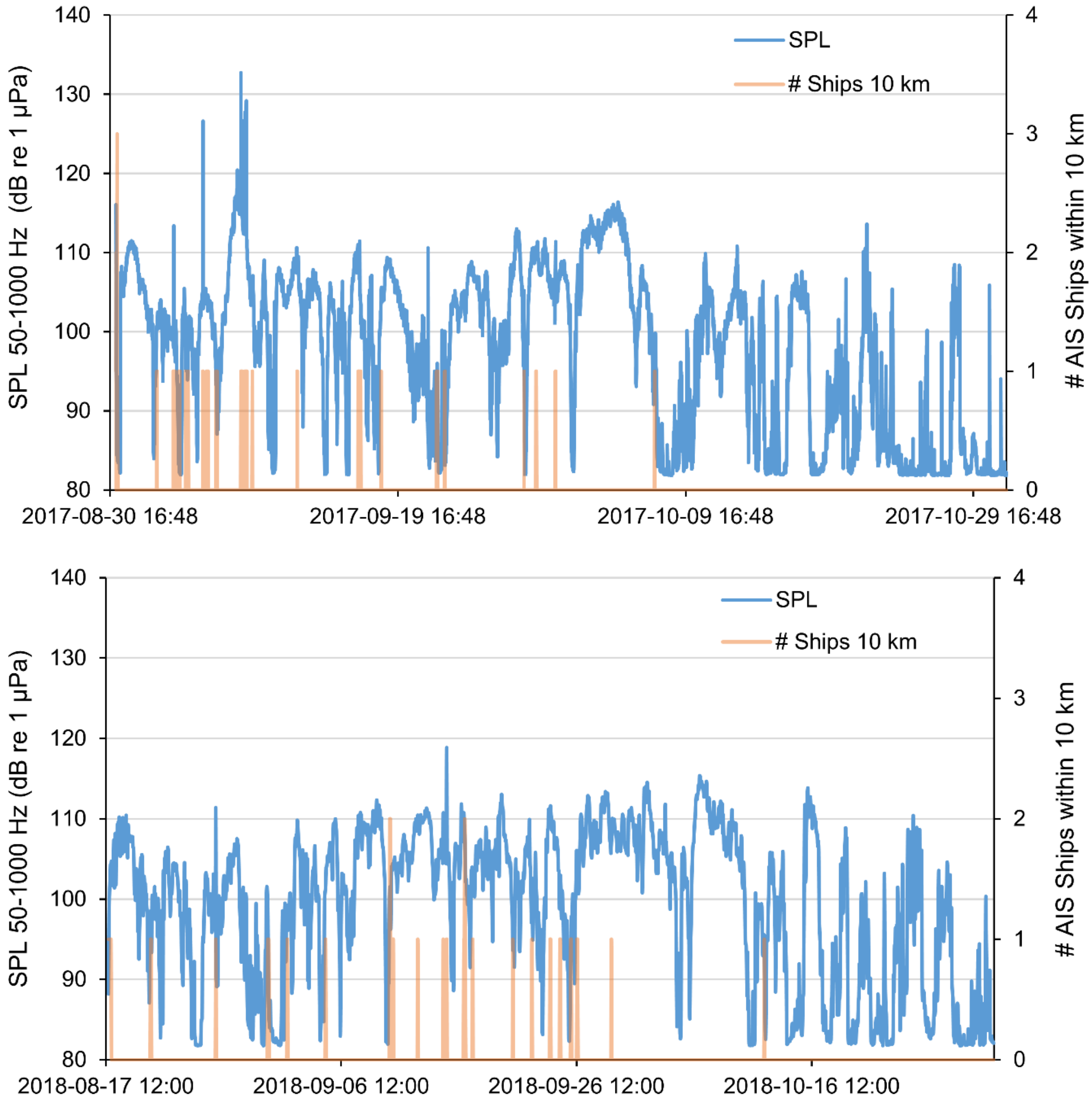

Figure 2. Time series of sound pressure level (SPL) in the 50-1000 Hz band in 2017 (upper) and 2018 (lower) (blue lines) and the number of AIS ships within 10 km of the acoustic recorders (orange lines). Most of the high SPL values are caused by increased wind speed, except when they overlap with ship activity. The low SPL values are from calm periods when ships were absent.

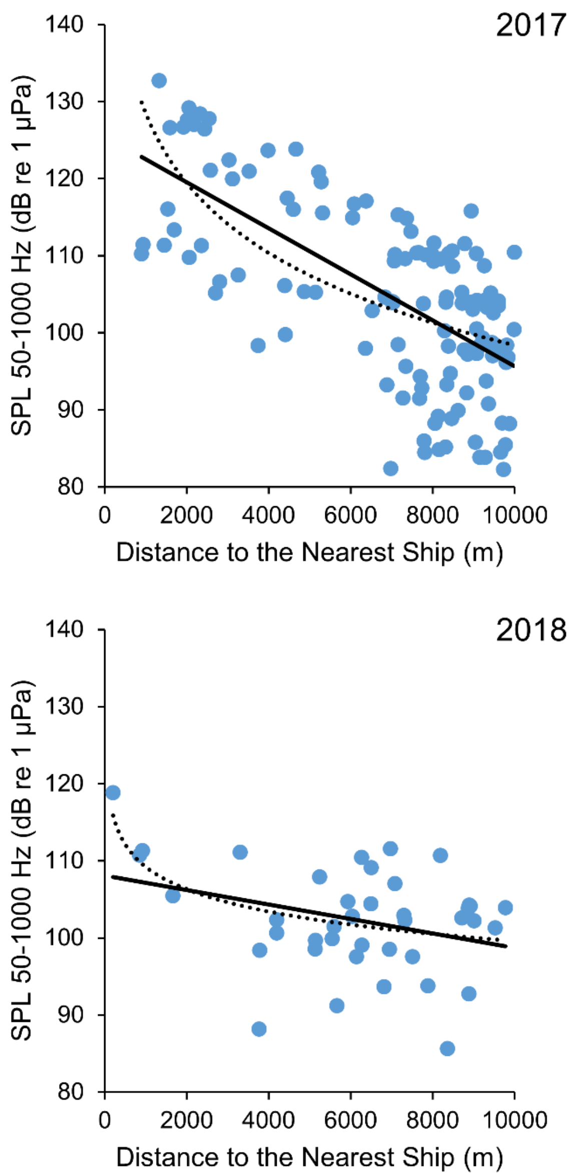

Figure 3. The relationship between sound pressure level (SPL) in the 50-1000 Hz band and distance to the nearest AIS ship in 2017 (upper) and 2018 (lower). Linear lines of best fit are shown as solid lines, and logarithmic lines of best fit as dotted lines. The logarithmic slope is -14.8 for 2017 and -11.9 for 2018 (Table 1).

Table 1. Slope estimates (± S.E.) for the impact of four different variables related to vessel traffic (presence of ship noise, number of ships within 10 km of the acoustic recorder; distance to the nearest ship; speed of the nearest ship) on sound pressure level (SPL) in three frequency bands (low: 50-1000 Hz; med: 1-10 kHz; high: 10-48 kHz).

	Ship Noise Present	# Ships 10 km (dB/# ships)	Distance Nearest Ship (dB/log10 m)	Speed Nearest Ship (dB/kts)
2017 – Low	n.s.	1.1 ± 0.5 *	-14.8 ± 2.3 ***	n.s.
2018 – Low	2.3 ± 1.1 *	3.0 ± 1.0 **	-11.9 ± 2.1 ***	n.s.
2017 – Med	-2.2 ± 0.5 ***	n.s.	-6.6 ± 1.9 ***	n.s.
2018 – Med	n.s.	2.2 ± 1.1 *	-4.8 ± 1.9 *	n.s.
2017 – High	-2.8 ± 0.3 ***	-1.9 ± 0.4 ***	n.s.	n.s.
2018 – High	n.s.	n.s.	n.s.	n.s.

n.s. = not statistical significant; * = $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

3.3 Analysis 2: Source level estimates of ships in acoustic data

Across both years of data collection, only 14 audio files had ships that came within 2.5 km of the acoustic recorders and were used for estimates of source level estimates. These 14 source level estimates were from 8 individual ships. Five of these ships only provided single source level estimates, whereas one ship (F/V Martin Bergmann) traveled within 2.5 km of the acoustic recorder three times in 2017, a second ship (Travestern; class = tanker) traveled within 2.5 km of the acoustic recorders three times in 2017, and another ship (CCGS Sir Wilfrid Laurier; class = government) traveled within 2.5 km of the acoustic recorder twice in 2017 and once in 2018. Because there were so few source level estimates (both the total number of ships measured and repeated measurements on the same ship), we were unable to conduct statistical analyses on these source level estimates, and instead, present the raw data for these source level estimates as broadband source levels in Table 2, 1/3-octave and PSD source levels in Figure 4, and the raw values for the 1/3-octave source levels in Appendix 1.

When examining the source levels across vessels, particularly when paying attention to vessel class, some patterns become clear. First, the four loudest source levels are from one tanker with three estimates (Travestern) and a bulk carrier (Qamutik). These four source levels were all above 180 dB re 1 μPa at 1 m, which is more than 10 dB greater than all but two other source levels. The Travestern, which was measured three times, had source levels ranging from 182.4 to 185.6 dB re 1 μPa at 1 m. The other bulk carrier in the dataset, Mitiq, is nearly identical to Qamutik in all physical characteristics, yet had a source level of 171.8 dB re 1 μPa at 1 m. Possible explanations for why Mitiq had a significantly lower source level than Qamutik include different propagation characteristics in the path between the vessel and the acoustic recorder, source directionality, or possibly that Mitiq operates differently than Qamutik and actually does have a lower source level.

The other types of vessels in the dataset were all significantly smaller than the tankers and bulk carriers discussed in the previous paragraph, with the aforementioned vessels all being > 130 m long, whereas the remaining vessels were all < 90 m. Vessel length is an important factor in the source level of the vessel (Chion et al., 2019; Simard et al., 2016; Veirs et al., 2016), therefore it is not surprising that all of the remaining vessels have much lower source levels. The CCGS Sir Wilfrid Laurier, a coast guard vessel, is the largest of these remaining vessels, and had three separate source level measurements, all of which ranged between 162.7 and 163.6 dB re 1 μPa at 1 m. CCGS David Thompson, the other coast guard vessel in this dataset, is about 1/3 the length of the Laurier, yet had a roughly equivalent source level at 163.6 dB re 1 μPa at 1 m.

The Martin Bergmann, the fishing vessel used to deploy the moorings and being used for other science missions in the area around the moorings, had three source level measurements in 2017. These source level measurements, which were with the vessel > 1.5 km from the mooring, were all relatively low, although consistent with the other smaller vessels in the dataset, and ranged from 167.4 to 170.1 dB re 1 μPa at 1 m.

Table 2. Source level estimates for ships that traveled within 2.5 km of the acoustic recorders. Ships with a dash followed by a number represent multiple source level measurements on the same ship in the same year. All received levels and source level estimates are provided as a broadband (50 Hz – 48 kHz) root mean squared sound pressure level. Note that speed data was not available for the Martin Bergmann, so NA is listed. Distance is the horizontal distance from the recorder location to the ship location.

Ship	Class	Length (m)	Date	Distance (m)	Speed (kts)	Received Level (dB re 1 μPa)	Source Level (dB re 1 μPa at 1 m)
2017-2018 Dataset							
Arcticaborg	Offshore Supply	65	2017-09-30	1447	10.5	114.7	167.7
Qamutik	Bulk Carrier	136	2017-09-06	1590	14.2	127.1	180.8
Martin Bergmann – 1	Fishing	20	2017-08-31	1539	NA	117.2	170.1
Martin Bergmann – 2	Fishing	20	2017-09-04	1690	NA	115.4	169.3
Martin Bergmann – 3	Fishing	20	2017-09-04	2059	NA	111.7	167.4
Sir Wilfrid Laurier – 1	Government	83	2017-09-17	971	6.2	112.9	162.7
Sir Wilfrid Laurier – 2	Government	83	2017-09-17	1133	6.1	112.2	163.3
Travestern – 1	Tanker	161	2017-09-08	1324	7.5	133.6	185.6
Travestern – 2	Tanker	161	2017-09-08	1918	8.2	127.7	182.4
Travestern – 3	Tanker	161	2017-09-09	2113	5.5	130.0	185.4
2018-2019 Dataset							
David Thompson	Government	29	2018-09-15	1095	9.0	112.9	163.6
Fathom Wave	Tug	19	2018-09-26	2410	6.7	109.2	169.9
Mitiq	Bulk Carrier	136	2018-09-15	1457	14.7	119.7	171.8
Sir Wilfrid Laurier	Government	83	2018-08-26	1409	10.9	111.9	163.6

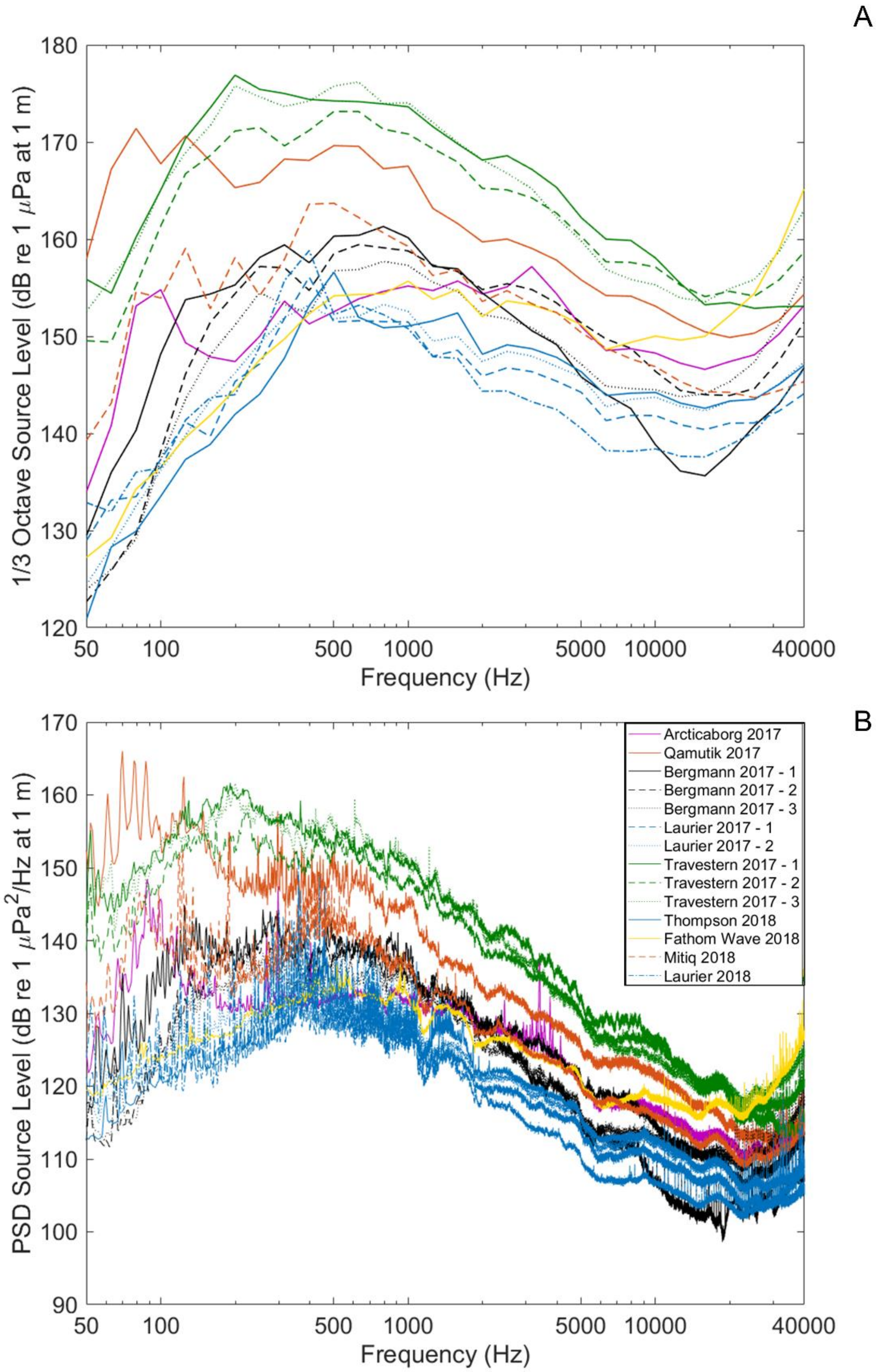

Figure 4. 1/3-octave source levels (A) and power spectral density (PSD) source levels (B) for all vessels that came within 2.5 km of the acoustic recorders. Lines are colour-coded by vessel category, where purple is an offshore supply vessel, orange is bulk carriers, blue is government ships, green is a tanker, yellow is a tug, and black is a fishing/research vessel.

The other two vessels in the dataset were an offshore supply vessel (Arcticaborg) and a tug (Fathom Wave). The offshore supply vessel was quite a bit larger (67 m), with an estimated source level of 167.7 dB re 1 μPa at 1 m, whereas the tug was the smallest vessel in the dataset, yet had the highest source level of all vessels < 90 m other than the Martin Bergmann (169.9 dB re 1 μPa at 1 m), likely because it was laden with supplies for the communities.

3.4 Analysis 3: Presence of marine mammal and fish vocalizations in acoustic data, and overlap with ships

The most common bioacoustic signals in this dataset were from ringed seal and fish (Figure 3A, B). We assume that the fish calls are from Arctic cod based on recordings made in captivity (Riera et al., 2018) and the prevalence of Arctic cod in this ecosystem (Majewski et al., 2016). However, these sounds could easily be made by other gadid (cod) species (Halliday et al., 2020b; Pine et al., 2020) or even from species in other genera, simply because no other studies have identified the vocalizations made by these other species. Both ringed seals and fish were detected on nearly every day between August and October (Figure 4). There was quite a bit of variation from day to day and throughout the season, but generally, ringed seal vocalizations were more numerous in October compared with August and September. Fish showed numerous spikes in vocalization activity that were not consistent between years.

Bearded seal vocalizations (Figure 3C) were entirely absent in September, but were prevalent in early August 2018 and occurred occasionally in October of both 2017 and 2018 (Figure 4). Bearded seal vocalization behaviour has previously been linked to the presence of sea ice, and onset of calling in the autumn typically begins as sea ice starts to form (Halliday et al., 2019a, 2018a), consistent with results from this study.

Beluga whales were detected on a single day, 7 October 2017 (Figure 4). We detected a total of seven whistles over five two-minute files (1-2 whistles per file) during a 2.5 hour period. The whistles were incredibly stereotyped (Figure 4D), lasting roughly 1.2 seconds, ranging between 4.95 and 5.72 kHz, with a peak frequency at roughly 5.5 kHz. Based on the consistent shape of the whistle, there is a good chance that this sound was made by a single beluga.

Ship noise was common in the acoustic data throughout August and September, but did not occur after 9 October in 2017 or after 22 October in 2018, and in general, ship noise was spread out in October (Figure 6). The most ship noise occurred in early August 2018, and occurred on days when ringed seals, bearded seals, and fish were detected. Throughout both years of data, ship noise overlapped on days with fish and ringed seal detections, so it can be assumed that ringed seals and fish are almost always exposed to ship noise when a ship travels through this area. Given that bearded seal vocalizations are seasonal, and that bearded seals may not vocalize even when they are present, it is unknown whether bearded seals were being exposed to ship noise when they were not detected.

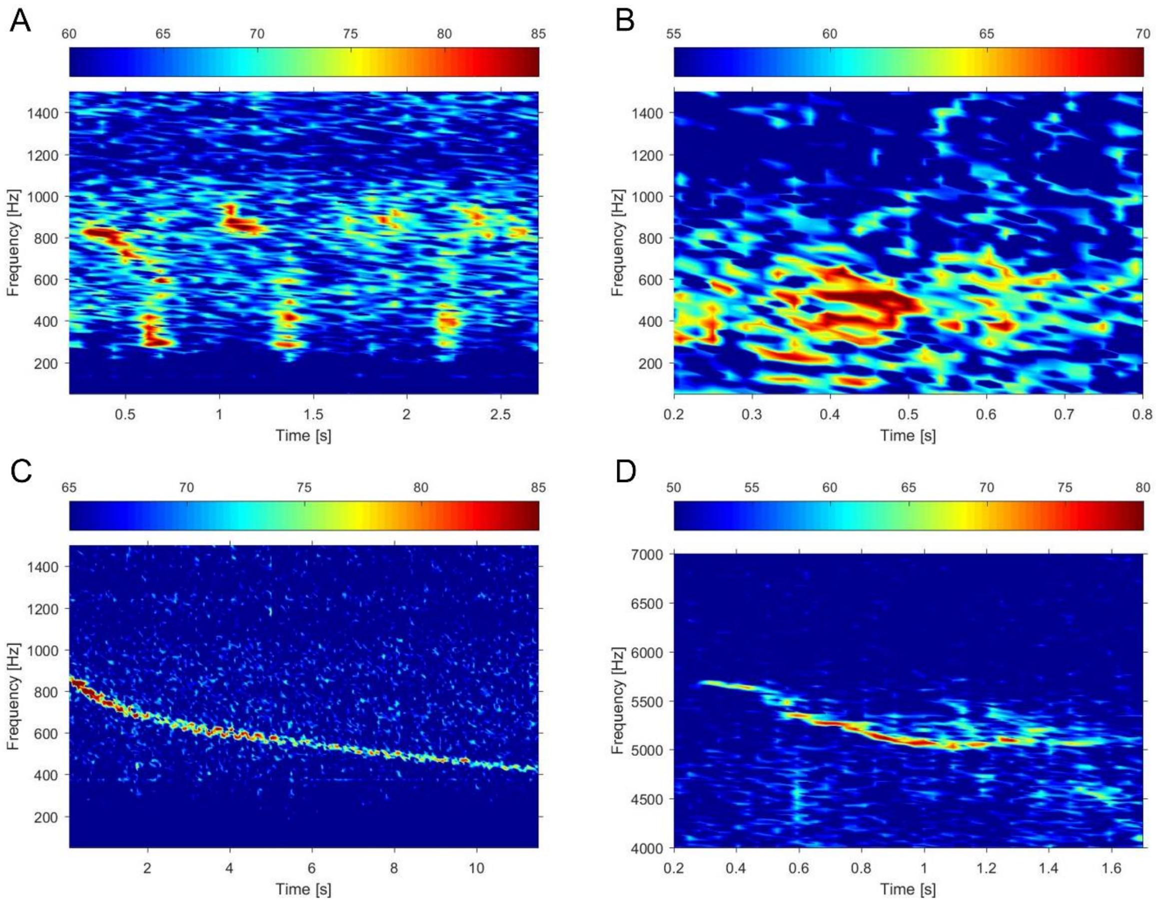

Figure 5. Example vocalizations of A) ringed seals (FFT = 12,000), B) fish (FFT = 4,000), C) bearded seals (FFT = 12,000), and D) belugas (FFT = 6,000). The colour bar is measured as power spectral density (dB re 1 μPa^2/Hz). The range of the axes and colour bar scales vary between panels.

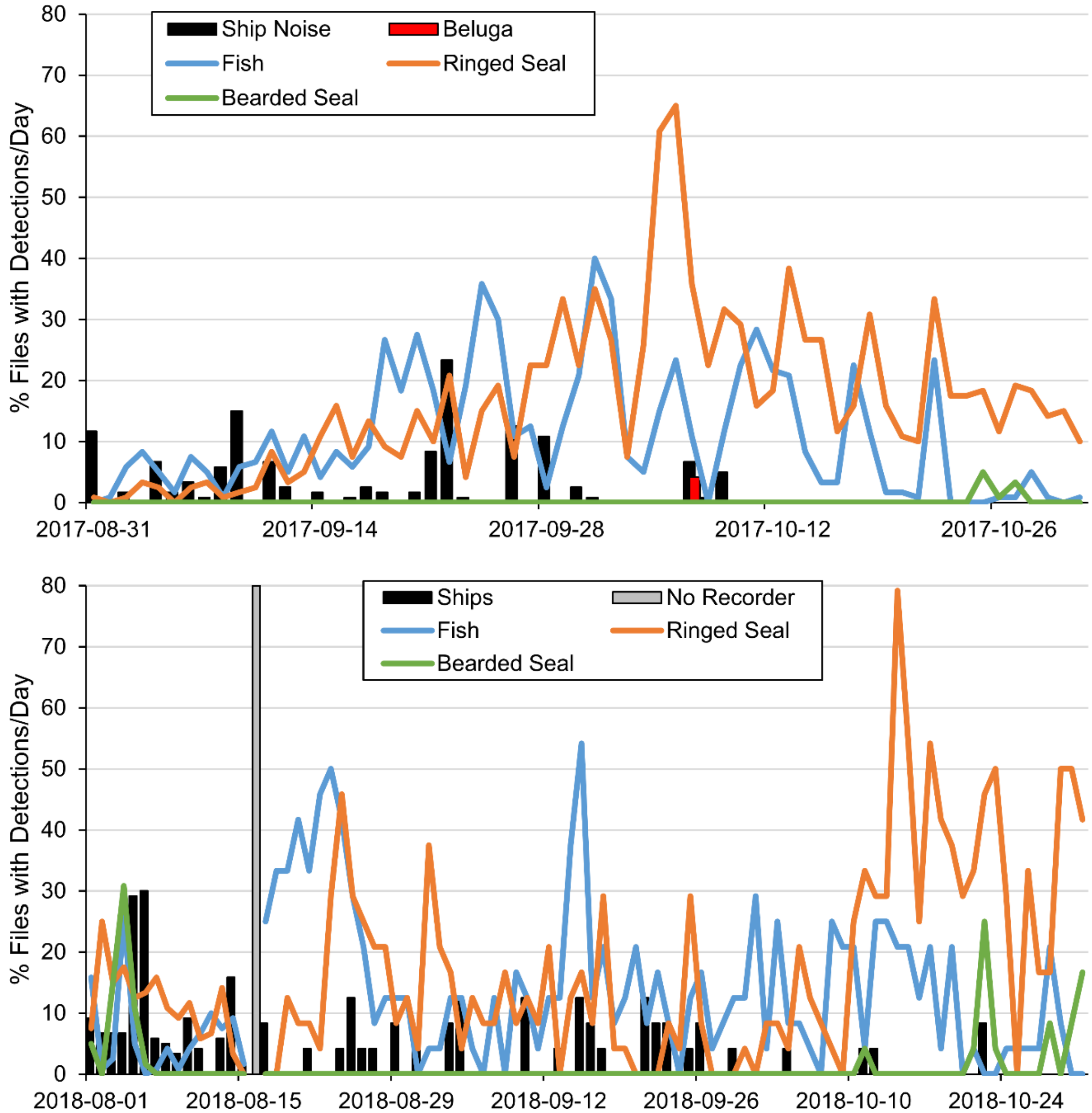

Figure 6. Time series of detections (% files/day) of ringed seals, bearded seals, fish sounds, belugas, and ship noise for acoustic data collected southwest of Cambridge Bay, Nunavut. The data in 2017 was from 31 August to 31 October, and in 2018 was from 1 August to 31 October, with a one day break on 16 August when the acoustic recorder was recovered and redeployed. Note that beluga whales were only detected on a single day in October 2017.

4. Conclusions

4.1 Summary of Study Findings

We analyzed underwater sound levels during the shipping season in 2017 and 2018 from acoustic recorders located southwest of Cambridge Bay in Dease Strait near the Finlayson Islands. We specifically examined the influence of ship traffic on underwater noise, measured source levels of ships, and examined the prevalence of sounds made by marine animals and the overlap between these animals and ship traffic. 15 unique ships with AIS transponders (or a GPS track) came within 10 km of the acoustic recorder in 2017, and 12 unique ships in 2018. Of these, there were a total of 14 passages by eight unique ships within 2.5 km of the acoustic recorder, which were used to measure the source levels of individual ships. The number of ships within 10 km of the recorder, as well as the distance to the nearest ship, were both important predictors of underwater noise levels. Estimated ship source levels ranged from 163.3 to 185.6 dB re 1 μPa at 1 m (bandwidth: 20 Hz to 48 kHz), with the higher source levels belonging to large ships like tankers and bulk carriers, and the lower levels for smaller ships like tugs and research ships. Both ringed seal and fish vocalizations were common in August-October, and typically occurred on the same days that ship noise was present. Bearded seal vocalizations were also common in early August 2018, and similarly occurred in close proximity to ship noise. These species therefore are likely exposed to all of the ship noise occurring at this site. Beluga whales were only present on a single day in this study period.

4.2 Implications for future data collection

These passive acoustic datasets have provided valuable examples for the implications of deployment location and recorder duty cycle on the quality of ship noise measurements within recordings. More restrictive duty cycles, where the recorder is only on for a few consecutive minutes every hour (like the 2018-2019 dataset) can lead to ships being entirely missed, and closest point of approach that are valuable for source level measurements are also missed. Less restrictive duty cycles that repeated every few minutes (like the 2017-2018 dataset) are less likely to miss a ship, but may still miss important events such as the closest point of approach, although this dataset always still had useable source level measurement when a ship traveled close enough. If a duty cycle is necessary, one must weigh the likelihood of capturing the event, such as a ship passage, against its frequency of occurrence and importance of recording the entire event, in order to calculate the optimal cycle. As evidenced here, any duty cycle can be restrictive and can miss the most opportune time for measuring source levels, therefore, for future data collection focused on ship noise, continuous recordings are recommended whenever possible.

Beyond the duty cycles of the acoustic recorders, the placement of the recorder is also key. Both of these datasets captured ships transiting through Dease Strait, but many ships only just barely came within 10 km of the acoustic recorder. A better placement would be directly in the main shipping route, whereas these recorders were a few kilometers away from the shipping corridor and were tucked beside an island that ships went around. Placing a recorder on the west side of the Finlayson Islands would avoid this issue in the future, but other key locations include slightly further south in Dease Strait to the west of Qikirtaarjuk Island, south of Cape Colborne or at the western entrance to Queen Maude Gulf, or the entrance to Cambridge Bay from Dease Strait. All of these locations would capture close passages by vessel traffic, and if multiple recorders were deployed across the shipping corridor in a transect, then all vessel traffic would be recorded and source level measurements could be obtained for every vessel transiting through the region.

5. Acknowledgements

We are extremely grateful to Bill Williams, Svein Vagle, and Mike Dempsey at the Institute of Ocean Sciences, Fisheries and Oceans Canada, for collecting these acoustic datasets and for sharing the data to make this analysis possible. We are also grateful to Annika Heimrich for helping with the bioacoustic analysis, and Steve Insley for providing editorial feedback. Satellite AIS data were provided by MEOPAR. Funding for this analysis was provided by Transport Canada and Fisheries and Oceans Canada.

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Appendix

Appendix 1. Table of values for 1/3-octave source levels (dB re 1 μPa at 1 m) of all vessels that came within 2.5 km of the acoustic recorders. Centre frequency for each 1/3-octave band (Hz) is labeled at the top of each column. Parameters (vessel class, distance, speed) available in Table 2. Page 1/3.

	50	63	79	100	126	158	199	251	316	398
Arcticaborg 2017	134	140.8	153.1	154.8	149.3	147.9	147.4	150	153.6	151.3
Qamutik 2017	158	167.2	171.4	167.8	170.6	168.1	165.3	165.9	168.2	168.1
Bergmann 2017-1	129.5	136	140.3	148.2	153.8	154.4	155.3	158.1	159.4	157.6
Bergmann 2017-2	122.7	125.9	129.7	138.2	146.1	151.4	154.4	157.2	157.1	154.7
Bergmann 2017-3	123.9	126	129.2	137.3	143.5	148.1	151.2	154.5	153.2	152.4
Laurier 2017-1	129	133.1	133.5	137.3	141.2	139.7	145.3	147.2	151.8	156.1
Laurier 2017-2	124.5	128.3	132.5	136.2	139.8	143.4	146.2	149.3	152	153.2
Travestern 2017-1	155.9	154.4	160.2	165.1	170.4	173.5	176.9	175.4	175	174.4
Travestern 2017-2	149.5	149.4	155.2	161.4	166.7	168.6	171.1	171.5	169.6	171.2
Travestern 2017-3	152.6	155.9	159.4	165.2	168.9	171.7	175.8	174.6	173.7	174.2
Thompson 2018	120.9	128.3	129.9	133.5	137.3	138.9	142	144	147.8	153.2
Fathom Wave 2018	127.2	129.3	134.3	136.5	139.6	141.9	144.5	147.6	149.7	152.3
Mitiq 2018	139.3	143.1	154.6	153.9	159.1	152.8	158.1	154.2	157.9	163.6
Laurier 2018	132.9	131.9	136	136.5	141.4	143.7	144	148.9	155.7	158.8

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	501	631	794	1000	1259	1585	1995	2512	3162	3981
Arcticaborg 2017	152.5	153.8	154.6	155.2	154.7	155.7	154.4	155.1	157.2	154.4
Qamutik 2017	169.6	169.6	167.2	167.5	163.2	161.6	159.7	160	159.1	157.8
Bergmann 2017-1	160.3	160.4	161.3	160.2	157.2	156.9	154.5	152.6	150.6	149.2
Bergmann 2017-2	158.5	159.4	159.1	158.8	157.3	156.7	154.8	155.4	154.8	153.4
Bergmann 2017-3	156.7	156.9	157.7	157.3	155.6	154.6	152.2	151.8	150.9	149.3
Laurier 2017-1	151.5	151.6	151.5	151.5	147.9	148.6	145.9	146.8	146.4	145.4
Laurier 2017-2	151.8	152.1	153.3	152.6	149.5	150	147.4	148.4	148	146.9
Travestern 2017-1	174.2	174.2	173.9	173.6	171.6	169.8	168.1	168.6	167.2	165.3
Travestern 2017-2	173.2	173.1	171.3	170.8	169.3	167.9	165.2	165.1	164.3	162.7
Travestern 2017-3	175.8	176.2	174	174	172	170	168.2	166.8	165.2	162.2
Thompson 2018	156.6	152	150.9	151.1	151.6	152.4	148.1	149.1	148.7	147.8
Fathom Wave 2018	154.2	154.3	154.4	155.7	153.8	154.8	152	153.6	153.2	152.4
Mitiq 2018	163.7	162.2	160.6	159.2	156.3	156.9	153.6	154.7	153.4	152.4
Laurier 2018	152.2	153.2	152.2	150.8	147.9	147.7	144.3	144.4	143.3	142.5

Appendix 1. Page 3/3.

	5,012	6,310	7,943	10,000	12,589	15,849	19,953	25,119	31,623	39,811
Arcticaborg 2017	151	148.5	148.7	148.3	147.2	146.6	147.4	148.1	150.2	153.2
Qamutik 2017	155.8	154.2	154.1	153.1	151.6	150.5	149.9	150.3	151.7	154.3
Bergmann 2017-1	145.8	144	142.6	138.8	136.1	135.6	137.9	140.8	143.1	146.7
Bergmann 2017-2	151.4	149.7	148.8	146.4	144.4	144	143.9	144.6	147.5	151.4
Bergmann 2017-3	147.1	144.9	144.6	144.5	143.8	144.1	145.3	147.3	151.3	156.2
Laurier 2017-1	144.2	141.3	141.9	141.8	140.9	140.4	141.1	141.1	142.3	144.1
Laurier 2017-2	145.8	142.7	143.5	143.7	142.8	142.3	143.3	143.5	145.1	147.3
Travestern 2017-1	162.2	160	159.9	158.1	155.5	153.2	153.5	152.9	153.1	153.1
Travestern 2017-2	160.3	157.7	157.6	157.1	155.3	154.1	154.6	154.1	155.8	158.6
Travestern 2017-3	159.8	156.9	155.9	155.3	154	153.6	154.9	155.8	158.7	162.9
Thompson 2018	146.3	143.9	144.1	144.2	143.1	142.6	143.3	143.5	145.1	147
Fathom Wave 2018	151.2	148.6	149.4	150	149.6	150	152.1	154.4	159	165.1
Mitiq 2018	150.4	148.8	147.7	146.9	145.4	144.3	144.2	143.7	144.4	145.3
Laurier 2018	140.5	138.2	138.2	138.4	137.6	137.6	138.8	140.2	143.1	146.6