

**Underwater soundscape and radiated noise from ships in Eclipse Sound, NE Canadian Arctic**

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## ABSTRACT

Commercial shipping is increasing in the eastern Canadian Arctic, raising concerns about changes to the marine soundscape and potential impacts to Arctic marine mammals.

Underwater radiated noise was measured for four types of commercial ships (bulk carrier, general cargo, fuel and chemical tankers, and an icebreaker) transiting Eclipse Sound, Nunavut during shipping months from Oct, 2018 through Sep 2019. Acoustic data were collected from two locations along the regular shipping route using seafloor-mounted acoustic recorders. Ship location and operational information was combined with received sounds to calculate acoustic characteristics of individual ship transits. Ship sound measurements included broadband (20 Hz-4 kHz) sound pressure level ( $SPL_{BB}$ ), sound pressure spectrum level (SPSL) at the closest point of approach, and SPL in three frequency bands to evaluate masking of communication signals produced by narwhals and ringed seals. Monthly (Jul, Aug, Sep, Oct) measurements were also calculated for periods selected to exclude sound from ships and for all recorded periods to compare the soundscape including and excluding sounds from nearby ships. Sound levels in all frequency bands were elevated for minutes to hours with each ship transit. The icebreaker and tankers had the highest sound levels, followed by general cargo and bulk carrier. Noise was greater at the stern than the bow aspect for all ship types (*e.g.* the icebreaker reached  $SPL_{BB}$  120 dB at range 4 km from the bow and 15 km from the stern). Long-range ship sound <200 Hz was present in median monthly SPSL including and excluding nearby ships at the deeper site. The shallower more acoustically sheltered site had substantially lower sound levels in all months, except during ship transits. The results presented facilitate prediction of underwater sound levels at higher density of shipping traffic in the future and provide a baseline description of the natural soundscape with minimal shipping.

## LIST OF ABBREVIATIONS

dB: decibel

kts: Nautical miles per hour

m: Meter

d, h, min, s: Time unit abbreviations (day, hour, minute, second)

Jul, Aug, Sep, Oct: Abbreviations for months (July, August, September, October)

## LIST OF ACRONYMS

AIS: Automated Information System

BIMC: Baffinland Iron Mines Corporation

CPA: Closest Point of Approach

HARP: High-frequency Acoustic Recording Package

LSR: Listening Space Reduction

LRR: Listening Range Reduction

LTSA: Long-term Spectral Average

MI: Milne Inlet

MRM: Mary River Mine

PI: Pond Inlet

SIO: Scripps Institution of Oceanography

SPL<sub>BB</sub>: Broadband received sound pressure level 20-4000 Hz in units of dB re 1  $\mu$ Pa

SPSL: Sound pressure spectrum level in dB re 1  $\mu$ Pa<sup>2</sup>/Hz

## INTRODUCTION

Throughout the world's oceans, commercial ships are a significant source of underwater sound (Ross, 1976; Hildebrand, 2009), raising concerns about potential impacts these sounds have on aquatic ecosystems and species (Clark *et al.*, 2009; Nowacek *et al.*, 2007). Ship traffic is increasing rapidly in some areas of the Arctic (Dawson *et al.*, 2018) and is projected to accelerate as decreasing sea ice coverage (Smith and Stephenson, 2013) opens new opportunities for industrial development, commercial shipping, and tourism across the region (Theocharis *et al.*, 2018). From 2005 to 2015, vessel traffic in the Canadian Arctic increased by an estimated 75% (Pizzolato *et al.*, 2016). Reductions in sea ice and the use of icebreaking ships have lengthened the Canadian Arctic shipping season (Stroeve *et al.*, 2014; Smith and Stephenson, 2013), while other factors such as tourism and industrial development may play a larger role in some areas.

Eclipse Sound in the eastern Canadian Arctic is one such region where ship traffic is increasing due to tourism and industrial development. The community of Pond Inlet, located on Eclipse Sound north Baffin Island (Fig. 1), experienced almost triple the annual shipping traffic during 2011-2015 when compared to the decade 1990-2000 (Dawson *et al.*, 2018). This was the largest proportional increase in shipping of any region in the Canadian Arctic. The change was due to increasing numbers of tourism-related vessels (*i.e.* passenger ships and pleasure craft) and in bulk carrier and tanker ships. While increasing traffic by tourism-related vessels is widespread across the Canadian Arctic, the additional cargo ship traffic past Pond Inlet was associated with the 2010-2015 development of the Baffinland Iron Mines Corporation (BIMC) Mary River Mine (MRM) on North Baffin Island.

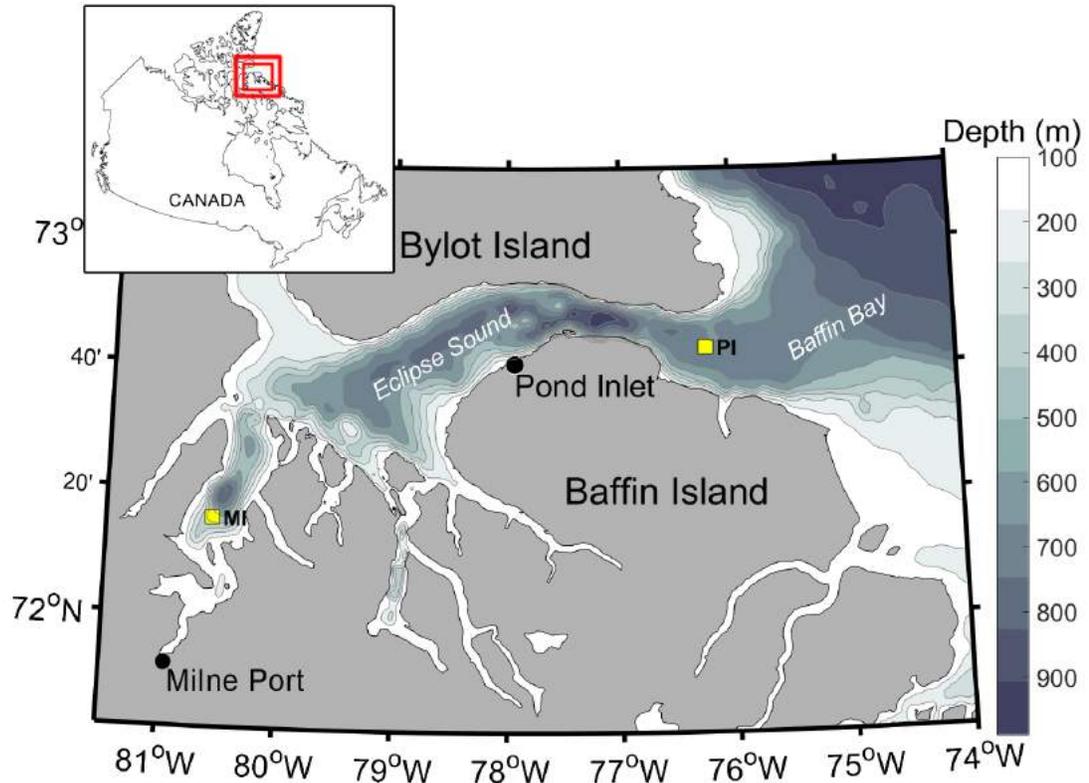


Figure 1. Long-term acoustic recording sites in Eclipse Sound, N. Baffin Island, Nunavut Territory, Canada. High-frequency Acoustic Recording Packages (HARPs) were deployed at the Pond Inlet site (PI; depth 670 m) from September 28, 2018 through September 21, 2019. A second location in Milne Inlet (MI; depth 313 m) recorded acoustic data from Sep 29, 2018 to Aug 18, 2019. The Baffinland Mary River Mine shipping terminal is located at Milne Port. Depth contour intervals 100 m.

Starting in 2015, bulk carrier ships began service to the newly constructed Milne Port (BIMC, 2015), a deepwater shipping terminal in Milne Inlet at the southeast end of Eclipse Sound (Fig. 1). Iron ore from the MRM is loaded onto bulk carriers in Milne Port and shipped to market via northern sea routes. Reported annual ore production has increased from 0.92 million metric tons (MT) in 2015 to 5.86 MT in 2019. Annual mining-related shipping has increased proportionately with ore production and includes bulk cargo ships, tugs, general cargo and

tanker ships (Appendix I). Eclipse Sound ship traffic occurs primarily during open water months from August through September, with an extension of the shipping season created in 2018 by the addition of an ice management vessel to escort ships servicing the MRM during July and October periods of ice cover. Increased ship traffic has raised concerns among community members, marine resource managers, and other stakeholders about the potential impacts of those sounds on the natural underwater soundscape and marine mammals (Ariak and Olson, 2019). Intensity of shipping in the Eclipse Sound region is projected to substantially increase with a proposed 2021 increase to 12 MT iron ore production at the MRM (BIMC, 2018).

Sources of sound in the ocean are abundant and varied, but generally can be classified as natural in origin or man-made. Low-frequency natural sounds less than 200 Hz are produced by earthquakes and surface wave interactions (Hildebrand, 2009). Wind-driven waves are a major contributor to underwater sound above 200 Hz and levels decrease by about 6 dB/octave above 500 Hz (Wenz, 1962; Urik, 1983). In Arctic waters, a positive strong relationship between sound pressure level and wind speed occurs during ice-free conditions, but is weaker during periods of ice cover (Roth *et al.*, 2012; Halliday *et al.*, 2020). Sounds associated with mechanical activity of sea ice can also be a major component of the underwater soundscape across frequencies from 20 Hz to > 4 kHz (Milne and Ganton, 1964; Kinda *et al.*, 2015). Sounds produced by marine animals, particularly marine mammals, can also be significant features of the natural underwater Arctic soundscape. For example, sound pressure levels between 50 Hz and 10 kHz increase with greater presence of bearded seal vocalizations in the Western Canadian Arctic (Heimrich *et al.*, 2020).

Marine mammals produce underwater sounds for navigation, foraging, socializing, and reproduction. In the Eclipse Sound region, the most abundant marine mammal species are ringed seals (*Pusa hispida*), which occur year-round (Yurkowski *et al.*, 2018), and narwhal

(*Monodon monoceros*), which are present annually from July-Oct (Marcoux *et al.*, 2019; Richard *et al.*, 2010). Ringed seals produce barks and growls in the 50-400 Hz range and yelps at frequencies to > 1 kHz (Jones *et al.*, 2014; Stirling *et al.*, 1983; Stirling, 1973). Narwhals produce high-frequency echolocation clicks from 20 kHz to > 100 kHz (Koblitz *et al.*, 2016; Rasmussen *et al.*, 2015). They also produce sounds for communication, including whistles from about 600 Hz up to 14 kHz and burst-pulse sounds from 800 Hz to 10 kHz (Marcoux *et al.*, 2012; Shapiro, 2006; Ford and Fischer, 1978).

Sounds from distant ships are a major underwater sound source from 10-200 Hz (Hildebrand, 2009; Wenz, 1962). Low-frequency sounds are generated by cavitation of the ship's propeller and can be measured in ambient noise levels throughout the world's oceans at great distances from any shipping traffic (Širović *et al.*, 2016; McDonald *et al.*, 2006). Shipping traffic is also a source of higher-intensity short-term (transient) noise events as ships pass closer to a listener's location. At closer ranges, ship sounds occupy frequencies to above 10 kHz (McKenna *et al.*, 2012; Gassmann *et al.*, 2017). These transient sounds from ships can be detected above the ambient sound levels when ships are at ranges of tens to > 100 km (*e.g.* Zhu *et al.*, 2018). Evaluating effects to marine mammals resulting from underwater ship sounds generally addresses two areas. One is the effect of long-range sound propagation on the ambient sound environment. Ambient sound levels can become louder as additional shipping traffic occurs within a region. The other is the effect of transient noise caused by ships transiting within an area of habitat. Noise from a transiting ship may have direct effects on individuals and groups of marine mammals along the ship's track.

Two concerns about how underwater noise from ships impacts marine mammals stem from noise-induced alteration of physiology or natural behavior (acoustic disturbance) and the potential for masking of biologically important signals where ship sounds overlap in frequency

(Southall *et al.*, 2007; Gomez *et al.*, 2016; Erbe *et al.*, 2016). Acoustic disturbance of marine mammals has been extensively studied through observation of animal behavior at various levels of underwater noise from ships. Generalized guidelines have been developed to help predict threshold broadband sound pressure levels ( $SPL_{BB}$ ) at which behavioral disturbance or avoidance of the sound source may occur for several taxonomic groups of marine mammal species (Southall *et al.*, 2007). Narwhal and ringed seals are classified in this system as mid-frequency cetaceans and pinnipeds, respectively. The generalized received  $SPL_{BB}$  at which behavioral disturbance is expected to occur for those taxonomic groupings is 120 dB, although actual observed behavioral disturbance has occurred at a wider range of received levels in published studies for narwhal and ringed seal (Golder, 2020; Golder, 2019; Golder, 2018; Southall *et al.*, 2007; Finley *et al.*, 1990). Masking of acoustic signals caused by the introduction of underwater sound from ships is evaluated at discrete frequency bands that overlap with biologically important signals, such as echolocation or social communication, and with consideration for the hearing systems of the species of interest. Although a signal, such as a whistle produced by narwhals, might occupy a narrow frequency band, there is some critical band around that frequency where other sounds from the environment may interfere with the ability of another animal to hear it. To account for these hearing system effects, sound levels are evaluated in  $1/3^{rd}$  octave frequency bands around the biologically relevant frequency being considered (Erbe *et al.*, 2016). Acoustic masking caused by changing levels of noise in the environment can be estimated as Listening Space Reduction (LSR; Erbe *et al.*, 2016), which is a function of the amount of potentially masking noise added by a source, such as a transiting ship, relative to some reference background sound level, such as the mean sound level of that frequency band in the absence of the additional sound source (Erbe *et al.*, 2016; Pine *et al.*, 2018).

This study reports levels of underwater sound associated with the natural acoustic environment and with man-made noise from shipping at two locations in Eclipse Sound on N. Baffin Island in the region of the community of Pond Inlet, Nunavut. Analysis of 2018 to 2019 regional Automated Information System (AIS) ship tracks and underwater acoustic recording data were completed to determine quantity and spatial patterns of ship traffic and to estimate underwater sound levels emitted by ships. Measurements of underwater sound levels during the July-Oct shipping season are presented for periods including and excluding times when ships transited past the recording site. Monthly sound pressure spectrum levels (SPSL) of periods selected to minimize recorded sounds from transiting ships are representative of the 'natural' acoustic environment. Monthly SPSL from all recorded periods, including ship transits and inter-ship periods, represent the soundscape including the total contribution of underwater sound from ships. Acoustic characteristics of transient underwater sound from commercial ships are quantified in relation to vessel design and operational parameters for the most common ship types. Characteristics were selected to prioritize evaluation of underwater shipping noise with respect to narwhal and ringed seal behavioral disturbance and potential masking of communication signals.

## METHODS

### A. Ship transit information

Satellite Automated Information System (AIS) data were obtained from ExactEarth ([www.ExactEarth.com](http://www.ExactEarth.com)) on ship traffic within 100 km of two acoustic recording stations. Locations were extracted from AIS data for all ships transiting past the recording sites, including time, latitude and longitude, speed, heading, maximum draft, Maritime Mobile Service Identity (MMSI) number, vessel name, vessel type and cargo class. Additional ship

specification data, including gross and deadweight tonnage (*i.e.* weight carrying capacity), were obtained from Lloyd's Registry of Ships. Distances between ship location and the recording location were used to calculate the radius along the sea surface from the acoustic recording location to the ship reported position.

Ship transits were defined as periods of continuous presence of a ship (*i.e.* unique MMSI number) within a maximum radius of two acoustic recording locations (Fig. 1) during which a ship's closest point of approach (CPA) occurred within 15 km of the recorder. Continuous presence was defined as having no greater than 60 min between AIS position updates during a 6-h time period centered on the CPA of each transiting ship. A 100 km maximum radius was selected for AIS ship transit data at the Pond inlet site (PI) to include vessels of speeds up to 18 knots, the maximum speed in the AIS data included in this study, within the 6-h transit window. A 30 km maximum radius was selected for AIS data at the Milne Inlet site (MI) to prioritize transiting ships while excluding ships engaged in port-related operations near the shipping terminal at southern terminus of Milne Inlet and ships anchored at a designated cargo ship anchorage 30 km northeast near Ragged Island. Due to irregularity in satellite transit and vessel transmission, all ship tracks and ship information were interpolated linearly to a uniform temporal resolution of 5 s.

## B. Acoustic recording and data processing

Underwater acoustic recordings were collected at two locations in the Eclipse Sound region (Fig. 1). One recording location was at depth 640 m between Baffin and Bylot Islands in eastern Eclipse Sound and will be referred to as the Pond Inlet (PI) recording site. The second recording location was at depth 313 m in Milne Inlet (MI) near the southwest end of Eclipse Sound.

Recordings at both sites were made using High-frequency Acoustic Recording Packages (HARP; Wiggins and Hildebrand, 2007; Fig. 2), which recorded acoustic data at a sampling rate of 200 kHz. Recordings were made continuously at PI from September 28, 2018 to September 21, 2019 and on a schedule of 25 min recorded of every 30 min at MI from September 29, 2018 to August 19, 2019. The HARPs were deployed to the seafloor and the hydrophone sensor was suspended approximately 20 m above the seafloor. The MI hydrophone consisted of two stages, one for low-frequency (<2 kHz) and one for high-frequency (>2 kHz). The low-frequency stage was composed of six cylindrical transducers (Benthos AQ-1) with a sensor sensitivity of -202 decibels root mean squared ( $\text{dB}_{\text{rms}}$ ) re: 1  $\text{V}/\mu\text{Pa}$ . The high-frequency stage consisted of a spherical omni-directional transducer (ITC-1042; [www.itctransducers.com](http://www.itctransducers.com)) with an approximately flat ( $\pm 2\text{dB}$ ) frequency response of -200  $\text{dB}_{\text{rms}}$  re 1  $\text{V}/\mu\text{Pa}$  between 1Hz and 100 kHz. The hydrophone transducer signals were fed into a preamplifier with approximately 50 dB of gain. The PI hydrophone used the same high-frequency stage and single omni-directional transducer as MI, but did not include a low-frequency stage. Acoustic calibrations of both hydrophones were made at the Scripps Institution of Oceanography (SIO) and these calibrations used to convert all acoustic recordings to sound pressure levels.



All recordings were converted to an adapted wav file format (xwav) and decimated by a factor of 20 to yield an effective bandwidth of 10-5000 Hz. Decimated recordings were processed into consecutive non-overlapping 5 s averaged sound pressure spectral density estimates with 1 Hz frequency bin spacing, which were assembled into Long-term Spectral Averages (LTSAs) to facilitate time-frequency analysis. To remove system self-noise resulting from HARP disk writes, the first three and last three 5 s spectra in each 75 s recording were not used for averaging. The retained 5 s spectra were further analyzed using custom Matlab-based ([www.Mathworks.com](http://www.Mathworks.com)) software to provide average and percentile SPSL, spectrograms, and sound pressure level (SPL) time series for specific frequency bands, including 20-4000 Hz to represent broadband noise radiated by ships and 1/3<sup>rd</sup> octave frequency bands centered at 250 Hz, 1 kHz, and 3.5 kHz to represent functional hearing of communication signals produced by ringed seals (250 Hz barks) and narwhal burst pulse (1 kHz burst pulse and 3.5 kHz whistle). All sound pressure level measurements are reported on a logarithmic scale as decibels (dB) with reference pressure 1  $\mu\text{Pa}$  and sound pressure spectrum levels are reported in dB re 1  $\mu\text{Pa}^2/\text{Hz}$ .

### C. Monthly underwater sound levels excluding and including ship transits

To estimate levels of natural and man-made underwater sound, recording periods were selected to exclude and include the presence of ships transiting past the recording site. Sound pressure spectrum levels excluding ship transits were obtained by analyzing all periods when the difference between successive ship transit CPA events was at least 8 h. This duration between ship transits was selected to reduce inclusion of the long-range components of ship sound in the estimation of natural sound levels. For each period meeting this condition, all 5 s sound pressure spectra were extracted from 4 h after the

first ship's CPA to 4 h prior to the second ship's CPA. These inter-transit times will be referred to as periods 'excluding ships'. A monthly random sample of 30,000 5s spectra was selected from the periods excluding ship transits during the shipping season to provide a consistent sample size for each month of shipping operations. Monthly sound pressure spectrum levels of periods excluding ships were evaluated from the 1<sup>st</sup>, 10<sup>th</sup>, 50<sup>th</sup> (median), 90<sup>th</sup>, and 99<sup>th</sup> percentiles of all 5 s LTSA subsampled from each time period. The 250 Hz, 1 kHz, and 3.5 kHz 1/3<sup>rd</sup> octave and 20-4000 Hz broadband SPL for all percentiles were calculated from the sum of the squared pressure across the frequency band of the percentile pressure spectra. Sound pressure spectrum levels and percentile SPL measurements were also made for all monthly recording periods during the shipping season. This will be referred to as periods 'including ships'. Measurements of received sound levels including and excluding ships were made for all monthly recorded periods during October 1 to 22, 2018 and between July 18 and September 21, 2019. These periods were selected to include all days of shipping traffic during the 2018 sea ice freeze-up, 2019 sea ice break-up, and two months of the 2019 open water season. Open water recording dates were separated by month to explore differences resulting from seasonal winds, which are higher in September than in August. The duration of monthly periods analyzed differed based on dates of recording and date limits of annual shipping traffic.

#### D. Environmental conditions near the recording site

Daily sea ice maps were obtained from the Canadian Ice Service, Environment and Climate Change Canada (<https://iceweb1.cis.ec.gc.ca/>) to estimate proportion of ice cover near the PI and MI recording sites during periods of acoustic data analyzed. Wind speed within a 100 km radius of the PI recording site was estimated from 25 km resolution Advanced Scatterometer (ASCAT) measurements processed for 10 m height ocean surface winds by the National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service

(<https://manati.star.nesdis.noaa.gov/products/ASCAT.php>). Wind vectors were available for time periods corresponding to ice-free conditions only and at locations in North Baffin Bay at ranges 25 to 100 km from the recording site. Wind speed was correlated with 1-min average received broadband sound pressure level by selecting all available wind vectors within radius 100 km and time +/- 60 min of SPL<sub>BB</sub> measurements. Only times during periods excluding ship transits were included to reduce overlap with ship noise. A least-squares regression line was fitted to the data to estimate the relationship between wind speed and SPL<sub>BB</sub>.

#### E. Acoustic characteristics of ship transits

Spectral characteristics of ship transits were analyzed in acoustic recordings at PI from the sound pressure spectrum levels within a 6-hour (6 h) window centered on each ship CPA. Acoustic ship transits were defined as the 6-h period, consisting of 3 h prior to and 3 h after the ship CPA. This time-window around each CPA was selected to include long-range propagation of underwater noise from ship transits and sometimes resulted in multiple ship transits occurring within the same 6-h window. Site PI recordings were used for ship transit measurements because the continuous recording schedule prevented any gaps in data during all transit windows. Sound pressure levels for the 20-4000 Hz band (SPL<sub>BB</sub>) and the 250 Hz, 1 kHz, and 3.5 kHz 1/3<sup>rd</sup> octave bands were calculated for each 5 s time bin in the ship transit LTSA data from the sum of the squared pressure across the frequency bands. SPL band one-min average received levels were also computed from the mean of all 5 s SPL values in each one-min time bin across the deployment period. One-min SPL was calculated to facilitate analyses of received level duration and range to ships at specific received levels.

The estimated levels of natural underwater sound occurring during each ship transit will be referred to as 'background levels'. The background levels for a ship transit were estimated from the median SPL for all frequency bands and the SPL during the 30 min from 2.5 to 3 h prior to the ship CPA time. This was intended to provide a reasonable estimate of underwater sound levels prior to each ship transit for comparison with sound introduced by the ship as it transited past the recording site. Received sound pressure spectra and band SPL were calculated for the CPA of each ship transit by averaging the received levels of all 5 s time bins within a data window during which the ship traveled a distance of 1.5 ship lengths with respect to the CPA, similar to the method described in McKenna *et al.* (2012).

Representative transits were selected for each vessel type to evaluate received level at varying ranges to the different ships and the durations of received levels above the band median and 90<sup>th</sup> percentile levels during periods excluding ship transits. If available, non-overlapping transits were chosen to represent a vessel type to minimize additional noise from other ships.

## RESULTS

### A. Ship transit information

During Sept 28, 2018 to September 21, 2019 95 unique ships made 266 transits within 15 km of the Pond Inlet (PI) recording location (Fig. 3, Table 1). At the Milne Inlet recording site (MI), 64 unique ships made 240 transits past the recording location (Fig. 4, Table 1). Ships that transited past the PI site, but not the MI site, were primarily pleasure craft, passenger vessels, military and Canadian Coast Guard vessels. With few exceptions, ship operations during the 6-h transit windows consisted of vessels making way at relatively constant speeds over ground while making minimal course corrections for navigation. A notable exception occurred occasionally in October and July when an icebreaker (*M/V Botnica*) approached the recording site then

reversed course within 15 km of the site (Fig. 29.b) while engaged in ice assistance activities. These instances of course reversal near the recording site were counted as a single ship transit. At the PI site, the general orientation of vessel traffic was east-west, entering or exiting Eclipse Sound from Baffin Bay (Fig. 3). In Milne Inlet, the general orientation of vessel traffic was north-south (Fig. 4). Ships were separated into 11 types based on AIS ship-type designation. Among the ship types, cargo vessels, including tankers, represented 74% of all ship transits at PI (n=197) and 79% at MI (n=189). Cargo vessels were separated into four categories to distinguish the three most common cargo sub-types (bulk carrier, general cargo, and tanker) from other less common cargo vessel types (heavy load carrier, deck cargo ship, offshore support vessel). Less common cargo vessel types are grouped in Table 1 as ‘other cargo’ vessels.

Table 1. Summary of AIS vessel transits, passing within 15 km of the Milne Inlet (MI) and Pond Inlet (PI) acoustic recording locations between Sep 28, 2018 and Sep 21, 2019.

Ship type	Milne Inlet		Pond Inlet	
	Number of transits	Percent of transits	Number of transits	Percent of transits
Bulk Carriers	152	63%	152	57%
General Cargo	21	9%	25	9%
Passenger Ships	0	0%	20	8%
Icebreaker-Support Vessel	39	16%	19	7%
Oil and Chemical Tanker	10	4%	15	6%
Pleasure Craft	1	0%	7	3%
Sailing	0	0%	6	2%
Tug	9	4%	6	2%
Military	2	1%	6	2%
Other Cargo	6	3%	5	2%
CCGS-SAR	0	0%	5	2%
Total	240		266	

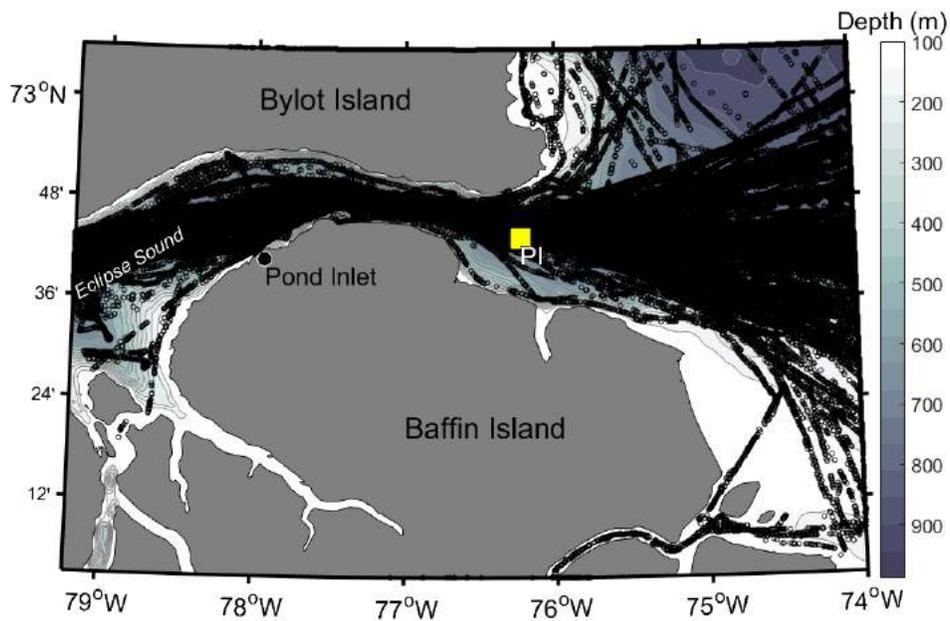


Figure 3. All Automated Information System (AIS) locations received by satellite from ships transiting past the Pond Inlet recording location (site PI) with closest point of approach (CPA) < 15 km between Sep 28, 2018 and Sep 21, 2019. Each black circle represents one AIS message received, which included ship identity, position, and operational information (*e.g.* heading, speed, draft).

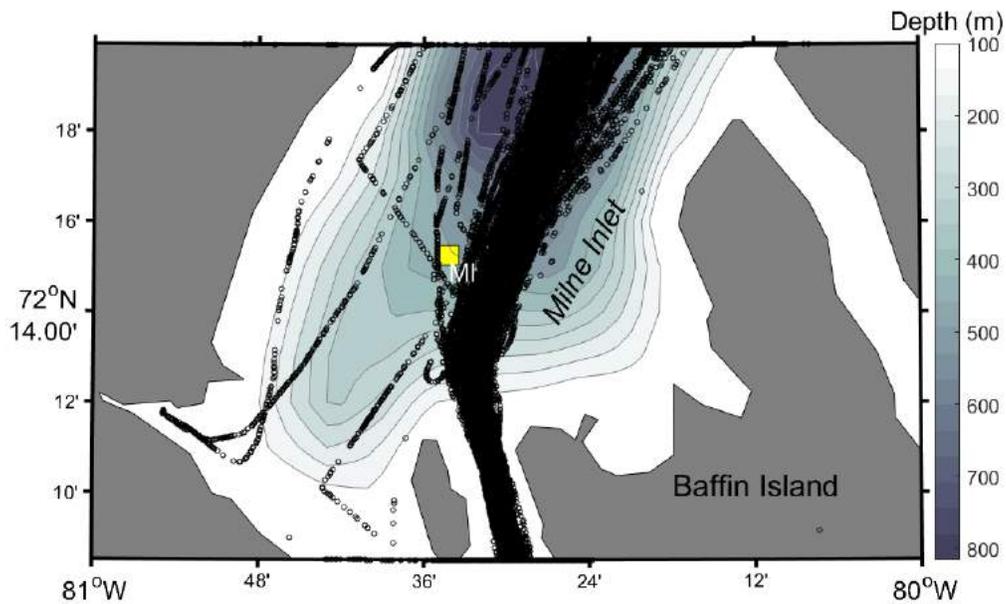


Figure 4. All Automated Information System (AIS) locations of ships transiting past the Milne Inlet recording location (MI) with CPA distance < 15 km between Sep 28, 2018 and Sep 21, 2019. Each black circle represents one AIS message received, which included ship identity, position, and operational information (*e.g.* heading, speed, draft).

The most common vessel type at both locations was the bulk carrier, with 43 unique vessels comprising 57% of transits at PI and 63% at MI. After bulk carriers, proportions of vessel types differed somewhat between sites. At PI, other vessel types with highest transit occurrence were general cargo (9%, n=25), passenger (8%, n=20), icebreaker (7%, n=19), and tanker (6%, n=15). Pleasure craft, and fishing, sailing, tugs, military, Canadian Coast Guard, and other cargo vessels together made up the remaining 13% of ship transits (n=35) at site PI.

At site MI, the other types with highest occurrence of transits were icebreaker (16%, n=39), general cargo (9%, n=21), tanker (4%, n=10), and tug (~4%, n=9). Other cargo and military vessels made up the remaining 3% (n=8). There was a single transit of a pleasure craft, the 36 m length private yacht *Noorderzon*, and no transits of passenger ships, sailing vessels, or Search and Rescue ships (SAR; *i.e.* Canadian Coast Guard Ships) at MI.

#### B. Monthly underwater sound levels excluding and including ship transits

1872 h of acoustic recordings from site PI were analyzed for underwater sound levels from 78 days across four periods of the shipping seasons of 2018 and 2019 (Fig. 5.a.). This analysis was performed on 1464 h of acoustic recordings from site MI from 61 days across Oct, 2018, and July and Aug, 2019. From these data, 870 h (47% of analysis periods) from site PI and 680 h (47% of analysis periods) from site MI were extracted for estimation of sound levels with transient ship noise events excluded (*i.e.* excluding ships; Fig. 5.b.). Daily durations of continuous recording periods excluding ships ranged from 1 to 24 h. Monthly and annual sound levels for periods including ship transits were calculated from the total recorded hours during each analysis period.

The first analysis period was Oct 1 to Oct 22, the last day of 2018 ship transits past sites PI and MI. This period includes the end of the 2018 open water season and the onset of sea ice freeze-up. The second analysis period was from the date of the first vessel transit of the year on July 18, 2019, through July 31. This period includes the beginning of 2019 shipping and the onset of continuous sea ice breakup leading to open water. The third and fourth periods at PI included open water shipping during Aug 1-26 and Sep 2-21, 2019. Acoustic data were not recorded at PI between Aug 27 and Sep 2, 2019. At MI, a third analysis period extended from Aug 1 to the end of recording on Aug 18, 2019. No acoustic recordings were made at site MI in Sep, 2019.

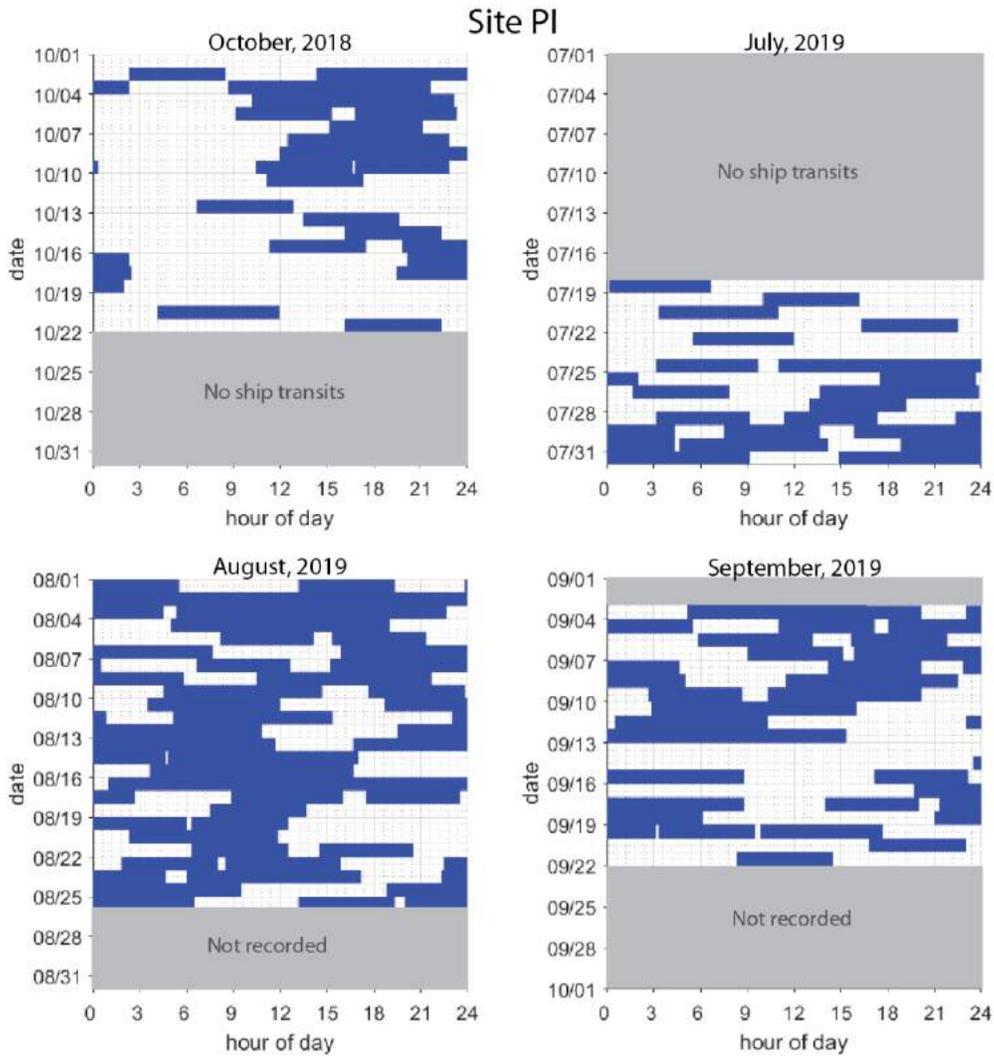


Figure 5.a. Monthly analysis effort for periods including and excluding ship transits at site PI from Oct, 2018 through Sept, 2019. Blue bars include all 6-h ship transit windows. White bars indicate periods excluding local ships. Gray areas indicate periods either outside of the shipping season (Oct 22-31, 2018 and July 1-17, 2019) or times not recorded. All recording times outside gray areas (blue and white bars) were included in analysis of total monthly sound levels, including ships.

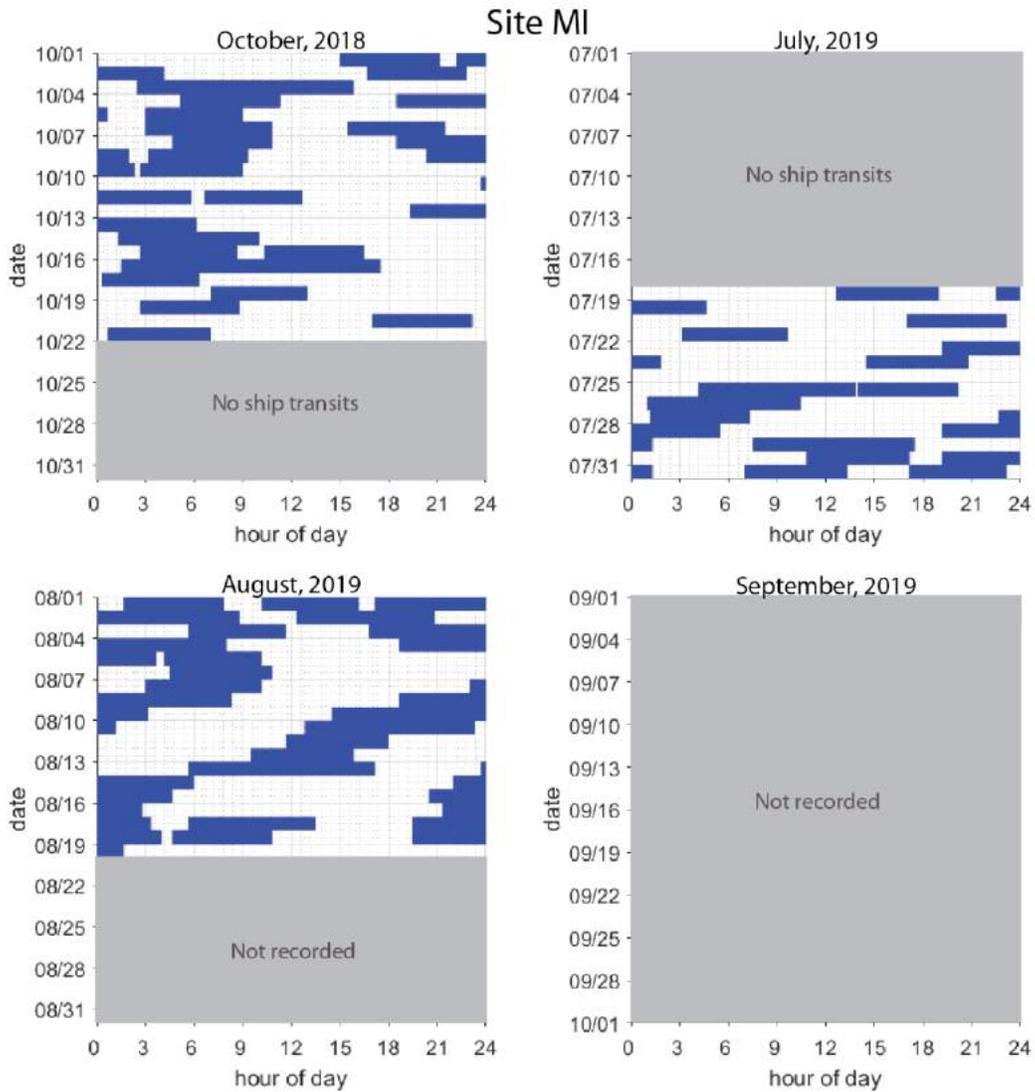


Figure 5.b. Monthly analysis effort for periods including and excluding ship transits at site MI from Oct, 2018 through Sept, 2019. Blue bars include all 6-h ship transit windows. White bars indicate periods excluding local ships. Gray areas indicate periods either outside of the shipping season (Oct 22-31, 2018 and July 1-17, 2019) or times not recorded. All recording times outside gray areas (blue and white bars) were included in analysis of total monthly sound levels, including ships.

In all months, noise from ships transiting past the recording sites is apparent in the acoustic recordings as <12h duration increases in received sound levels with energy concentrated below 2000 Hz and with few exceptions, when hourly median SPL<sub>BB</sub> exceeds 110 dB (Figs 6-12). Episodic increases in natural underwater sound levels occurred at varying intensities and durations during the periods excluding ship transits. In all months except October, median hourly SPL<sub>BB</sub> rarely exceeded 110 dB except during ship transits near the recorders. Monthly SPL excluding ship transits was substantially lower below 200 Hz at MI than PI (Figs 12-13). Monthly SPL for all frequency bands and percentile levels was lower at site MI than at PI during periods including and excluding ship transits (Table 2). Exceptions to this pattern in SPL occurred during several time periods with ship transits, namely the Oct and Jul 99<sup>th</sup> percentile SPL<sub>BB</sub>, the Aug 50<sup>th</sup> and 10<sup>th</sup> percentile 1 kHz band level, and the Aug 99<sup>th</sup> percentile 3.5 kHz band level. Sound levels in the 1<sup>st</sup> and 10<sup>th</sup> percentiles represent relatively quiet times during the recording periods. At site PI sound levels during 'quiet' periods were lowest in Jul and Aug. At MI, the 1<sup>st</sup> and 10<sup>th</sup> percentile SPL were lowest in October.

At site PI, intermittent periods of elevated wind-driven sound are apparent during ice free conditions early to mid-Oct, 2018 (Fig. 6.b.1), in late-Aug 2019 (Fig. 10.b.1), and throughout Sept, 2019 (12.b.1, b.2). These natural acoustic events can be > 1 d in duration, as in the Oct 6-7 period of elevated received levels across the 20-4000 Hz frequency range (Fig. 6.b.1). This event generated the highest SPL<sub>BB</sub> measured during all periods excluding ship transits, with a maximum one-min mean SPL<sub>BB</sub> of 114 dB re 1  $\mu\text{Pa}^2$ .

Sound pressure spectrum levels from periods excluding ship transits reveal seasonal differences in the natural underwater soundscape (Fig. 13 upper panels; Table 2). July and August had the lowest levels and included only one period between July 18 and July 20

during which > 1% sea ice cover remained within a 15 km radius of the recording location. Noise from an icebreaker (*M/V Botnica*) is apparent at 200 Hz in the July 90<sup>th</sup> and 99<sup>th</sup> percentile ship-excluded sound pressure spectrum level (Fig. 13), reaching apx. 77 and 89 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  respectively. This suggests that  $\sim$  200 Hz noise from the ship is detectable at ranges greater than 40 km from the ship in at least some transits. Wind noise (sound pressure spectrum levels above 200 Hz in the 90<sup>th</sup> and 99<sup>th</sup> percentiles) appears rarely in August. Median and lower percentiles in August reflect relatively quiet periods above 200 Hz with lower wind noise apparent at those frequencies. September and October periods excluding ship transits had higher sound pressure spectrum levels than July and Aug. Increased wind-generated noise is apparent during these months by the increased median spectrum levels above 200 Hz, 5 to 8 dB re 1  $\mu\text{Pa}^2/\text{Hz}$  higher than August. October had the highest sound pressure spectrum levels at all frequencies, with additional broadband noise possibly associated with sea ice formation. Icebreaker harmonic noise at 200 Hz is again visible in October's 99<sup>th</sup> percentile samples of periods excluding ship transits.

Monthly sound pressure spectrum levels for all analysis periods, including ship transit windows, (Fig. 13. lower panels) were similar to ship-excluded noise spectra in the median and lower percentiles. Ship-inclusive median sound pressure spectrum levels were higher by 1-3 dB in the 50-100 Hz range where the largest contributions from ship noise would be expected. Some additional low-frequency noise <40 Hz was apparent in the ship-inclusive median-level spectra, consistent with cavitation noise from large ship propellers (Ross, 1976). The 90<sup>th</sup> and 99<sup>th</sup> percentile ship-inclusive levels for July and October clearly exhibit substantial additional noise consistent with ships and the icebreaker operating in the area during both months. In all months, all one-min time bins with average  $\text{SPL}_{\text{BB}} > 115$  dB were associated with ship transits. The 99<sup>th</sup> percentile sound pressure spectrum level including ship transits was higher at all

frequencies by 1 to 15 dB than during periods excluding ship noise. The greatest relative differences in spectrum level between ship-excluded and ships-included periods occurred in the 50-250 Hz range.

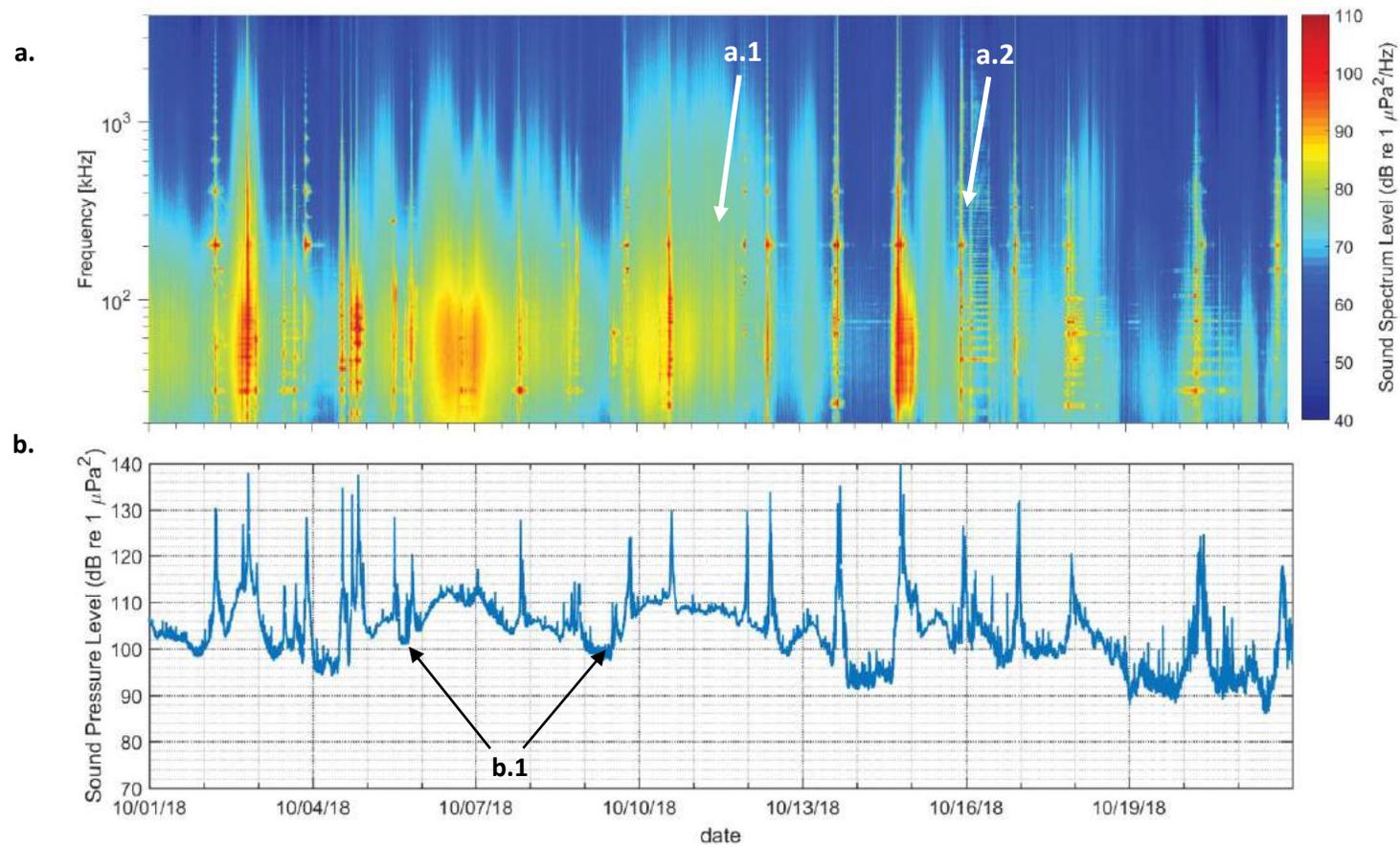


Figure 6. Long-term spectral average (LTSA; a) and 1-min average 20-4000 Hz broadband sound pressure level (SPL<sub>BB</sub>; b) for all recorded periods at the Pond Inlet recording site (PI) from Oct 1 to the date of last ship transit Oct 22, 2018. Elevated sound levels from natural sources, likely wind-generated noise, can be seen Oct 6-7 and Oct 9-12 (b.1). Example icebreaker transits on Oct 12 (a.1) and Oct 16 (a.2).

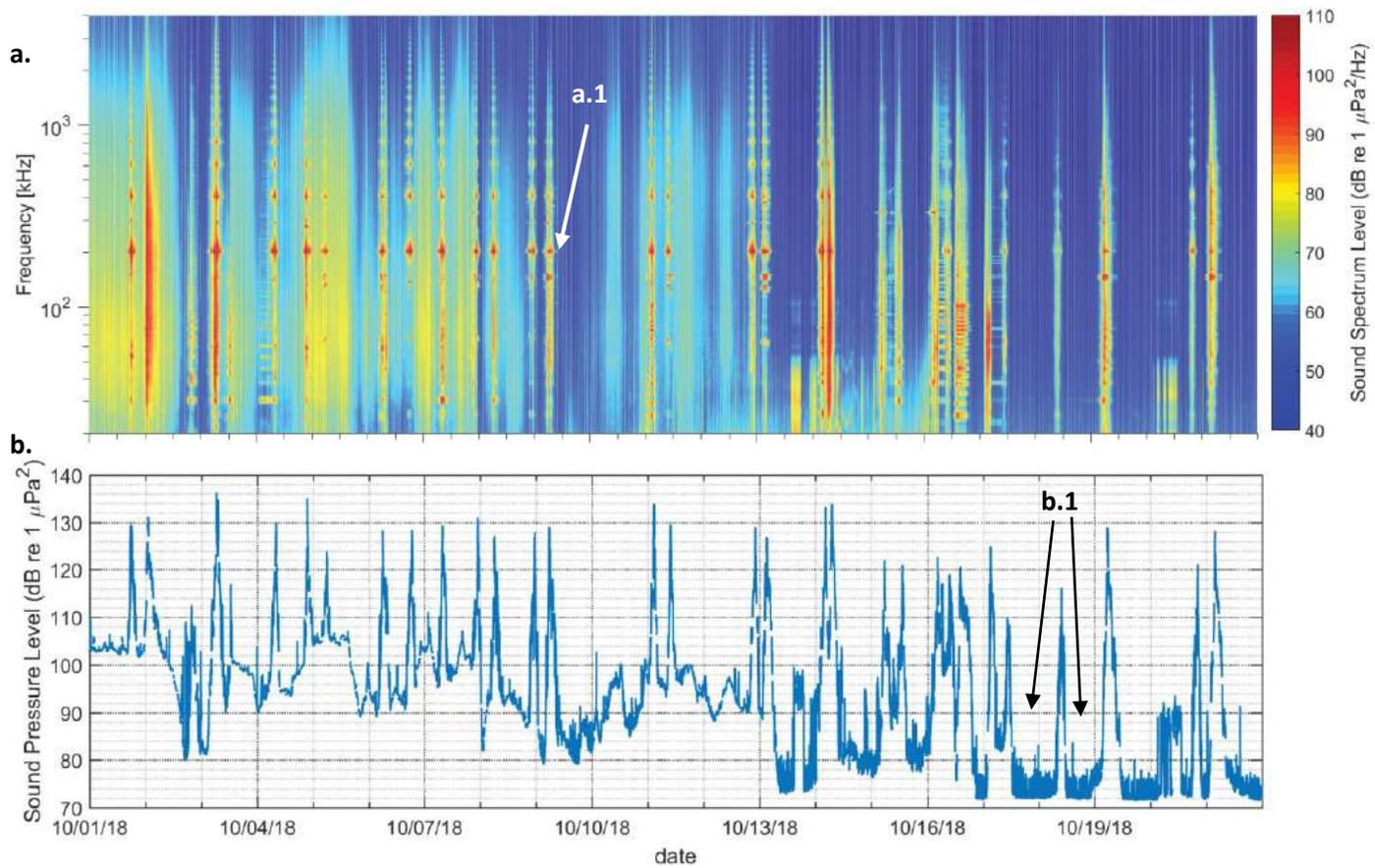


Figure 7. Long-term spectral average (LTSA; a) and 1-min average  $\text{SPL}_{\text{BB}}$  (b) for all recorded periods at the Milne Inlet recording site (MI) from Oct 1 to the date of last ship transit Oct 22, 2018. Periods of low natural sound levels (b.1) apparent in LTSA and  $\text{SPL}_{\text{BB}}$  after Oct 13 coincide with sea ice formation. Icebreaker transits identifiable by tonal energy at fundamental frequency 200 Hz (a.1).

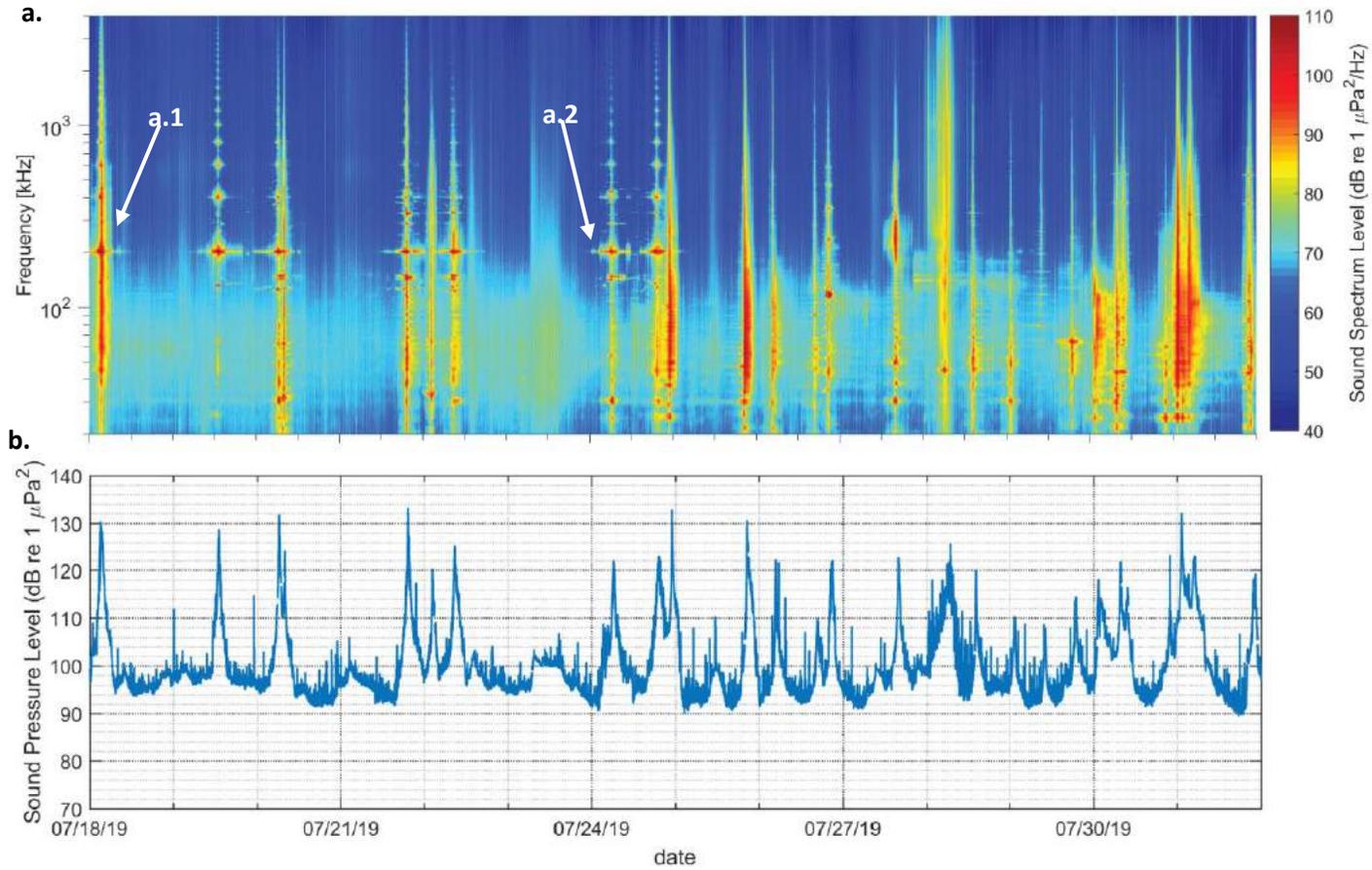


Figure 8. LTSA ( a) and 1-min average SPL<sub>BB</sub> (b) for all recorded periods at the Pond Inlet recording site (PI) from Jul 18, the first ship transit of 2019, to the end of Jul. Representative transits of the icebreaker, *Botnica*, on Jul 18 (a.1) and Jul 24 (a.2).

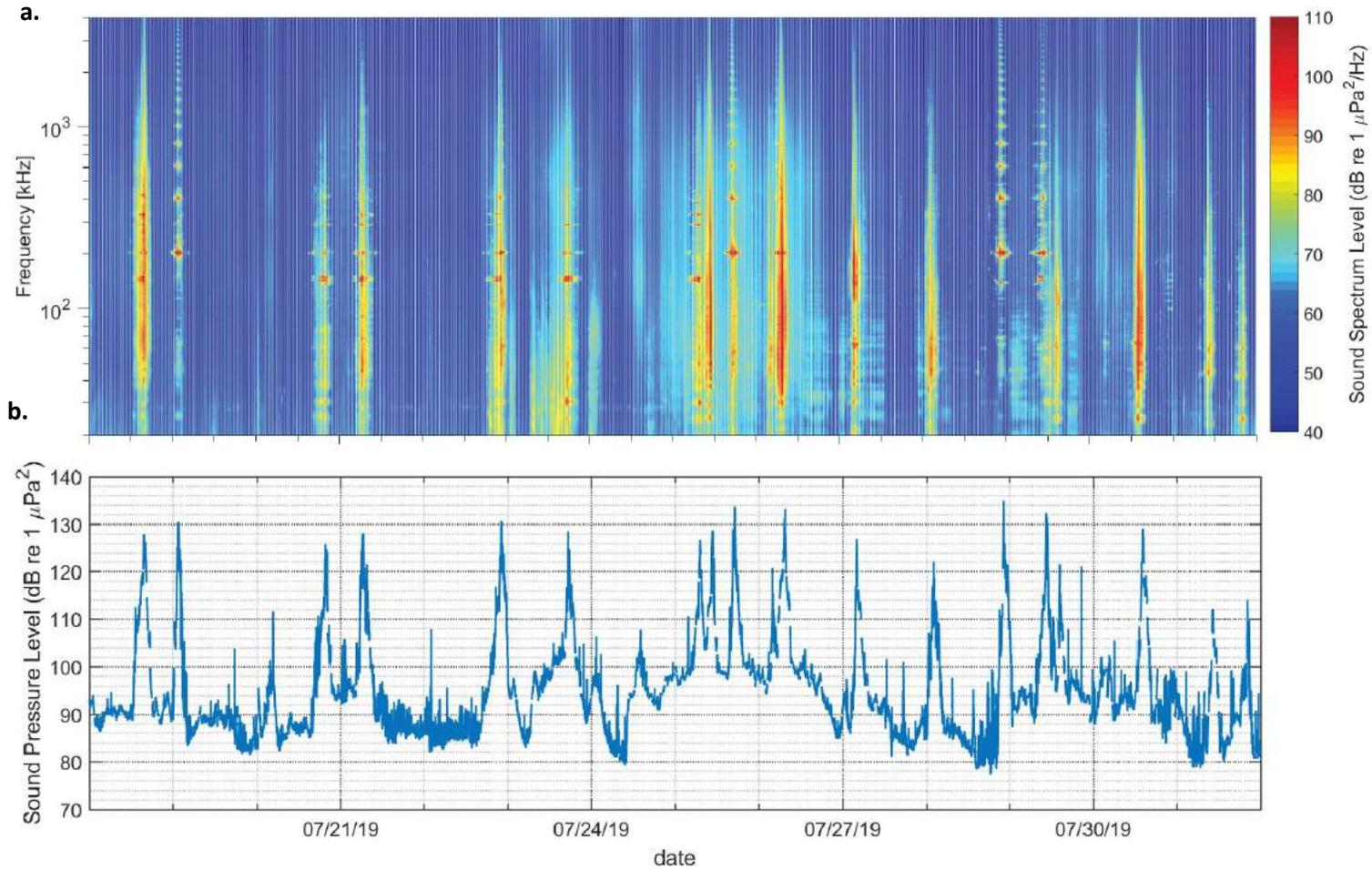


Figure 9. LTSA (a) and 1-min average  $\text{SPL}_{\text{BB}}$  (b) for all recorded periods at site MI from Jul 18, the day of the first ship transit of 2019, to Jul 31, 2019.

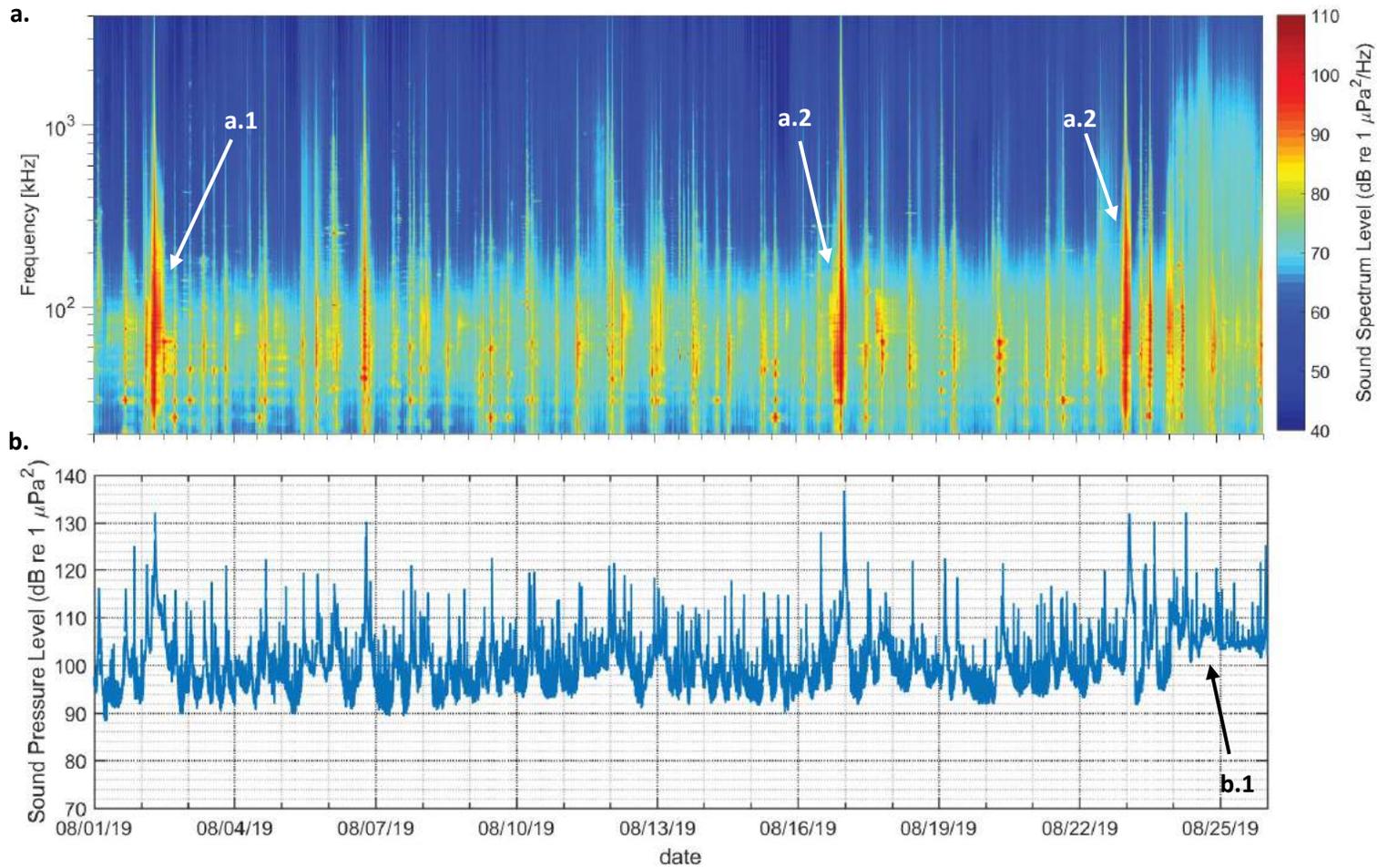


Figure 10. LTSA (a) and 1-min average  $\text{SPL}_{\text{BB}}$  (b) for all recorded periods at site PI from Aug 1 to Aug 26, 2019 during open water conditions.

Example period of elevated sound levels from natural sources, likely wind-generated noise, can be seen Aug. 24-25 (b.1). Transits of the fuel and chemical tanker, *Sarah Desgagnes* (a.1-3).

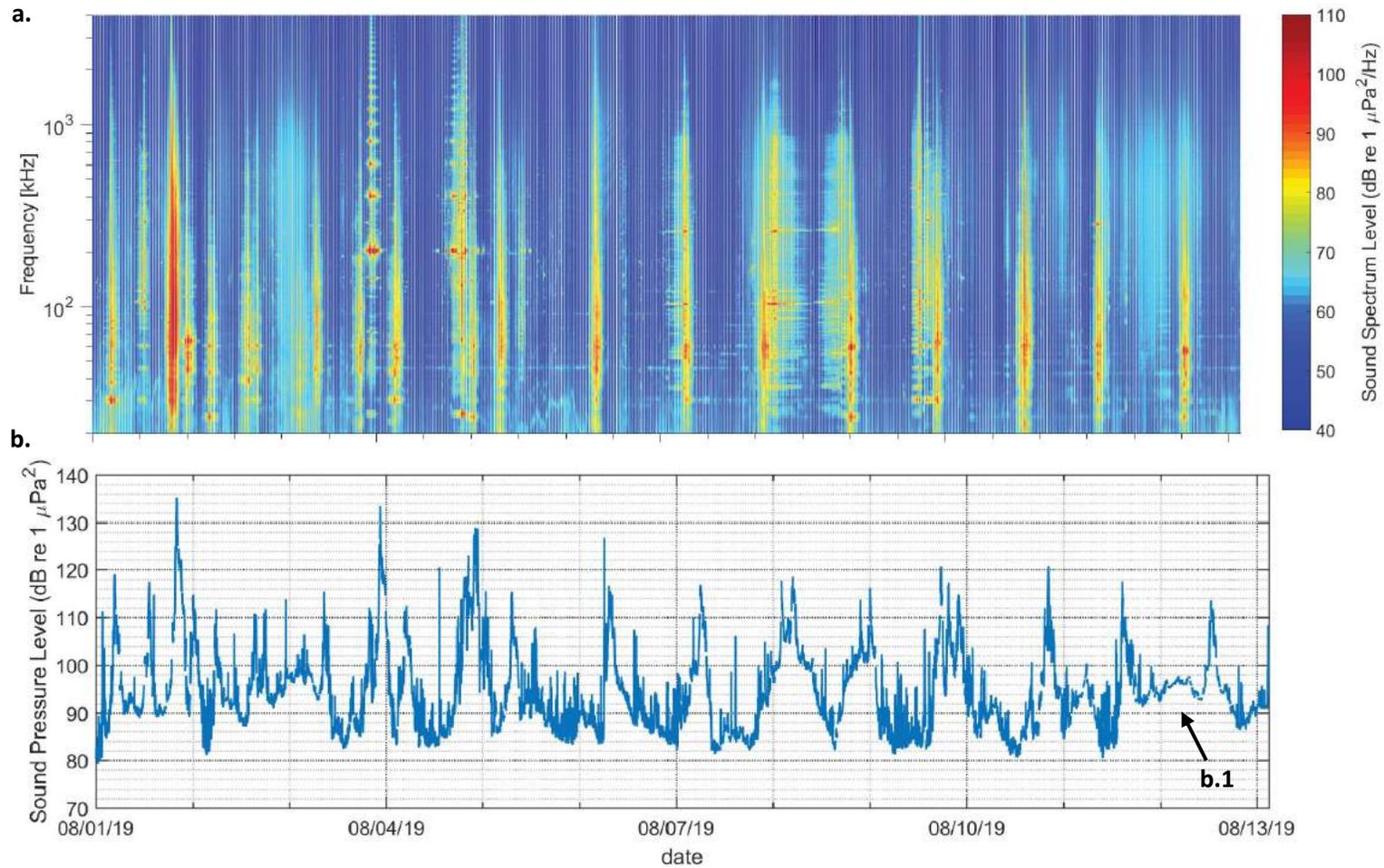


Figure 11. LTSA (a) and 1-min average  $\text{SPL}_{\text{BB}}$  (b) for all recorded periods at site MI in Aug, 2019. Example period of elevated sound levels from natural sources, likely wind-generated noise, can be seen Aug. 12 (b.1).

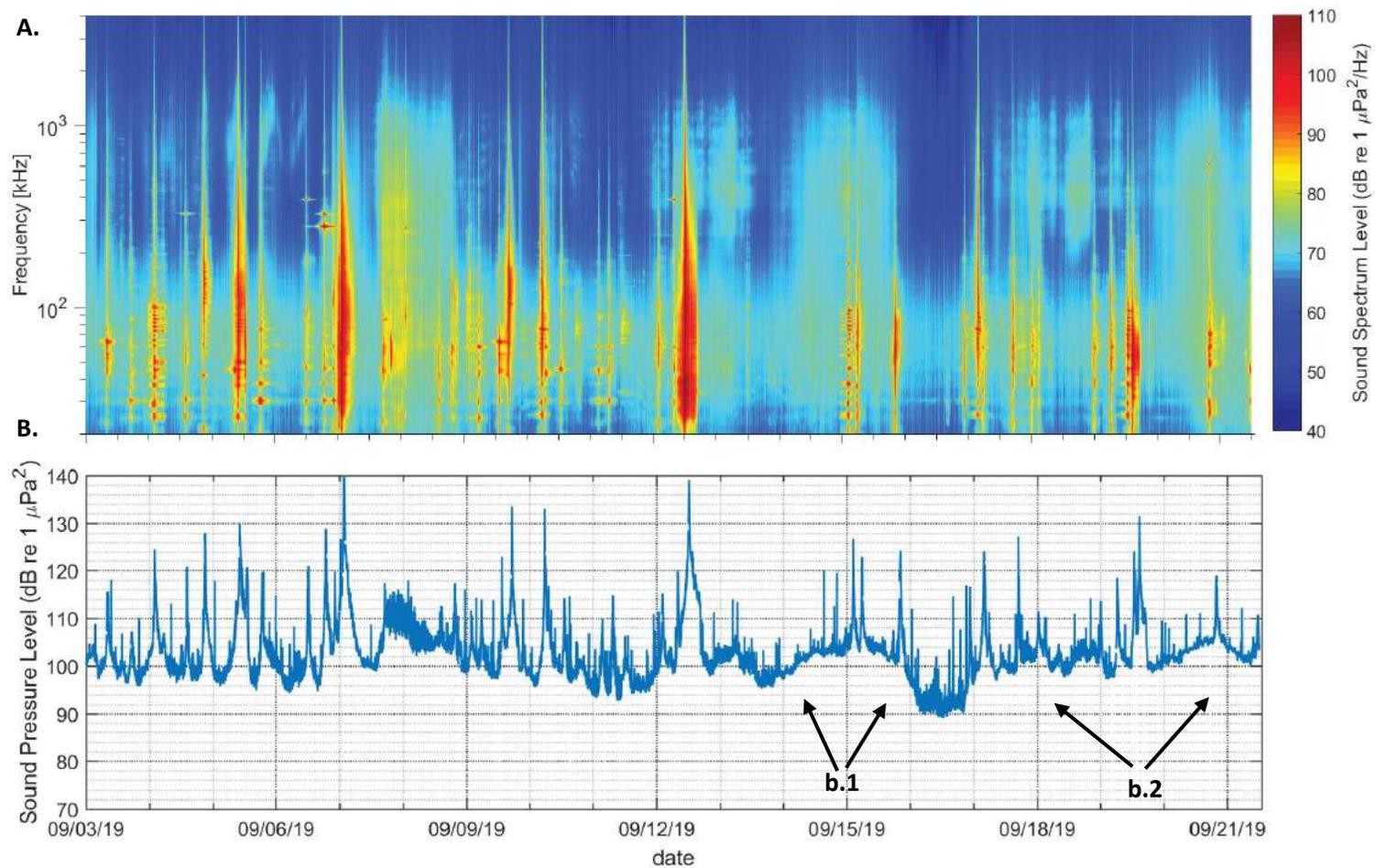


Figure 12. LTSA (a) and 1-min average  $\text{SPL}_{\text{BB}}$  (b) for all recorded periods at site PI in Sep, 2019. Example periods of elevated sound levels from natural sources, likely wind-generated noise, can be seen Sep. 14-15 (b.1) and Sep 18-21 (b.2).

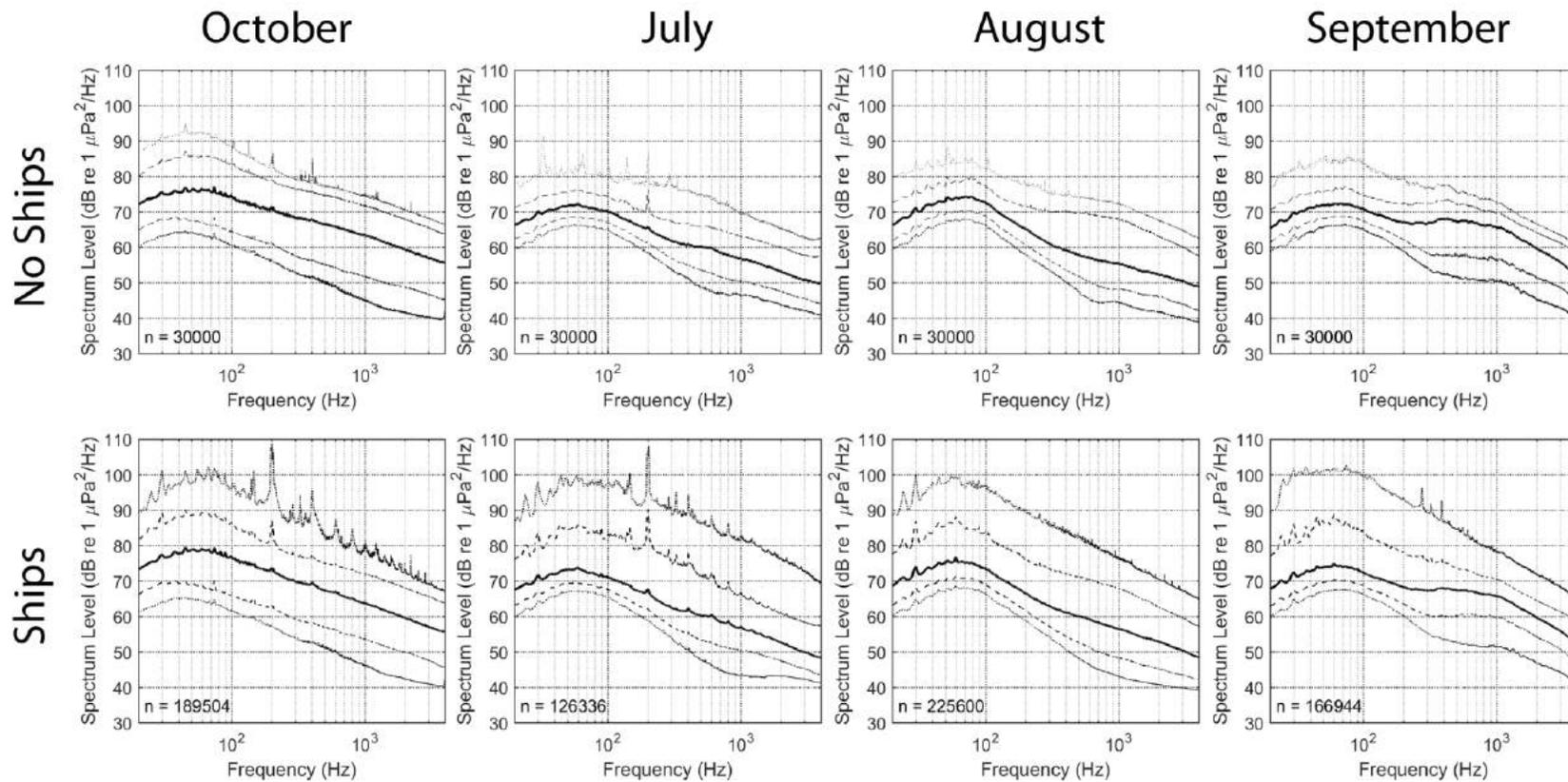


Figure 13. Sound pressure spectrum levels for Jul, Aug, and Sep, 2019 and for Oct, 2018. Levels are represented by the 1st, 10th, 50th (median), 90th, and 99th percentiles of 30,000 random 5 s samples from times excluding 6-h ship transit windows in each period ('No Ships') and of all recorded times, including ship transits ('Ships').

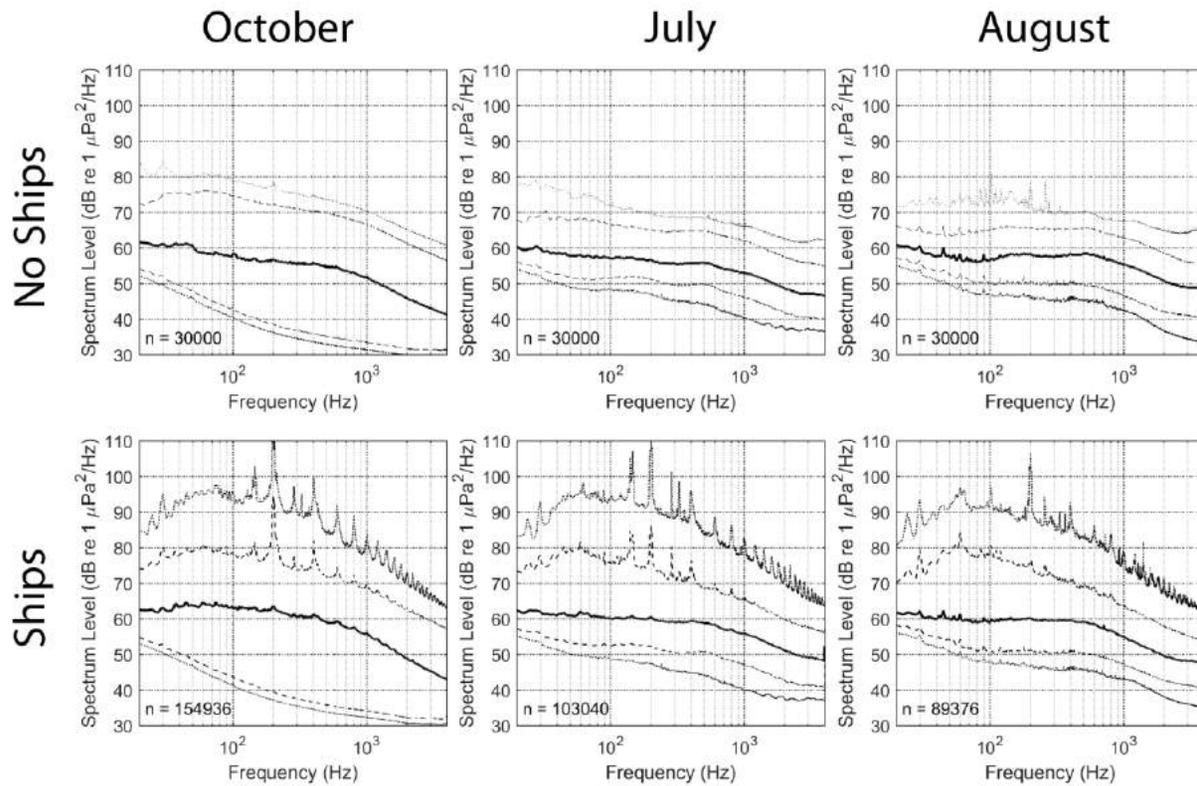


Figure 14. SPSL at site MI for periods excluding ('no ships') and including ('ships') 6-h ship transit windows during monthly analysis periods Oct, 2018 and July and Aug, 2019. Levels are represented by the 1st, 10th, 50th (median), 90th, and 99th percentiles of 30,000 random 5 s samples from times excluding 6-h ship transit windows in each period ('no ships') and of all recorded times, including ship transits ('ships').

Table 2. 10<sup>th</sup>, 50<sup>th</sup> (median) 90<sup>th</sup>, and 99<sup>th</sup> percentile SPL (in dB re 1 μPa) in the 250 Hz, 1 kHz, and 3.5 kHz 1/3<sup>rd</sup> octave and 20-4000 Hz frequency bands for monthly periods excluding 6-h ship transit windows in each period ('no ships') and of all recorded times, including ship transits ('ships').

		<b>Site PI</b>															
		October '18				July '19				August '19				September '19			
Frequency Band		10th	50th	90th	99th	10th	50th	90th	99th	10th	50th	90th	99th	10th	50th	90th	99th
20Hz - 4 kHz	no ships	90.2	100.2	108.9	113.4	90.4	94.7	100.0	107.2	90.9	95.3	103.1	108.2	92.2	99.3	103.9	108.7
	ships	91.7	101.7	110.6	122.5	90.8	95.4	107.7	122.5	91.4	96.6	106.9	119.1	94.4	99.8	108.2	122.4
250 Hz	no ships	76.9	87.1	95.0	98.2	76.6	81.0	85.9	95.2	76.1	80.6	88.5	94.6	77.7	84.7	90.1	95.4
	ships	78.4	88.8	96.1	106.4	77.0	81.8	95.4	109.3	76.9	82.1	92.3	105.5	79.4	85.5	94.8	109.6
1 kHz	no ships	75.4	87.1	95.3	98.1	74.0	80.4	86.7	93.2	71.7	78.9	91.6	95.9	80.2	89.3	93.3	96.4
	ships	77.2	87.3	95.6	102.2	74.1	80.3	89.6	105.5	66.7	80.1	91.5	100.1	83.4	89.3	94.1	102.1
3.5 kHz	no ships	74.9	85.3	93.6	96.3	73.8	79.3	89.5	91.3	72.0	78.6	87.8	92.6	76.0	82.9	89.0	91.2
	ships	75.6	85.3	93.6	97.1	73.3	78.1	86.7	100.0	68.6	78.4	87.3	95.1	78.0	83.2	89.1	95.9

		<b>Site MI</b>															
		October '18				July '19				August '19				September '19			
Frequency Band		10th	50th	90th	99th	10th	50th	90th	99th	10th	50th	90th	99th	10th	50th	90th	99th
20Hz - 4 kHz	no ships	71.6	86.8	101.8	106.4	81.5	87.7	96.7	101.8	81.6	89.7	97.2	103.7	-	-	-	-
	ships	72.1	91.0	107.4	123.7	82.3	90.5	103.7	122.8	82.2	90.0	102.9	116.9	-	-	-	-
250 Hz	no ships	55.3	73.8	89.3	93.6	68.0	73.6	82.4	86.6	67.8	75.5	83.3	89.8	-	-	-	-
	ships	57.8	79.2	92.2	103.3	69.0	77.1	90.1	107.3	70.0	77.0	90.3	105.2	-	-	-	-
1 kHz	no ships	57.2	75.2	90.2	94.0	69.8	76.6	85.6	89.8	70.2	79.0	86.5	91.3	-	-	-	-
	ships	56.1	79.1	93.0	108.9	70.7	79.3	88.9	102.5	70.8	83.4	88.8	99.7	-	-	-	-
3.5 kHz	no ships	60.4	71.1	86.4	90.6	69.3	76.0	84.5	91.4	69.6	77.8	84.9	94.4	-	-	-	-
	ships	61.0	73.1	87.3	93.7	70.2	77.8	85.9	94.6	70.0	76.9	86.0	96.3	-	-	-	-

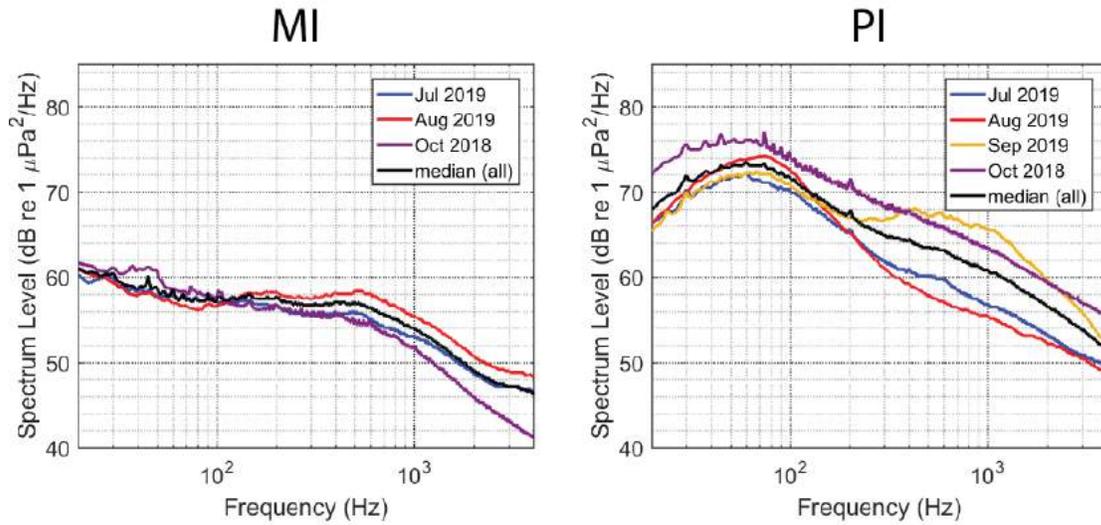


Figure 15. Median monthly sound pressure spectrum levels (SPSL) for periods excluding ship transit windows during months of Jul-Oct in Eclipse Sound. Monthly SPSL based on 30,000 5-sec SPSL selected randomly from all times in each month with nearest ship CPA time and range  $\geq 4$  h and  $\geq 40$  km, respectively.

### C. Environmental correlates with ship-excluded sound levels

Sound pressure level above 1 kHz was positively correlated with wind speed from satellite measurements ( $n=189$ ) at 25 to 100 km from the recording site (Fig. 16). A total of 189 5 sec acoustic measurements were made during periods within 2 h of a satellite estimate of sea surface winds. A general pattern is apparent of increasing  $SPL_{BB}$  with wind speed. Drawing a linear fit to the data gives an estimate of + 0.8 dB for each increase of 1 m/s in wind speed.

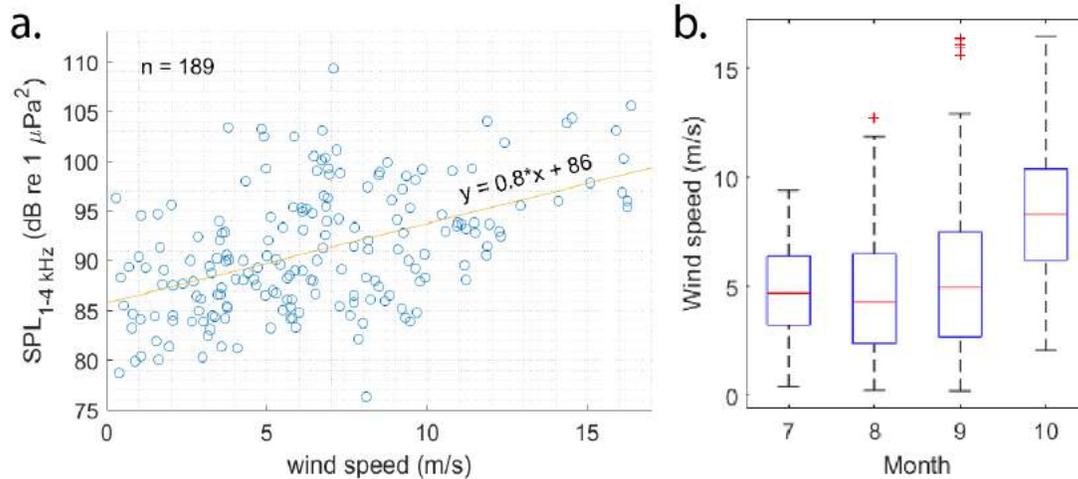


Figure 16. One-min averaged sound pressure levels for the 1-4 kHz frequency band versus wind speed for all monthly periods excluding 6-h ship transit windows (a). Wind measurements included within 100 km of the recording site and +/- 2 h from the SPL measurement. A linear fit is plotted (orange line) to estimate the dependence of SPL on wind speed. Box plots (b) with mean (red line), 25<sup>th</sup> and 75<sup>th</sup> percentiles (blue box), and most extreme data points (whiskers). Outliers noted with red plus symbol.

#### D. Acoustic characteristics of ship transits

There were 220 ship transits recorded acoustically at site PI during the periods analyzed. Design characteristics, operational information, and acoustic measurements of ships detected at site PI are summarized in Table 3.

The five most common ship types (*i.e.* bulk carrier, general cargo, passenger, fuel and chemical tanker, icebreaker) each had different six-hour long-term spectral averages producing distinctive spectral characteristics of underwater noise (Figs 18-32). These ship types represented 87% of transits past site PI (n=231) and 92% of transits past site MI (n=221). Icebreakers (Figs 27-32), fuel and chemical tankers (Figs 24-26), and general cargo

vessels (Figs 21-23) produced the highest received levels in all frequency bands. For all ship types, the farthest propagating noise occurs in frequencies at or below 200 Hz, including tonal sounds below 100 Hz caused by cavitation of the ship's propeller. Generally, the noise bandwidth extends into higher frequencies as the ship approaches the CPA during a transit and higher-frequency harmonics of the tonal cavitation noise become apparent. The LTSA typically exhibits a U-shaped pattern of ship noise during most close transits of the CPA (*e.g.* Fig. 18; bulk carrier). This effect is also evident in the alternating peaks and valleys in received level across frequency band in the sound spectrum levels near the CPA (*e.g.* Fig. 19.d; bulk carrier).

As in other studies of underwater noise from ships (*e.g.* McKenna *et al.*, 2012; Gassmann *et al.*, 2017), there is more energy radiating from the stern than from the bow aspect of ships. The result of this aspect dependence of source level is a longer period with elevated noise levels following a ship transit than preceding it. This pattern is most pronounced in the fuel and chemical tanker example LTSA (*e.g.* Table 3, Figs. 24-26). Relationship between received  $SPL_{BB}$  and range to the ships generally was different between vessel types, with longer range propagation of noise evident in the icebreaker and tanker ships than in bulk carriers or general cargo ships (Fig. 17).

- 1 Table 3. Design characteristics and acoustic measurements of a representative set of ships during transits past the PI recording location.
- 2 Received broadband sound pressure levels (in dB re 1  $\mu$ Pa) at ship closest point of approach (CPA) with ranges to the ship for 110 and 120 dB
- 3 received levels. Where values for bow and stern aspect differ substantially, both are given (*i.e.* bow range (km), stern range (km)).

Ship information							Acoustic measurements				
Ship type	MMSI number	Ship name	Ship length (m)	Year built	Gross tonnage ( $10^3$ )	Deadweight tonnage ( $10^3$ )	Speed at CPA (kts)	Range at CPA (km)	Received level at CPA	Range to 110 dB (km)	Range to 120 dB (km)
Bulk Carriers	356364000	NORDIC ODIN	225	2015	41071	76180	8.7	0.9	121	4,7	0.9
	373437000	NORDIC ORION	225	2011	40142	75603	7.5	2	119	5,7	2
	374322000	NORDIC ODYSSEY	225	2010	40142	75603	8.4	1	127	10	3
	538008053	GOLDEN PEARL	225	2013	41718	74300	8.6	0.3	125	5,7	1
	636015651	NS YAKUTIA	225	2013	40972	74559	8.1	1	115	2,3	-
	636015650	NS ENERGY	225	2012	40972	74518	7	3.1	116	4,6	-
	636092901	KAI OLDENDORFF	229	2019	44029	81243	8	1.9	120	4,7	1.9
	255805765	GISELA OLDENDORFF	229	2013	44218	80839	8.8	1	119	3,7	1
	538004978	AM QUEBEC	230	2013	43987	81792	7	1.1	130	10,20	4,5
General Cargo	316015133	ZELADA DESGAGNES	139	2009	9611	12692	12	1.4	132	20,30	4,7
	316011358	ROSAIRE A. DESGAGNES	138	2007	9611	12776	8.2	0.6	127	10,15	3
	246770000	MOLENGRACHT	143	2012	9524	11744	8.9	0.2	135	13,15	4,7
	316015251	SEDNA DESGAGNES	139	2009	9611	12612	12	0.2	134	10,30	3,5
Fuel and Chemical Tankers	316012308	SARAH DESGAGNES	147	2007	11711	17998	9	2	133	10,35	4,16
	316095000	DARA DESGAGNES	124	1992	6262	10511	8.5	0.3	130	7,20	2,4
	316037373	KITIKMEOT W	150	2010	13097	19983	13	3.1	123	10,25	5
Passenger Ships	311000419	OCEAN ENDEAVOUR	137	1982	12907	1762	11	2	122	8,13	3,4
Pleasure Craft	319030600	ARCADIA	36	8	308						
	304977000	HANSE EXPLORER	48	2006	885	198	11	2.7	119	5,6	3,4
Icebreaker	276805000	BOTNICA	97	1998	6370	2850	8.9	0.3	134	14-28	4-10
	276805000	BOTNICA	97	1998	6370	2850	8	2.7	133	18,30	7,16
	265182000	ODEN	108	1989	9605	4906	8	3.4	118	10	4
CCGS-SAR	316050000	CCGS AMUNDSEN	98	1979	5910	2865	13	1.9	122	9,10	3
	316050000	CCGS AMUNDSEN	98	1979	5910	2865	10	7	119	15,22	8,12
	316122000	TERRY FOX	88	1983	4233	2113	14	0.7	136	20,25	6

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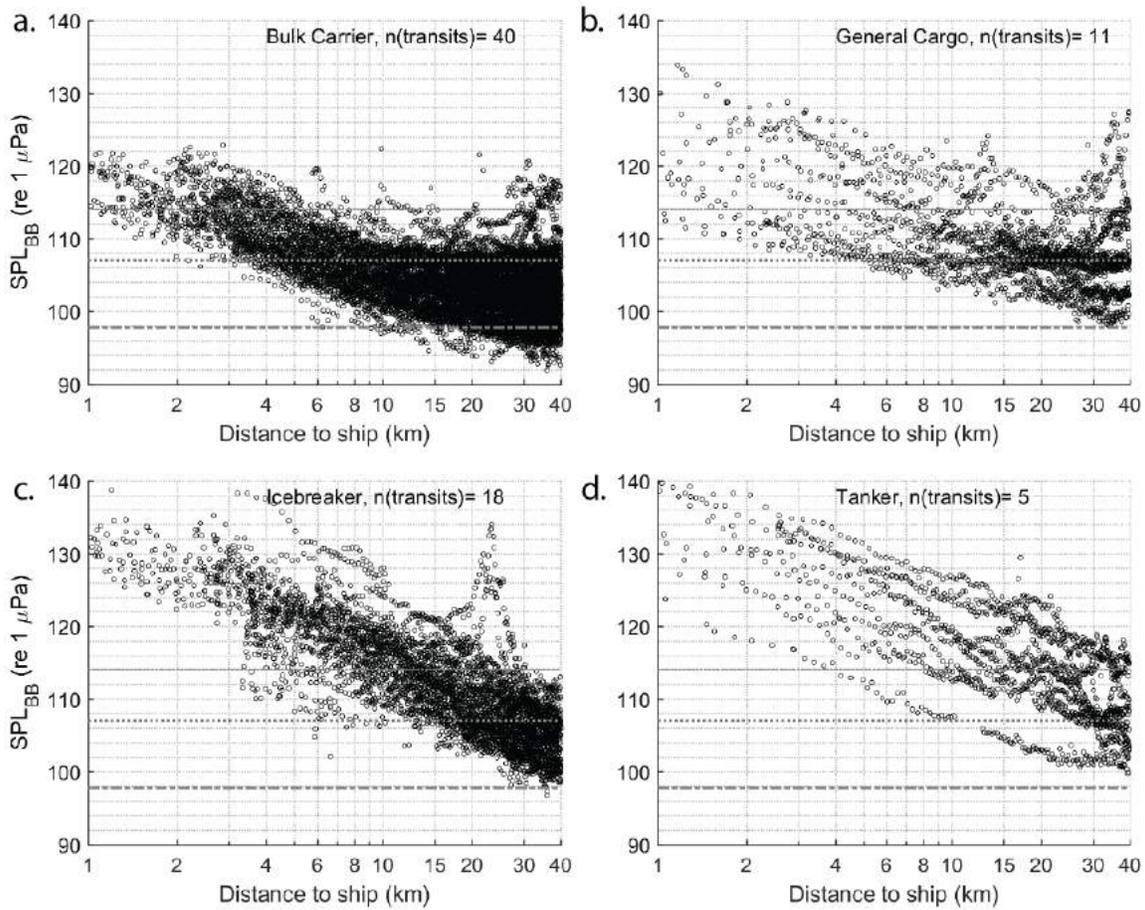


Figure 17. Received SPL<sub>BB</sub> (1-min average) at site PI with range to ship for transit examples in which the closest point of approach (CPA) was within 4 km of the recording location. Transits are separated by vessel type. Only transits during open water (no icebreaker) with no other ship CPA within 2 h are included for bulk carrier, and 1 h for tanker and general cargo. Icebreakers were usually transiting with other vessels, so all transit events with CPA <4 km are plotted. Number of transits plotted (n) is included in each panel title. Median, 90<sup>th</sup>, and 99<sup>th</sup> percentile SPL<sub>BB</sub> of all ship-excluded periods (gray horizontal lines) are plotted for reference.

## Bulk carriers

Two typical open water transit scenarios for a bulk carrier (*Nordic Orion*) are exemplified in Figures 18-20, one at about the median background sound level during the transit (Sep 5, 2019) and one representing 'quieter' background conditions (Aug 1, 2019). Received sound pressure spectrum level was highest at frequencies between 30 and 200 Hz (Figs 19.d, 20.d) throughout the transits, with energy to >4 kHz also present at ranges closer to the CPA. Low-frequency noise below 50 Hz from transiting bulk carriers was apparent from distances >30 km in both background sound conditions (Figs 19.d.1, 20.d.1).  $SPL_{BB}$  during the Aug 1 transit was about 6 dB below the median background sound level (Fig. 19.a.1) until the ship was at range 15 km from the receiver.  $SPL_{BB}$  increased above the relatively quiet transit background sound from 1.5 h prior to CPA to > 3 h after CPA (range >40 km), with levels changing more rapidly within 10 km of the vessel. The 250 Hz, 1 kHz, and 3.5 kHz band SPL followed a similar pattern during the ship transit with relative increases in frequency band SPL at CPA of 15-25 dB above pre-transit levels (Fig. 19.c.). During the Sep 5 transit, pre-CPA background sound was close to median levels (Fig. 20.a and c).  $SPL_{BB}$  began increasing about 1.5 h prior to CPA with relative increases in  $SPL_{BB}$  and band SPL of 15-25 dB at CPA. Relative changes in all frequency bands and in the SPSL were similar in both transit scenarios. Distance to receiver at  $SPL_{BB} > 110$  dB was also similar in both transits and a pattern of higher received levels at the stern aspect is visible.  $SPL_{BB}$  of 110 dB was reached at range to ship of 4 and 7 km from the bow and stern aspects, respectively (Table 3, Figs. 19.a., 20.a.).

Patterns in received level versus range were examined for a subset of 40 bulk carrier transits during which the nearest time to CPA of another ship transit was > 2 h and with maximum CPA distance to the receiver of 4 km.  $SPL_{BB}$  was greater than 110 and 120 dB at

ranges from the recorder of apx 2-10 and 1-4 km, respectively (Fig. 17.a). A notable exception was the ship *AM Quebec* (MMSI 538004978), for which 110 and 120 dB SPL<sub>BB</sub> occurred 10-20 km and 4-5 from the ship, respectively. Typical speeds of transiting bulk carriers resulted in duration of received SPL<sub>BB</sub> >110 dB at the recording location for periods of 0.5-1 h and 120 dB for about 0.5 h. A separate analysis was conducted of received level with range to ship for bulk carriers entering and exiting eastern Eclipse Sound. Bulk carrier ships entering from the east and in route to Milne Port had mean draft 7.6 m, as reported by the ships via AIS transmission. When exiting, presumably after loading at Milne Port, bulk carriers had mean draft 14.2 m. Received level with range was similar in both load states.

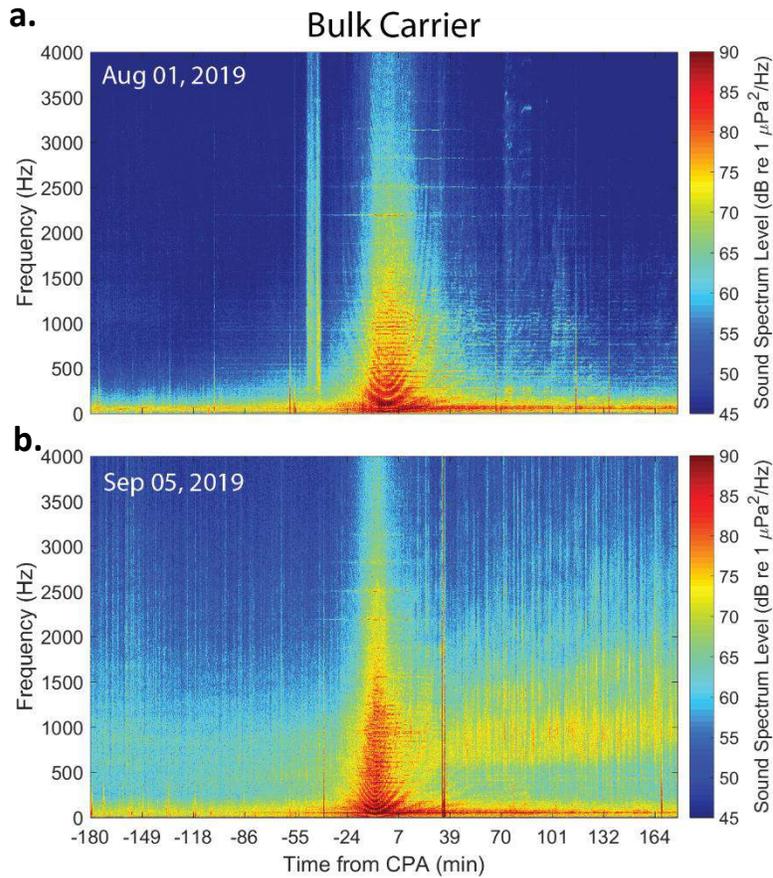


Figure 18. Long-term spectral average (LTSA) of the 6-h window about the closest point of approach (CPA) of 225 m bulk carrier *Nordic Orion* (MMSI 373437000) during two transits past the recording location. Wind-generated noise below 4 kHz is evident in the Sep 5, 2019 transit (top panel; CPA range 2 km). A transit of the same vessel Aug 1, 2019 (bottom panel; CPA range 2.4 km) occurs during lower background noise at the start of the ice-free season.

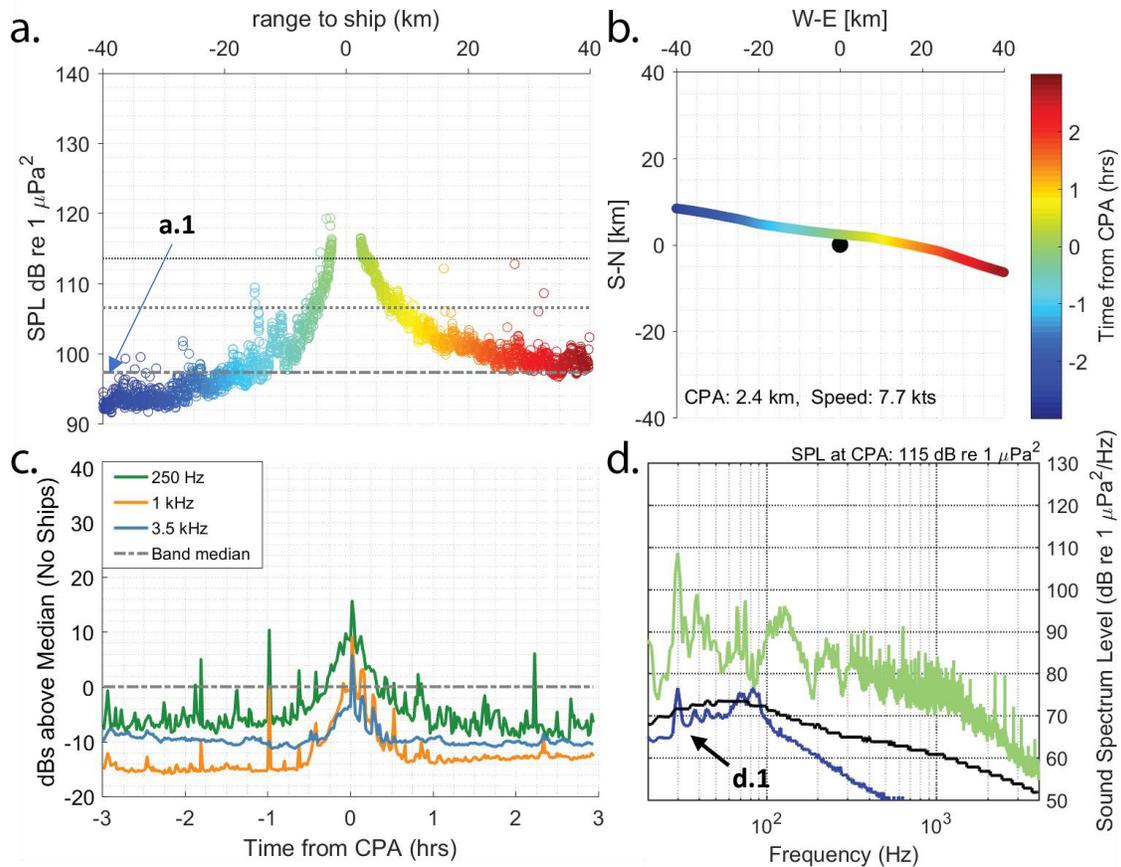


Figure 19. Ship transit analysis for bulk carrier *Nordic Orion* Aug 01, 2019.  $\text{SPL}_{\text{BB}}$  averaged every 5s (a; open circles) increases beginning at approximately range 40 km prior to CPA.  $\text{SPL}_{\text{BB}}$  115 dB at CPA range 2.4 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{\text{rd}}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

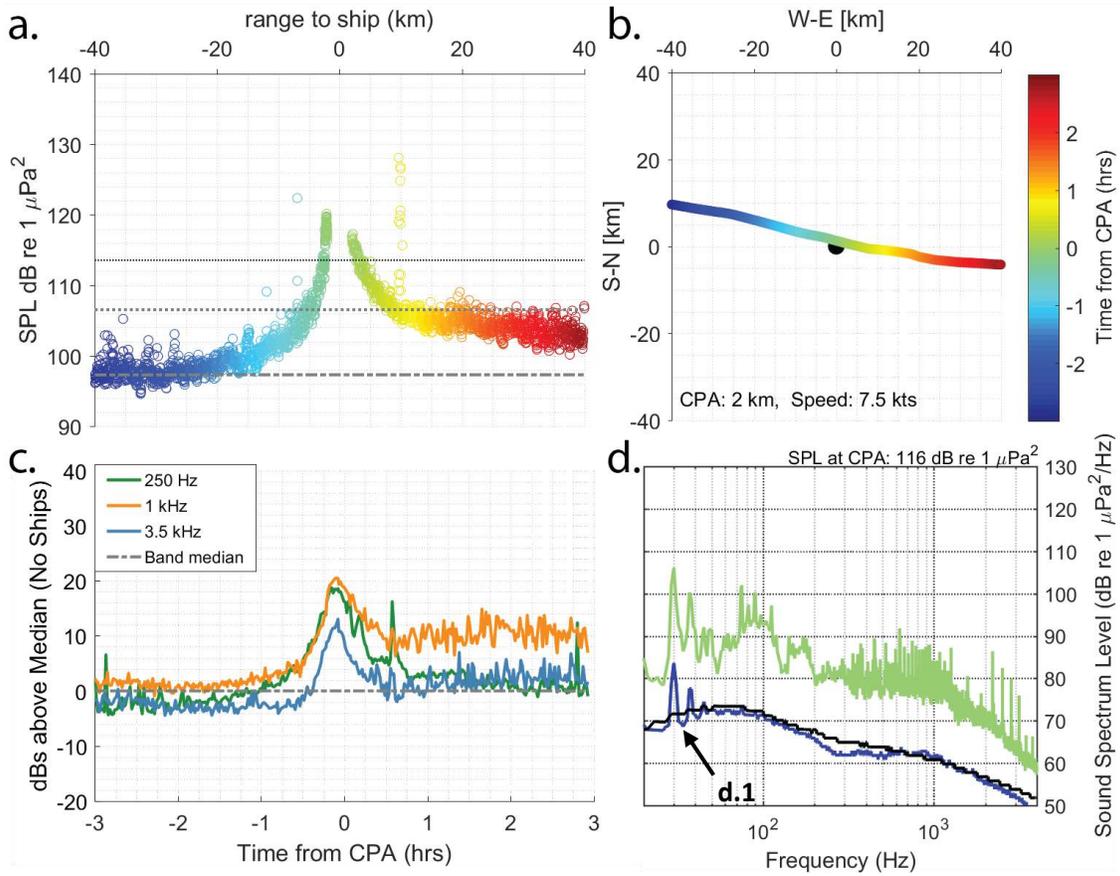


Figure 20. Ship transit analysis for bulk carrier *Nordic Orion* Sep 05, 2019. SPL<sub>BB</sub> (a, open circles) averaged every 5s increases starting 30 km range to ship pre-CPA. SPL<sub>BB</sub> was 116 dB at CPA range 2 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line) 1/3<sup>rd</sup> octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

## General cargo vessels

Two transit scenarios are exemplified for general cargo vessels in figures 21-23, one with median background sound levels pre-CPA (*Zelada Desgagnes*, Aug 23, 2019; Fig. 22) and one with relatively noisy (90<sup>th</sup> percentile background sound level) pre-CPA conditions (*Sedna Desgagnes*, Aug 24, 2019; Fig. 23). General cargo vessel received SPL was highest at frequencies from 20-200 Hz (Figs 22.d, 23.d) with long-range propagation of 20-30 Hz noise apparent at ranges > 30 km from the receiver. Estimated background SPL<sub>BB</sub> during the Aug 23 transit was 103 dB (Fig. 22.a.1), but determining initial onset of elevated noise at the receiver was complicated by the transit of Canadian Warship *HCMS Kingston* (MMSI 316139000) past the recorder 2 h prior to CPA (Fig. 21.a.1, 22.c.1). Continuous increase in SPL<sub>BB</sub> is evident from 1.5 h pre-CPA and SPL<sub>BB</sub> returned to pre-transit levels 1.5 h after CPA at range 30 km from the receiver. Duration of > 110 dB SPL<sub>BB</sub> was 2.5 h, starting and ending at ranges 15 and 25 km from the bow and stern aspects, respectively. Duration of SPL<sub>BB</sub> >120 dB was 0.5 h starting at range 4 km from the bow aspect and ending at range 7 km from stern.

On Aug 24, 2019, estimated background sound during the transit of the *Sedna Desgagnes* (MMSI 316015251) was close to 90<sup>th</sup> percentile background sound levels (Fig. 23.a.1). SPL<sub>BB</sub> was elevated above pre-CPA background levels from 0.5 h before to 1.5 h after ship CPA. Duration of > 110 dB SPL<sub>BB</sub> was 2 h, starting and ending at ranges 10 and 25 km from the bow and stern aspects, respectively. Duration of SPL<sub>BB</sub> >120 dB was 0.4 h starting at range 3 km from the bow aspect and ending at range 5 km from stern. Relative changes in band SPL and in SPL were smaller and the difference in bow and stern received levels was less visible than in the lower background sound scenario in figure 22.

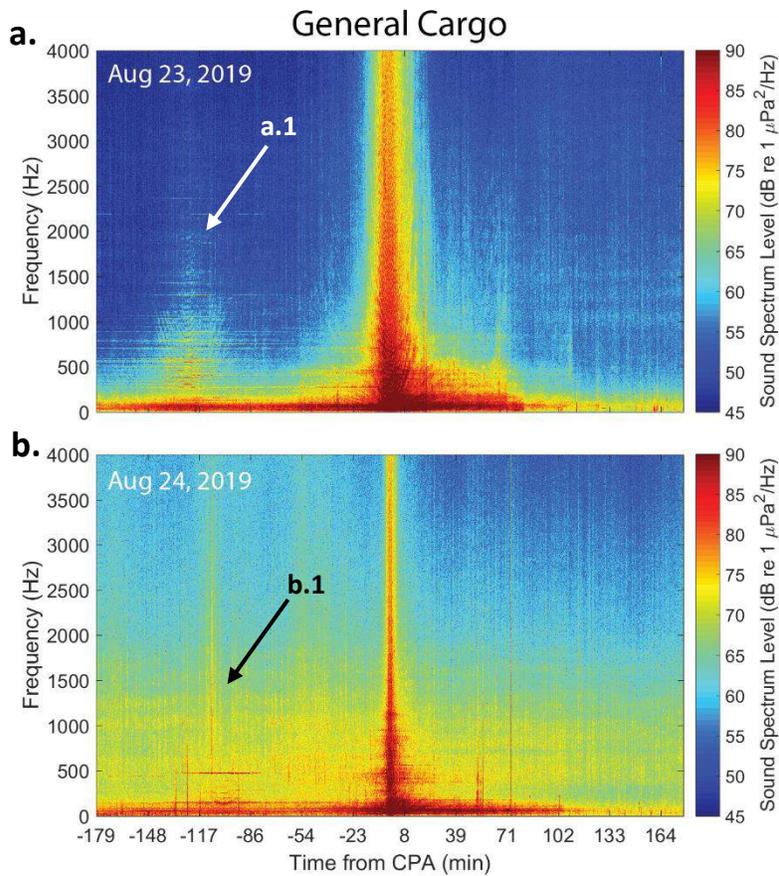


Figure 21. LTSA of the 6-h window about the CPA of two general cargo vessels transiting past the PI recording site in open water. (a) 139 m general cargo vessel, *Zelada Desgagnes* (MMSI 316015133) Aug 23, 2019 (CPA 1.4 km). Canadian Warship, *HCMS Kingston* (MMSI 316139000) passes at range 1.5 km 2 h prior to CPA (a.1). (b) 139 m general cargo vessel *Sedna Desgagnes* (MMSI 316003010) on Aug 24, 2019. Passenger ship, *Fram* (MMSI 258932000) passes at range 1.6 km from recorder 1.7 h prior to CPA (b.1).

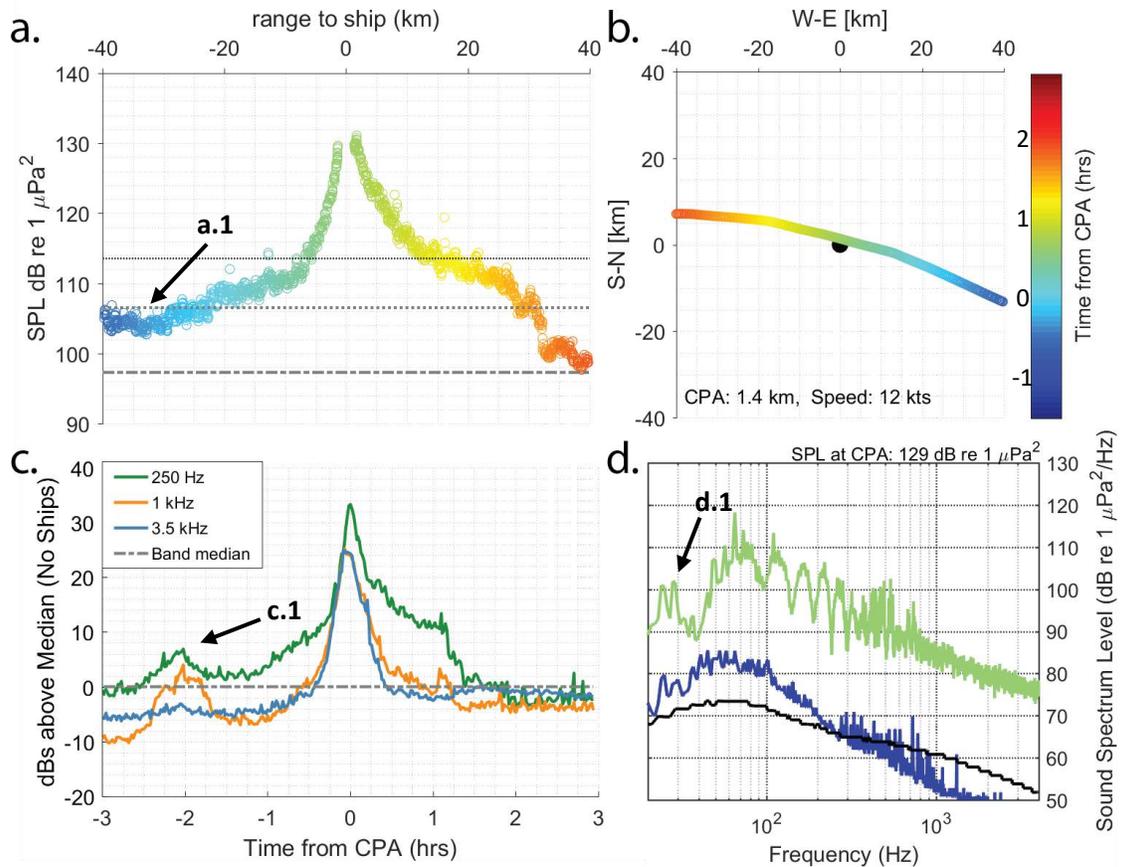


Figure 22. Ship transit analysis for general cargo vessel, *Zelada Desgagnes* Aug 23, 2019.  $\text{SPL}_{\text{BB}}$  (a, open circles) averaged every 5s increases starting 30 km range to ship pre-CPA.  $\text{SPL}_{\text{BB}}$  was 129 dB at CPA range 1.4 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{\text{rd}}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

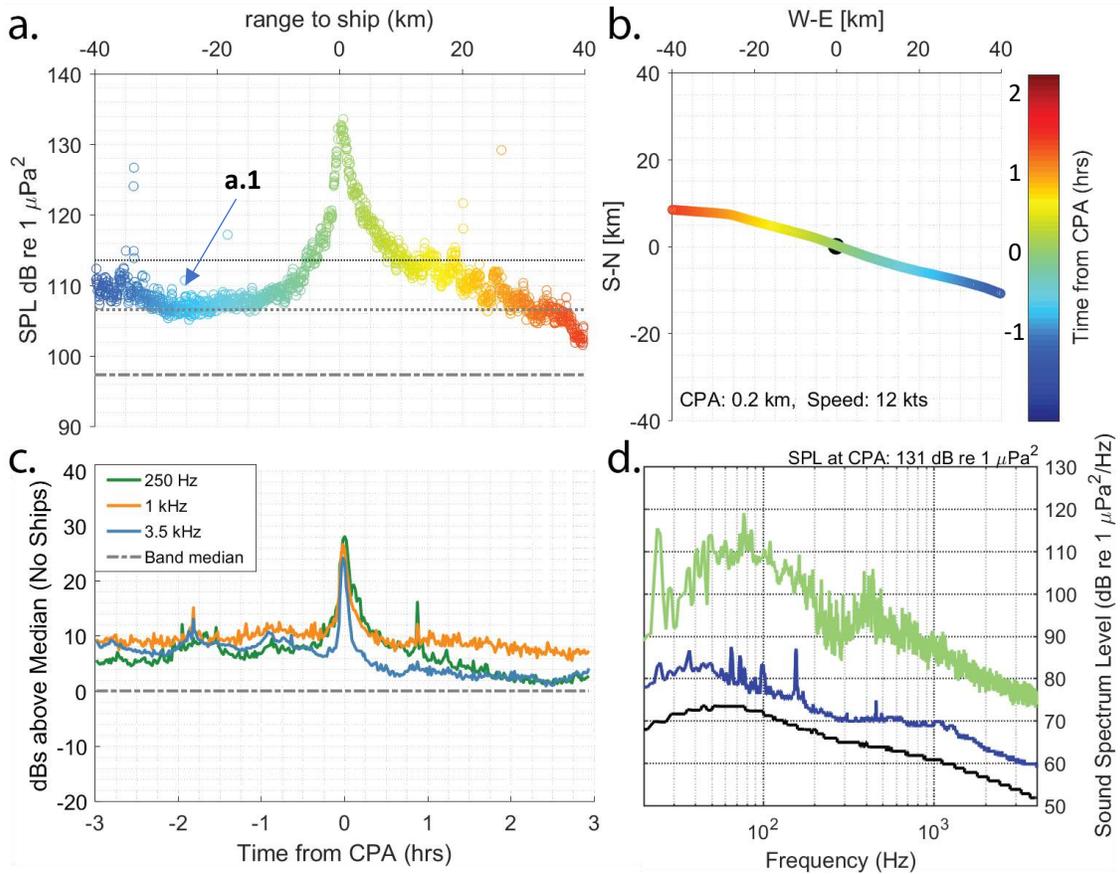


Figure 23. General cargo vessel *Sedna Desgagnes* (MMSI 316015251) Aug 24, 2019.  $\text{SPL}_{\text{BB}}$  (a; open circles) averaged every 5s increases above pre-transit background level (a.1) starting at 10 km range to ship pre-CPA and ending 30 km post-CPA.  $\text{SPL}_{\text{BB}}$  was 131 dB at CPA range 0.2 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{\text{rd}}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPL (d) of CPA period (green line) with median SPL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

Patterns in received level versus range were examined for a subset of 11 general cargo ship transits during which the nearest time to CPA of another ship transit was > 1 h and

with maximum CPA distance to the receiver of 2 km.  $SPL_{BB}$  was more variable between individual ships and transits with this vessel type due to background sound conditions and the presence of other ships within the 6-h ship transit windows. Greater than 110 and 120 dB  $SPL_{BB}$  occurred at ranges from the recorder of about 2-30 and 1-15 km, respectively (Fig. 17.b).

#### Fuel and chemical Tankers

Two similar transits of the fuel and chemical tanker, *Sarah Desgagnes* (MMSI 316012308), were selected to exemplify the ship type (Figs 24-26). This ship made about half of total tanker transits past site PI during the analysis periods. Acoustic characteristics of the vessel had higher SPL and SPL approaching the CPA and longer range and duration of elevated noise levels compared to other cargo vessel types. Received SPL was highest at 30-200 Hz with peak energy at 70-90 Hz (Figs 25.d. and 26.d.). Low-frequency noise propagation >100 Hz is less apparent at ranges > 30 km in transits of this vessel type than in bulk carriers. In both representative transits, background sound levels were within 5 dB of the median  $SPL_{BB}$  excluding ship transits.  $SPL_{BB}$  increased above estimated pre-CPA background sound from 2 h prior to CPA (range 20-30 km) to > 3 h after CPA (range >40 km). The 250 Hz, 1 kHz, and 3.5 kHz band SPL (Fig. 31) followed a similar pattern during the ship transits with relative increases in SPL at CPA of about 30 dB above pre-transit levels for all bands.

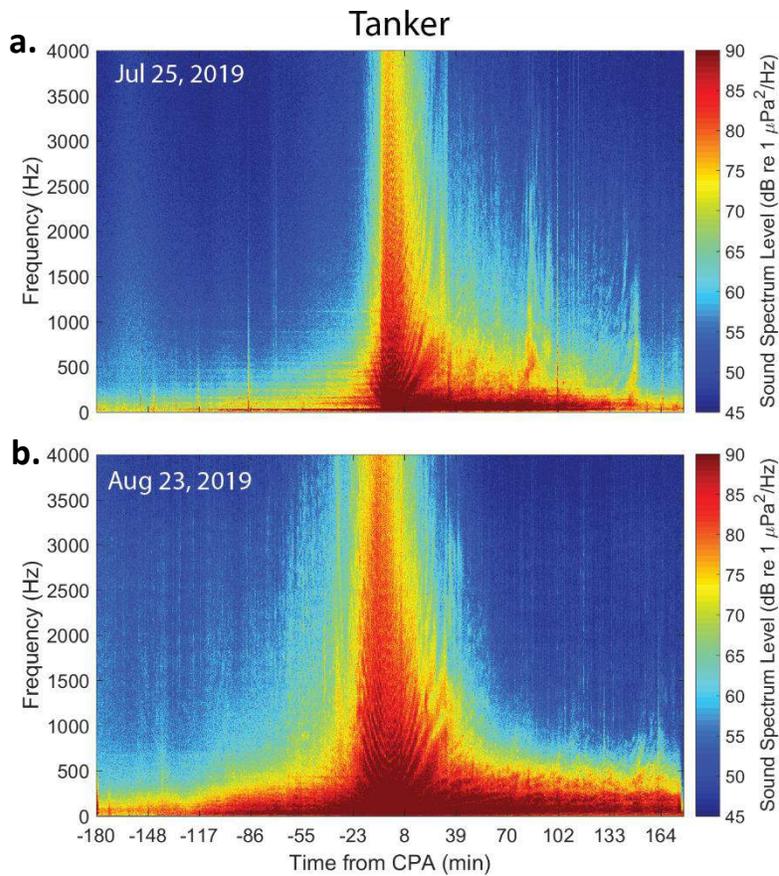


Figure 24. Long-term spectral average (LTSA) of the 6-h window for 147 m fuel and chemical tanker *Sarah Desgagnes* (MMSI 316012308) transiting past the PI recording site on Jul 25 (top) and Aug 23 (bottom), 2019. Underwater sound from the ship at <200 Hz is evident throughout the transits, with higher levels of low-frequency noise persisting longer at the stern aspect (positive time from CPA) than when ship is approaching (negative time from CPA).

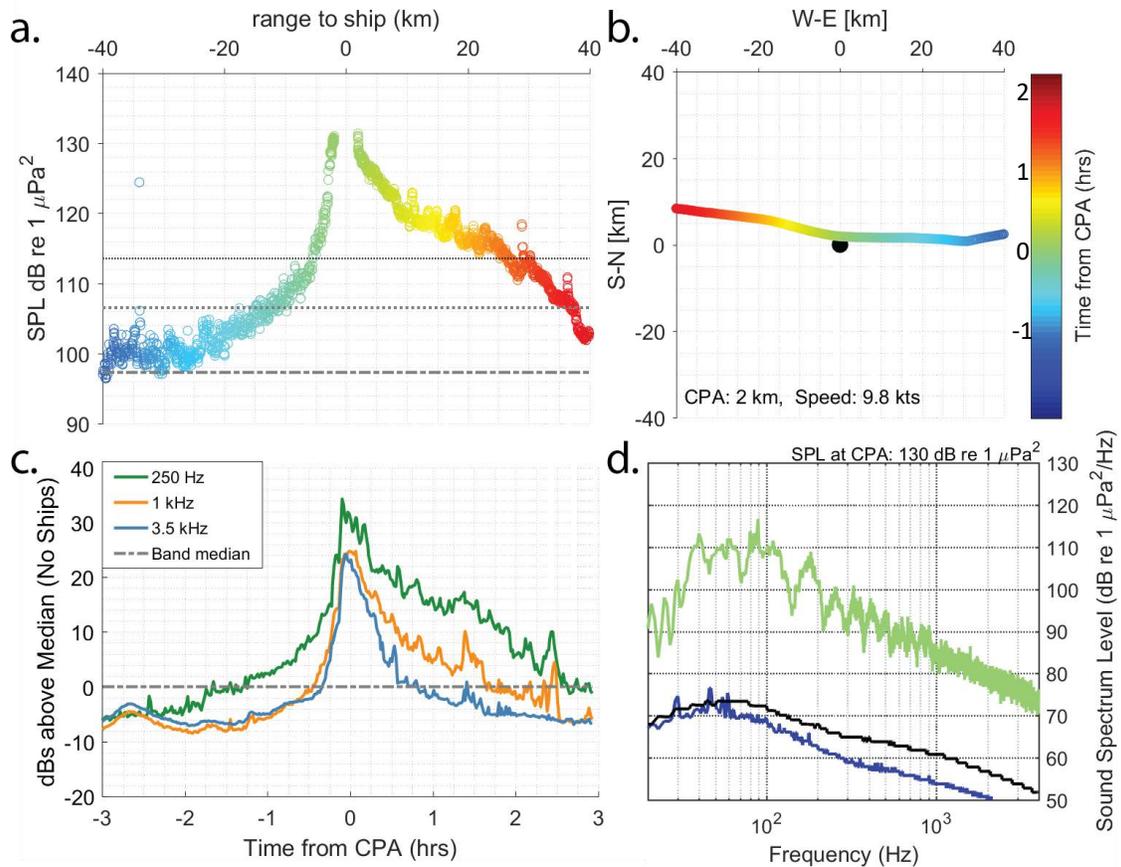


Figure 25. Ship transit analysis for fuel and chemical tanker, *Sarah Desgagnes* July 25, 2019.

SPLBB (a; open circles) averaged every 5s increases above pre-transit background level starting at 25 km range to ship pre-CPA and ending >40 km post-CPA. SPLBB was 130 dB at CPA range 2 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line) 1/3rd octave band levels during ship transit plotted relative to 50th percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1st 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

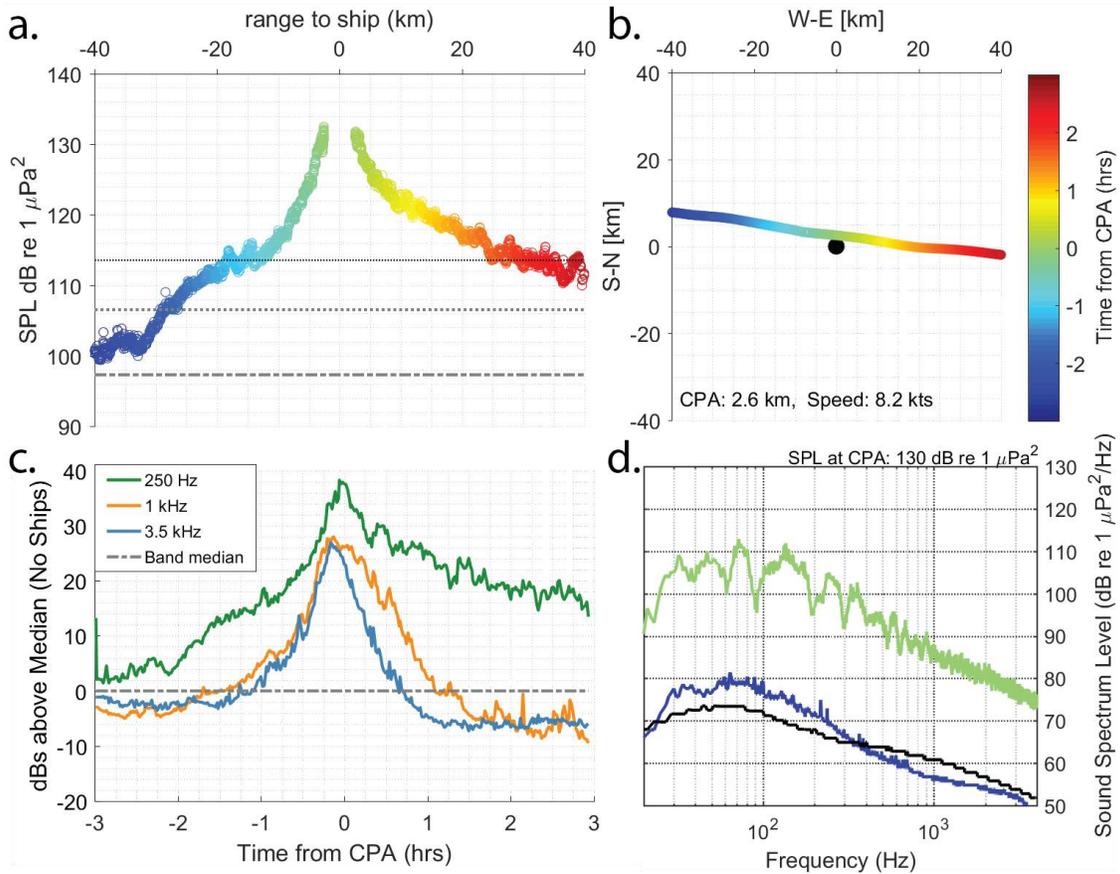


Figure 26. Ship transit analysis for fuel and chemical tanker, *Sarah Desgagnes* August 22, 2019.

SPL<sub>BB</sub> (a; open circles) averaged every 5s increases above pre-transit background level starting at 30 km range to ship pre-CPA and ending >40 km post-CPA. SPL<sub>BB</sub> was 130 dB at CPA range 2.6 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line) 1/3<sup>rd</sup> octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

Patterns in received level versus range were examined for a subset of 6 tanker ship transits during which the nearest time to CPA of another ship transit was > 4 h and with maximum CPA distance to the receiver of 2 km. Greater than 110 and 120 dB SPL<sub>BB</sub> occurred at ranges from the recorder of about 7 to >40 km and 2-20 km, respectively (Fig. 17.d). At speeds of about 9 knots, the duration of SPL<sub>BB</sub> exceeding 110 dB was 2.5 to >4 h and duration of >120 dB was 1.5-2 h.

#### Icebreaker-Offshore Support Vessel

One icebreaker-offshore support vessel, *Botnica* (MMSI 276805000), operated in Eclipse Sound and Milne Inlet to assist commercial shipping operations September 29 to October 22, 2018 and July 17 to August 10, 2019, making a total of 19 and 39 transits past the PI and MI sites, respectively (Table 1). On most transits, *Botnica* was escorting one or two bulk carriers in convoy. At the end of 2018 and start of 2019 shipping, the icebreaker convoys also included up to two additional ocean tugs. Two representative transits are presented for October (Figs. 27-29) and two for July to exemplify icebreaker operations in freeze-up and break-up periods with different background sound scenarios (Figs. 30-32). Generally, icebreaker transit SPL were distinguished from other vessel transits by the presence of strong tonal noise with harmonic bands of fundamental frequency 200 Hz, extending above 4 kHz as the vessel approached the CPA. During typical ambient noise conditions, the 200 and 400 Hz tonal bands were elevated above background levels at distances exceeding 40 km from the receiver at both the bow and stern aspects. When background sound levels were at or below the median, tonal bands up to 1 kHz were apparent throughout the 6-h transit window and to ranges > 40 km (e.g. Fig. 30). These characteristic bands of noise radiated from the ship were present with and without sea ice in the vicinity and both when the ship was traveling alone and escorting other vessels.

A representative multi-vessel icebreaker transit was selected during which the 97m icebreaker *Botnica* escorted bulk carriers *Nordic Oasis* and *Nordic Odin* and tugs *Ocean Taiga* and *Ocean Tundra* at a speed of 8 knots into Eclipse Sound in 2/10 ice cover (Figs 30.a and 31). The background SPL<sub>BB</sub> during the transit was estimated as 95 dB re 1 μPa, which was approximately the median SPL<sub>BB</sub> during July ship-excluded periods. At the CPA, range to the ship was 2.7 km from the recording site and the SPL<sub>BB</sub> was 130 dB re 1 μPa. In the long-term spectral average (Figure 30.a), 200 Hz tonal noise from the ship and harmonics are apparent during the entire 6-h window about the ship CPA. This 200 Hz tonal noise and harmonics at 400, 600, and 800 Hz are also apparent in the background spectrum and at much higher spectrum levels in at CPA (Fig. 31.d.1). During the transit, the SPL<sub>BB</sub> increased to 110 dB by 1 h pre-CPA and 120 dB at 30 min before the CPA. Durations of received levels greater than 110 and 120 dB were apx. 2.75 and 1.25 hrs. Range to the 110 and 120 dB received levels were 18 and 8 km, respectively as the vessels approached (Fig. 31.a). After passing, received levels fell below 110 and 120 dB at ranges of 15 and 30 km.

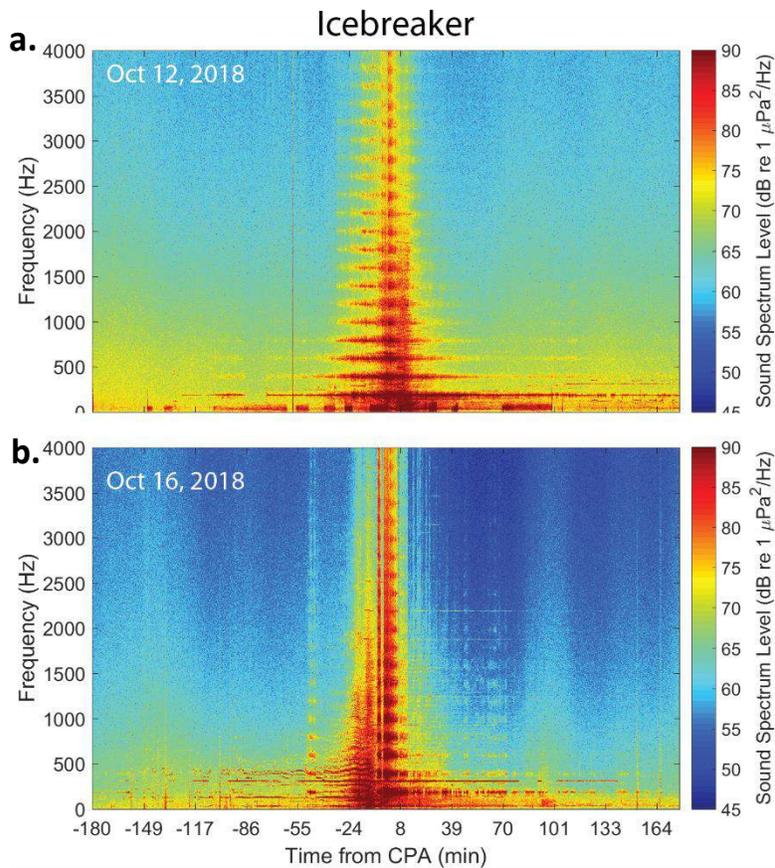


Figure 27. Long-term spectral average (LTSA) of the 6-h window for the icebreaker *Botnica* (MMSI 276805000) escorting one bulk carrier ship, *Nordic Oshima* (MMSI 357629000), when transiting past the PI recording site in 5/10 to 9/10 ice cover on Oct 12 (top) and Oct 16 (bottom), 2018. Tonal noise from the icebreaker is evident throughout the transit time windows with higher-frequency harmonics extending to above 4 kHz as the ships approach CPA.

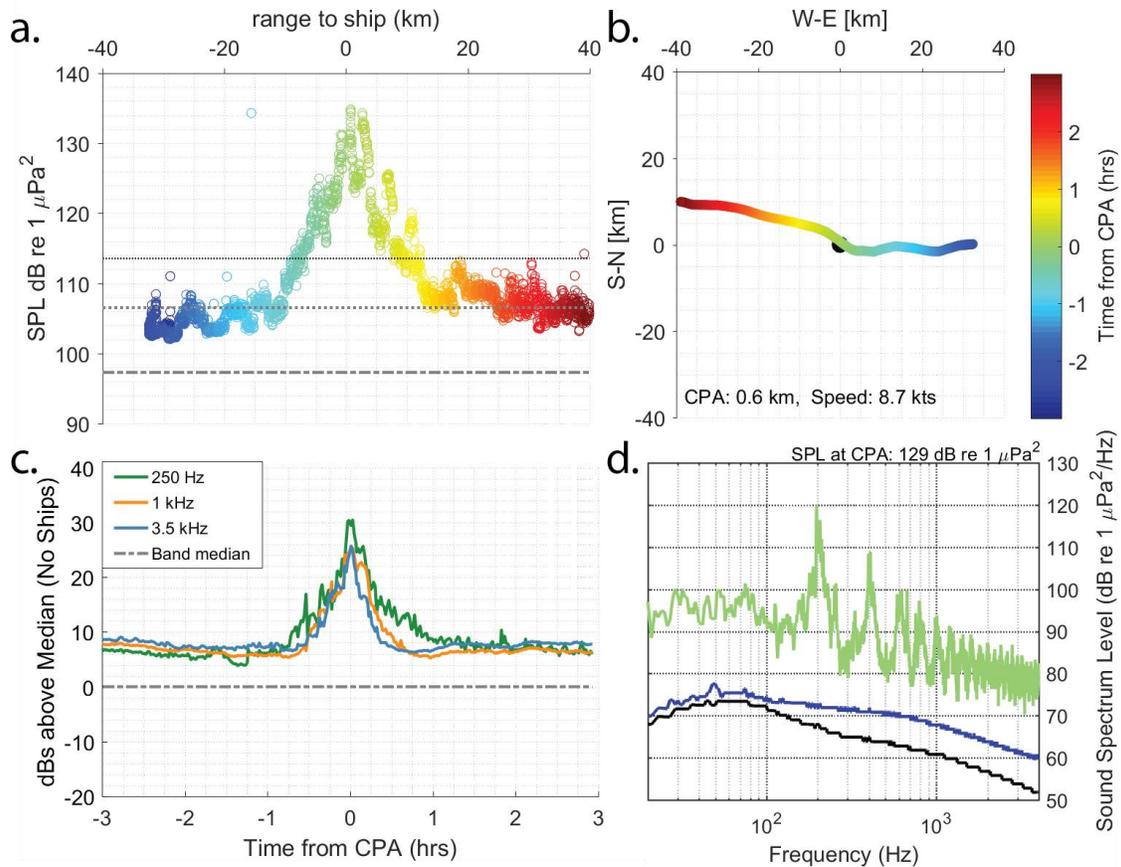


Figure 28. Ship transit analysis for icebreaker *Botnica* escorting the bulk carrier *Nordic Oshima* (MMSI 357629000) into Eclipse Sound from Baffin Bay Oct 12, 2018 in 5/10 to 9/10 ice cover. Ships separated by 2 km distance and reach their respective CPA to the recorder 8 min apart.  $\text{SPL}_{\text{BB}}$  (a; open circles) averaged every 5s increases above pre-transit background level starting at 20 km range to ship pre-CPA and ending >40 km post-CPA.  $\text{SPL}_{\text{BB}}$  was 129 dB at CPA range 0.6 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{\text{rd}}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

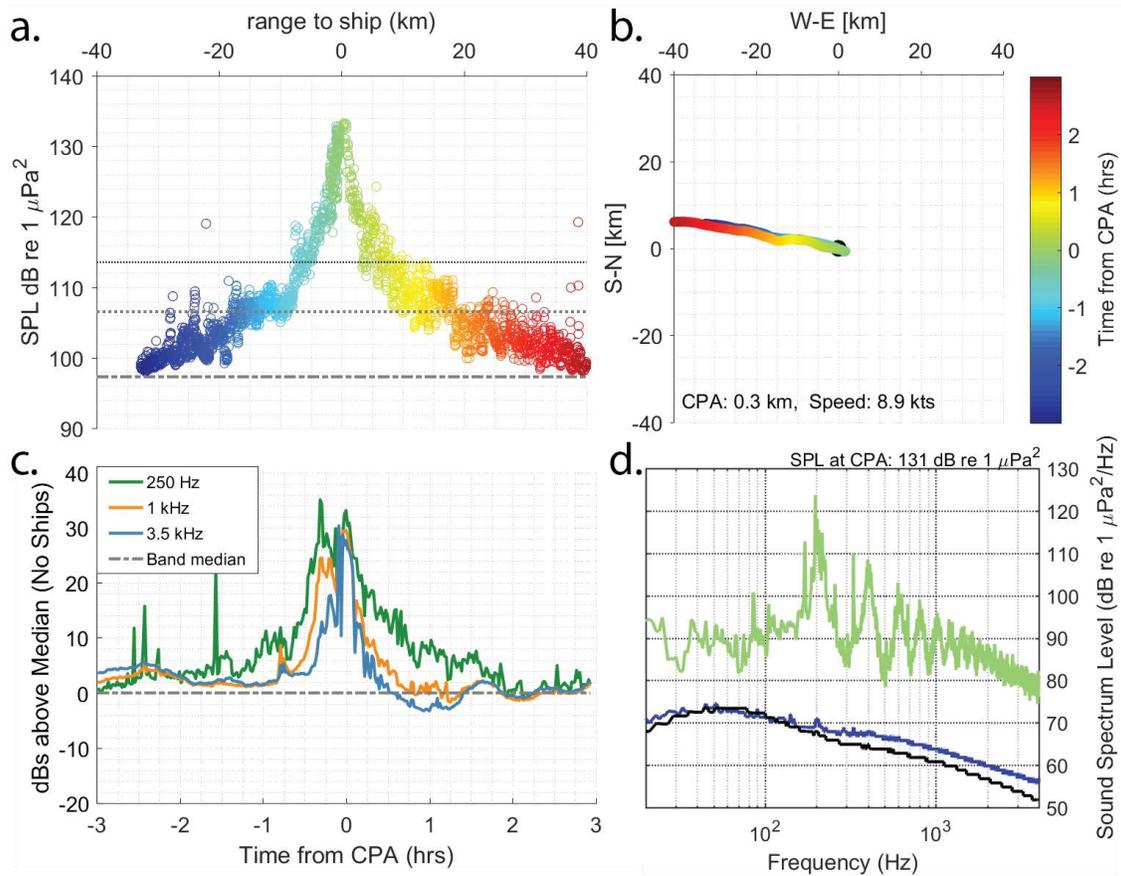


Figure 29. Ship transit analysis for icebreaker *Botnica* escorting the bulk carrier *Nordic Oshima* out of Eclipse Sound toward Baffin Bay Oct 16, 2018 in 5/10 to 9/10 ice cover with icebreaker turnaround maneuver near the recording site. Ships separated by 3 km distance and reach their respective CPA to the recorder 11 min apart.  $SPL_{BB}$  (a; open circles) averaged every 5s increases above pre-transit background level starting at 20 km range to ship pre-CPA and ending >40 km post-CPA.  $SPL_{BB}$  was 129 dB at CPA range 0.6 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{rd}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

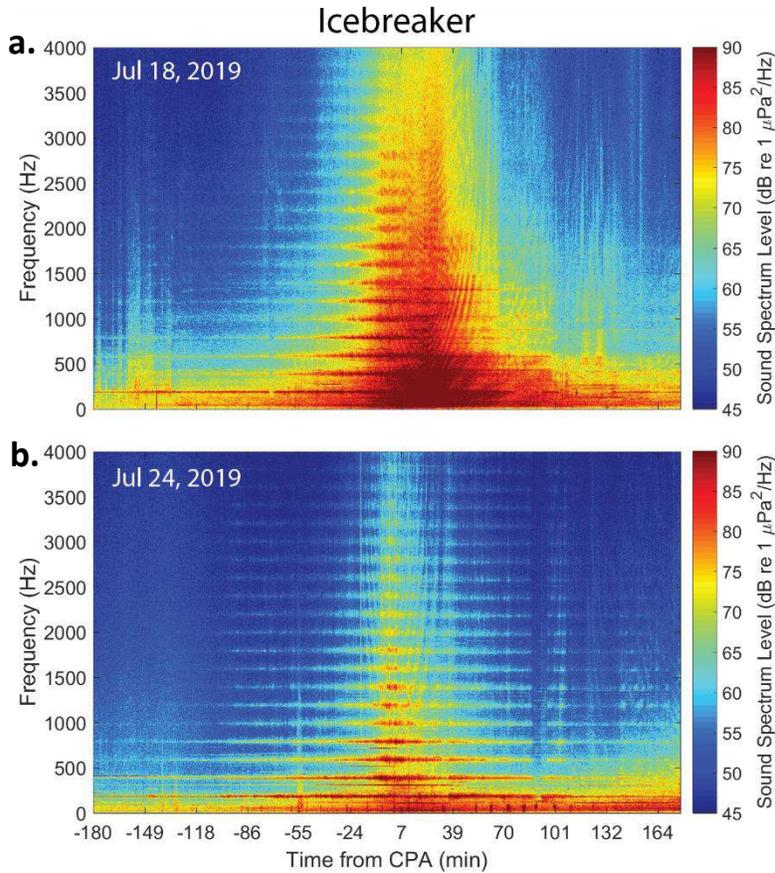


Figure 30. Long-term spectral average (LTSA) of the 6-h window for icebreaker *Botnica* (MMSI 276805000) escorting two bulk carriers and two tugs in convoy and transiting past the PI recording site on July 18 (top) and *Botnica* escorting three bulk carriers on July 24, 2019. Tonal noise up to 1 kHz from the icebreaker is evident throughout the transit time windows with higher-frequency harmonics extending to above 4 kHz as the ships approach CPA. Tonal noise to 3 kHz is evident on July 24 up to 3 h after the CPA.

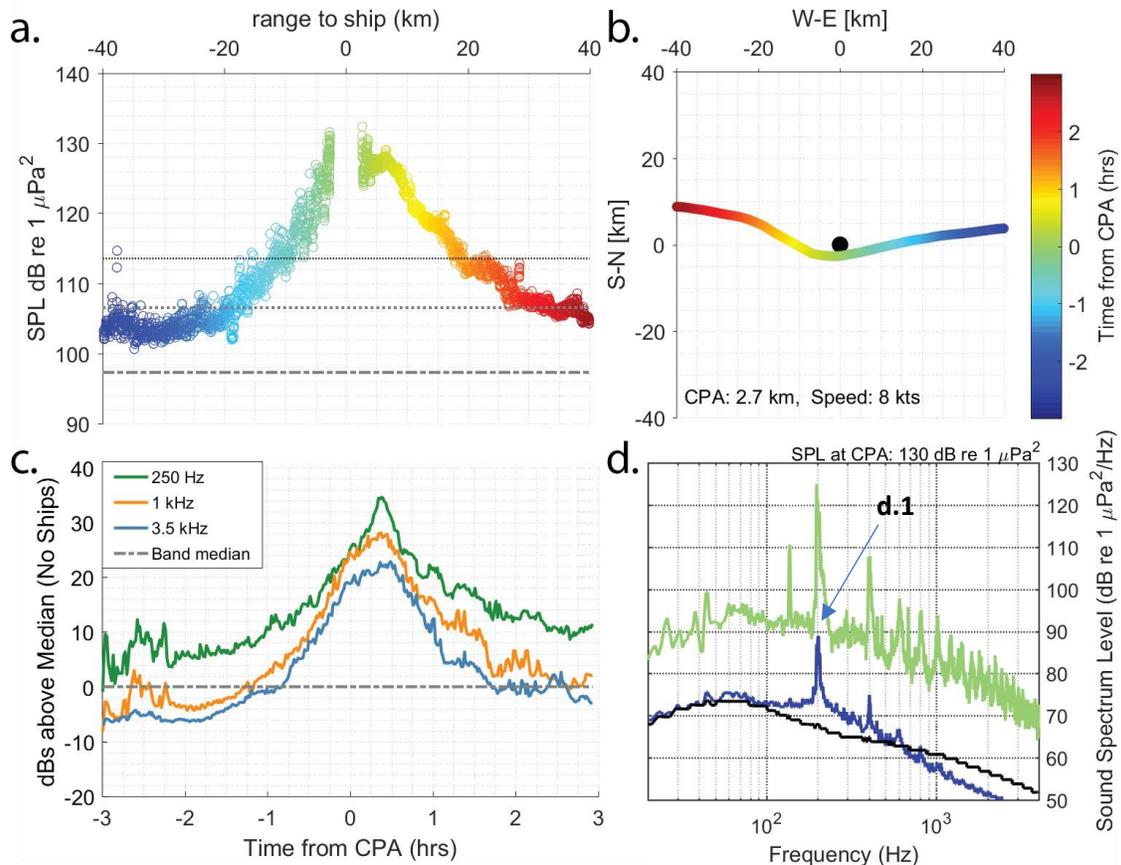


Figure 31. Ship transit analysis for icebreaker *Botnica* escorting bulk carriers *Nordic Odin* (MMSI 356364000) and *Nordic Oasis* (MMSI 374322000) and tugs *Ocean Tundra* (MMSI 316025785) and *Ocean Taiga* (MMSI 316007572) into Eclipse Sound from Baffin Bay July 18, 2019 in 2/10 ice cover. Time from icebreaker passing to last ship CPA was 23 min.  $\text{SPL}_{\text{BB}}$  (a; open circles) averaged every 5s increases above pre-transit background level starting at 30 km range to ship pre-CPA and ending >40 km post-CPA.  $\text{SPL}_{\text{BB}}$  was 130 dB at CPA range 2.7 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{\text{rd}}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

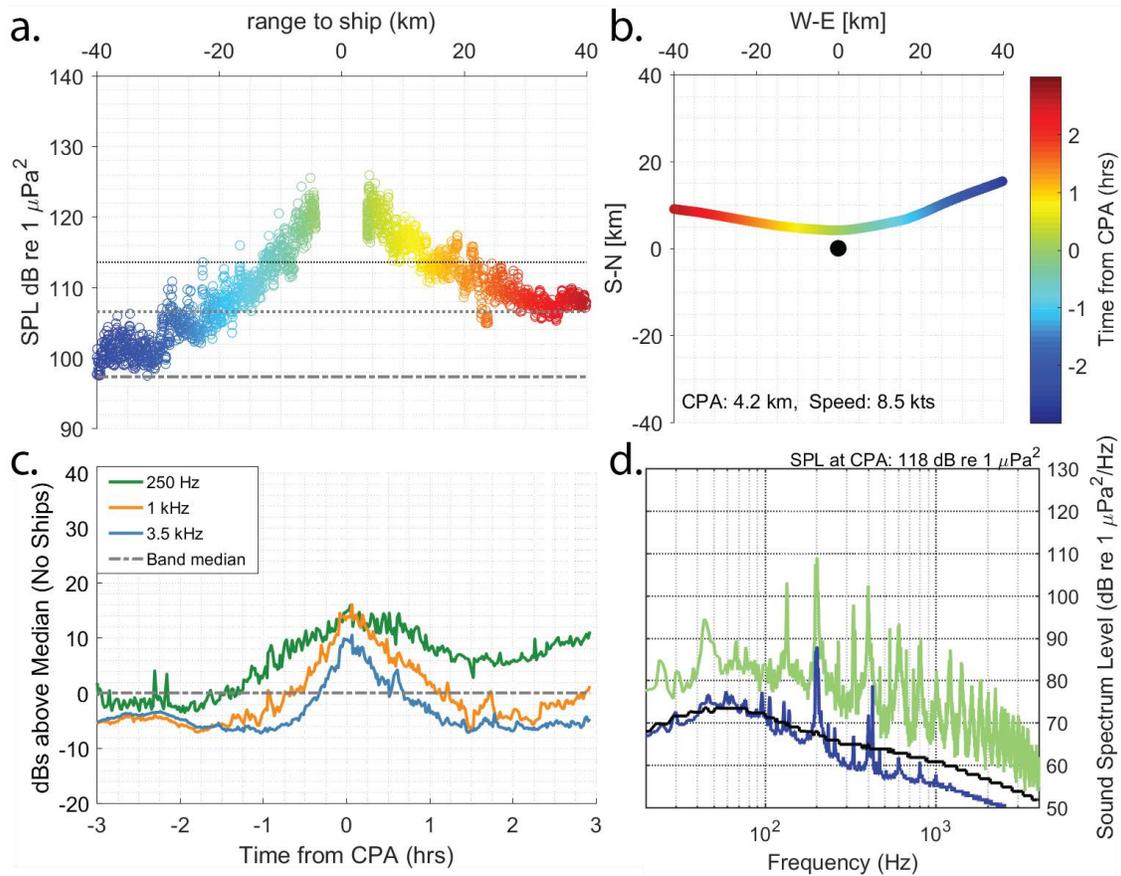


Figure 32. Ship transit analysis for icebreaker *Botnica* escorting three bulk carriers (*Nordic Olympic*, *Golden Strength*, and *Golden Ruby*) into Eclipse Sound on July 24, 2019 at a speed of 8.5 knots in 0/10 ice cover. Time from icebreaker passing to last ship CPA was 28 min.  $\text{SPL}_{\text{BB}}$  (a; open circles) averaged every 5s increases above pre-transit background level starting at 30 km range to ship pre-CPA and ending >40 km post-CPA.  $\text{SPL}_{\text{BB}}$  was 118 dB at CPA range 4.2 km. Colors in SPL scatter plot (a) and map showing ship track (b) represent time from CPA. 1-min average 250 Hz (c; green line), 1 kHz (orange line), and 3.5 kHz (blue line)  $1/3^{\text{rd}}$  octave band levels during ship transit plotted relative to 50<sup>th</sup> percentile for the frequency band excluding ship transits (dash-dot line). SPSL (d) of CPA period (green line) with median SPSL of the 1<sup>st</sup> 30 min of transit plot (blue line) and shipping season median levels during periods excluding ship transits (black line).

## DISCUSSION

### Sound levels in the absence of local ships

We compare the overall underwater soundscape at two Eclipse Sound locations to monthly estimates of the soundscape with transient ship noise events excluded. At both locations when excluding ship transit events, underwater natural sound levels are variable seasonally and on shorter timescales of days and hours. Much of the variability on timescales of hours to months is likely due to the combined effects of sea ice cover and sea surface wind patterns on sources and propagation of sound. Sound levels excluding ship transits are generally higher during open water periods than when sea ice is present, consistent with other studies of Arctic ambient underwater sound levels (Halliday *et al.*, 2020; Roth *et al.*, 2012). The lower received sound levels during ice cover are likely due to the scattering effects of sea ice on propagating sound and on the fact that sea ice acts as a barrier preventing sea surface waves from forming and generating noise.

At site PI, the quietest month of the year was July, a time with relatively low winds (mean 4.7 +/-2.8 m/s). Wind interaction with the sea surface generates noise from 200 Hz to >4 kHz, which is positively correlated with wind velocity (Wenz, 1962). Although Jul and Aug mean wind speeds were within 0.5 m/s of each other, the variability in wind speed increased in Aug relative to July (Fig. 16.b). In Aug, the sporadic wind-generated noise events become apparent in the 90<sup>th</sup> and 99<sup>th</sup> percentiles of periods excluding ship transits past the recorder (Fig. 13). In September and October wind-generated noise becomes a more prevalent feature of the soundscape, raising the median SPL by 5-10 dB at frequencies above 300 Hz. Median and 90<sup>th</sup> percentile SPL<sub>BB</sub> in Oct increase to 5 and 9 dB, respectively, above July levels.

As Oct sea ice formation progresses at both sites,  $SPL_{BB}$  decreases as expected with increasing ice cover (e.g. Roth *et al.*, 2012; Halliday *et al.*, 2020). While impulsive natural sound events continue through Oct at PI, likely associated with sea ice formation and the return of pack ice from N. Baffin Bay, variability in underwater sound levels excluding ship transits decreases as the ice layer forms. Median SPSL at 1 kHz was within 2-4 dB between the sites during July and Aug, but the two locations strongly differed during Oct. October SPSL at PI was about 12 dB higher than MI at frequencies > 1 kHz, possibly due to the formation of landfast ice within Milne Inlet at that time. Sea ice formation occurred around the same time at both sites, but ice at PI was likely unconsolidated pack ice and subject to dynamics that can generate substantial underwater noise (Kinda *et al.*, 2015; Mahanty *et al.*, 2020). The relatively stable sea ice connected to shore at MI would presumably generate lower levels of sound related to dynamic forces in the ice.

Except for the August median 1 kHz band level, all ship transit excluded monthly band percentile and SPSL levels are lower at MI than PI. Local acoustic propagation and environmental characteristics may explain much of these differences. The relatively complex bathymetry of MI may act to shelter the site from long-range propagation of sound. In the frequencies below 200 Hz, median SPSL at MI were substantially lower in all months in the absence of ships within 30 km of the recording site. For example, at 50 Hz monthly median SPSL was 56-58 dB at MI and 72-76 dB at PI. This difference coincides with frequencies of long-range shipping noise found throughout much of the world ocean and attributed to distant shipping. A study in a bathymetrically complex coastal region off California yielded similar results when compared to a deeper location in the same region open to long-range sound propagation (McDonald *et al.*, 2008;

McDonald *et al.* 2006). In the California study, lower received levels than expected at frequencies below 200 Hz were attributed to the quieter location being sheltered from long-range propagation of shipping noise. Results of this study suggest a similar protection from long-range ship noise at site MI.

#### Sound levels including local ships

A comparison of sound levels during the periods excluding ships with those of periods including ship transits clearly shows the addition of sounds from the ship transits in the upper percentiles of sound pressure spectrum levels and SPL<sub>BB</sub>. July through August 90<sup>th</sup> and 99<sup>th</sup> percentile spectrum levels are up to 10 and 20 dB higher, respectively, in the 20-200 Hz band with ship transit periods included. This is the frequency band in which most underwater acoustic energy from ships occurs (Ross, 1976; McKenna *et al.*, 2012a; Gassman *et al.*, 2017). With each ship transit during July and August, SPL<sub>BB</sub> reaches levels 10-20 dB higher than the 90<sup>th</sup> percentile of level excluding ships and up to 40 dB higher than median. These levels are substantially higher than those occurring in the natural acoustic environment and the combined effect of multiple daily ship transits past the recorder is evident in the soundscape. During September and October, the difference between the natural sound levels excluding ship transits and those including them become less pronounced. For example, the 90<sup>th</sup> percentile SPL<sub>BB</sub> including and excluding ship transits during October were 111 and 109 dB.

The highest sound levels from ship transits occurred during October and July, which could be due to the presence of greater numbers of noisier icebreaker, tanker, and general cargo vessels. Some contribution may also result from changes in the sound propagation environment. During the times when the noisiest ships are present, the physical properties of the water column may also increase propagation of the ship noise. In July and Oct, the sea

surface temperature is colder and water column more mixed, which increases propagation of radiated sound from ships (Jensen *et al.*, 1993). In summer, the opposite effect may occur as warming of the surface layer creates a sound speed profile that decreases radiated noise (Jensen *et al.*, 1993).

#### Acoustic characteristics of ship transits

Each of the most common ship types exhibits a different characteristic pattern of underwater noise. The characteristic signals of different ship types also appear in the monthly sound pressure spectrum levels. In July and October, the characteristic intense tonal sounds from the icebreaker, *Botnica*, appear in the median to 99<sup>th</sup> percentile ship-inclusive spectra and some of the 200 Hz tonal sound appears in the sound pressure spectrum levels for the periods excluding ships when ships are >40 km from the recorder. It is apparent that the icebreaker becomes a substantial feature of the acoustic environment when operating in the Eclipse Sound region.

In Aug and Sep the sound pressure spectrum levels including ship transits have peaks at 15 and 20 Hz. These peaks are characteristic of cavitation sound associated with rotation of the propeller in the bulk carriers and other cargo ships (Ross, 1976). Cavitation sounds are also apparent in the sound levels during periods excluding ships, suggesting that long-range propagation of ship noise is occurring and potentially adding to ambient noise levels regionally as in other ocean basins with extensive shipping traffic (Hildebrand, 2009).

Other operational characteristics may play a significant role in noise emitted by ships transiting Eclipse Sound. Ore carriers enter the region unloaded with draft c. 7 m and exit loaded with draft c. 14 m after taking on iron ore at the Milne Port. The higher received sound levels of exiting ships than for bulk carriers entering the region is consistent with expectation that the

deeper propeller increases dipole source levels. When ships have a shallower draft they are predicted to have lower strength of the dipole source and less underwater radiated noise as a result (Ross, 1976; Wilmut *et al.*, 2007).

Some individual ships had noteworthy signatures. The intense tonal sounds from the icebreaker, *Botnica*, were likely a result of machinery on board the ship and not the cavitation of the propeller. These tones are present and constant in frequency throughout each transit and the pattern of received level from the bow and stern aspects is symmetrical, suggesting that the source is not the propeller that would exhibit the bow/stern asymmetry observed in other studies of ship noise (Gassmann *et al.*, 2017). The intense tones from the icebreaker also add more than other ship types to the 1/3<sup>rd</sup> octave bands chosen to represent some social communication signals used by ringed seal and narwhal. The potential for that ship to have impacts on biologically relevant frequency bands is higher than other ships because of these acoustic characteristics that may result from design or operational parameters. Acoustic characteristics of this ship could be further investigated for potential mitigation or noise abatement measures. Another intense source of man-made sound was the fuel and chemical tanker, *Sarah Desgagnes*, which had higher SPL<sub>BB</sub> and sound pressure spectrum levels than other ships with similar operational speeds and routes. This ship may also be a good candidate for mitigation measures to address some of the excess sound generating characteristics.

#### Ship sounds overlap with marine mammal communication frequencies

Acoustic measurements of ship transits demonstrate that underwater sounds from the ships overlap with each of the biologically relevant frequency bands selected to represent ringed seal (250 Hz) and narwhal communication (1 kHz and 3.5 kHz). In most background sound conditions that occurs during ship transits, SPL in the 250 Hz, 1 kHz and 3.5 kHz is elevated

above background levels for periods of hours with each ship transit. Levels in this frequency band were elevated for durations of 1-h to > 6-h, raising the possibility for communication masking in this species occurring across substantial portions of the day when multiple vessels are transiting the region. Bowhead whales are also seasonally present in the study area (Heide-Jørgensen et al., 2006; Chambault et al., 2018) and produce sounds for communication at frequencies below 300 Hz (Clark & Johnson, 1984; Blackwell *et al.*, 2007) where most energy from ship noise occurs. The species should also be considered when evaluating potential communication masking from sounds of ships transiting in the Eclipse Sound and N. Baffin Bay region.

The 1 kHz and 3.5 kHz frequency bands also had elevated levels of sound generated by passing ships, although the duration of measurable noise increases was generally shorter for these bands than at 250 Hz. Tanker and icebreaker ships had higher levels in the 1 kHz and 3.5 kHz bands that extended to longer distances from the ship than for the more common bulk carriers. In the example icebreaker transits (Figs. 27-32), periods during which these levels were elevated above the pre-transit background range from 1 to 5 h. The maximum duration of elevated 1 or 3.5 kHz levels for the example bulk carrier or general cargo transits was 2 h.

## Conclusions

The natural soundscape of the Eclipse Sound region of North Baffin Island is geographically variable, likely due to differences in bathymetry and sea ice characteristics between the more interior protected inlets and the waters exposed to the expansive Baffin Bay. Shipping traffic introduces substantial noise to the underwater soundscape in both locations examined in this study. Regional shipping may have a

larger effect on the soundscape below 300 Hz in areas more exposed to long-range sound propagation than in bathymetrically complex areas that may be more sheltered acoustically. Individual ship transits through the region introduce transient noise at frequencies from 20 Hz to 4 kHz for periods lasting minutes to several hours. Underwater sound levels from ship transits of the most common ship types are sufficient to cause behavioral disturbance to narwhals along the shipping routes. Disturbance and avoidance behavior by narwhals caused by ship traffic has been observed in previous behavioral response studies in the study region (Golder, 2018; Golder, 2019; Golder, 2020). Underwater sounds from ship transits may also be sufficiently intense to cause masking of communication signals in narwhals, ringed seals, and bowhead whales, especially in the quieter areas like the MI site where levels of natural sounds are low relative to other regions of the ocean. The cumulative impacts to Eclipse Sound marine mammals resulting from repeated daily exposure to noise from transiting ships are unknown but should be further considered given the rapid pace of increasing shipping traffic in the region.

An additional analysis of 2015-2019 Eclipse Sound AIS data was performed for the purpose of historical comparison (Appendix I). Shipping levels during 2019 were 384% and 583% higher at sites PI and MI, respectively, than during 2015. Of the additional ship transits occurring in 2019, 84% passing PI and 99% of additional ships passing MI were transiting to and from the Mary River Mine. Increased iron ore production proposed by the BIMC and under environmental impact review in 2018-20 would double bulk carrier transits through Eclipse Sound by 2022 (BIMC, 2020). Proposed shipping in Eclipse Sound may also include larger Capesize ore carriers with 150,000-250,000 deadweight ton (DWT) capacity, substantially larger ships than the Panamax ships (65,000-85,000 DWT) servicing the mine during 2015-2019. The expectation is that the larger vessels with deeper prop depth will have higher radiated sound levels, potentially with a larger impact on the soundscape than has resulted from commercial ships measured to

date. Broadband source level estimates of Capesize ore carrier may be 5-10 dB higher than smaller bulk carriers (Golder, 2018). Additional measurements may be required to determine acoustic characteristics of Capesize ore carriers and impacts of vessel speed on radiated noise.

Future studies could analyze previous years of recordings at this and other regional recording sites to compare measurements of the 2018-19 natural underwater soundscape during prior years with substantially lower shipping intensity. This will help to make a more robust estimate of natural soundscape, excluding noise from ships, and facilitate comparison with future measurements. With the results presented here, it may also be possible to predict the relative increase above the baseline natural soundscape that will be caused by higher levels of shipping predicted to occur locally in Eclipse Sound and across the Canadian Arctic.

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APPENDIX I. 2015-2019 Eclipse Sound shipping traffic summary from AIS data

Table A.1.1 Numbers of annual ship transits past acoustic recording sites in Pond Inlet (PI) and Milne Inlet (MI) during the annual period from July 1 through November 1, 2015-2019. Ship locations obtained from Automated Information System (AIS) messages received by satellite ([www.ExactEarth.com](http://www.ExactEarth.com)). 'Project-related' transits are those specifically contracted to service the Baffinland Mary River Mine in southern Milne Inlet or to provide vessel support for mine-related shipping activities in the Eclipse Sound region.

Vessel Type	2015		2016		2017		2018		2019		BIMC phase II estimated
	PI	MI									
Bulk Carrier	26	26	76	76	112	114	145	142	166	168	332
General Cargo	11	6	9	6	31	30	17	12	26	22	22
Other Cargo	0	0	2	0	0	0	0	0	3	4	8
Oil/chemical Tanker	9	4	8	4	10	6	17	8	14	10	16
Commercial Icebreaker	0	0	0	0	0	0	22	39	22	26	52
Tug	4	4	4	4	7	4	8	8	0	11	22
Other Commercial Vessel	0	0	0	10	1	0	0	0	2	2	4
SAR	2	0	6	4	7	2	6	0	5	0	0
Military	2	1	2	0	7	0	0	0	7	1	1
Fishing	0	0	2	0	8	2	5	2	7	0	0
Passenger Ship	19	1	15	2	19	3	29	0	23	0	0
Sailing	2	0	7	2	9	3	9	0	6	0	0
Pleasure Craft	0	0	2	3	5	2	2	0	7	1	1
Research/Survey Vessel	0	0	2	0	2	0	0	0	0	0	0
<b>Total transits</b>	75	42	135	111	218	166	260	211	288	245	458
<b>Project-related transits</b>	-	40	-	100	-	154	-	209	-	243	
<b>Ore produced (Mt)</b>		1.3		3.2		4.1		5.1		6	12

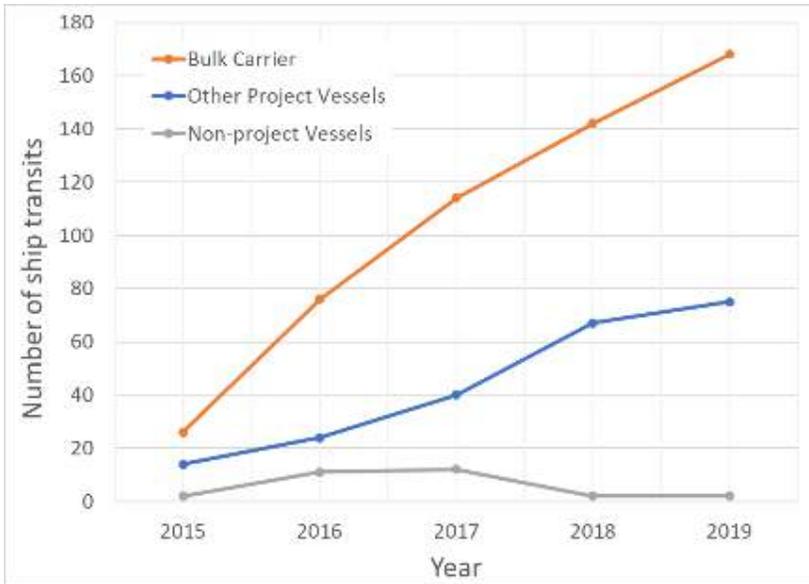


Figure A.1.1. Annual July 1-Nov 1 transits of vessels past the recording location in Milne Inlet (MI) obtained from satellite AIS data. Transits are one-way passages of vessels passing within a radius of 10 km of the recording location.

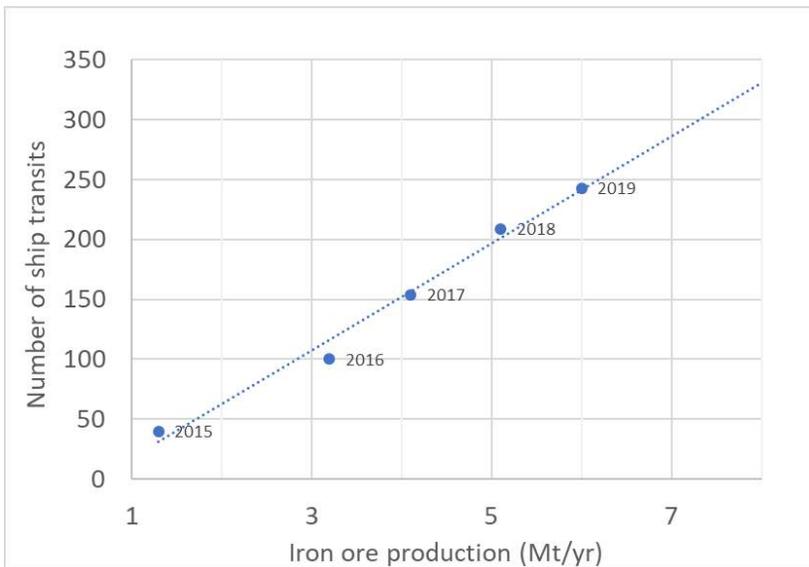


Figure A.1.2. Annual number of ship transits past recording location MI between July 1 and Nov 1 of each year from 2015 to 2019. Ship numbers plotted with the annual iron ore production reported by the Baffinland Mary River Mine. The line fit to the data has a slope of 44.8 ship transits per million tons (Mt) of ore produced per year.

## APPENDIX II. Listening space reduction (LSR) estimate for narwhal and ringed seal communication signals

### METHODS

An analysis of proportional reduction in available listening space (reported as listening space reduction; LSR) was performed for all ship transit windows. Frequency bands were chosen to include ringed seal barks (apx. 250 Hz, Jones *et al.*, 2014) and narwhal burst pulse calls and whistles (1 kHz and 3.5 kHz; Marcoux *et al.*, 2010).

LSR was evaluated for the three frequency bands using methods consistent with previous studies of LSR in Arctic waters (*e.g.* Pine *et al.*, 2018) with the equation,

$$LSR = 100 \left( 1 - 10^{2 \left( \frac{NL_2 - NL_1}{N} \right)} \right) \quad \text{Eqn. 1}$$

where N is the sound propagation loss coefficient, estimated conservatively as N=15 to represent cylindrical spreading.  $NL_2$  is the masking noise approximated by the 1/3<sup>rd</sup> octave SPL (in dB re 1  $\mu$ Pa) for each frequency band averaged across a 1-min time bin.  $NL_1$  is chosen to approximate the perceived ambient sound level during the ship transit. For each frequency band during a transit,  $NL_1$  was set as the maximum of the auditory threshold for the species at the band's center frequency and either the median or 90<sup>th</sup> percentile Jul-Oct ambient noise SPL for the frequency band. The median and 90<sup>th</sup> percentile ambient noise levels were chosen to represent 'quiet' and 'noisy' background noise conditions, although the median more closely reflects average noise conditions across the months. Switching between  $NL_1$  referenced to the median and the 90<sup>th</sup> percentile ambient noise levels results in generally lower estimates of LSR during ship transits with relatively 'noisy' background conditions than when using a single reference noise level such as the median. This method for estimating  $NL_1$  was intended to

approximate the change in effective listening space perceived during each transit relative to the ambient noise conditions at the time, similar to the method described by Pine *et al.* (2018).

An estimated auditory threshold was also included in determining  $NL_1$  for LSR estimation. For ringed seal at 250 Hz, the auditory threshold was estimated as 75 dB (Sills *et al.*, 2015). Experimental audiograms are not available for the narwhal hearing system, so available beluga composite audiograms were used as an approximation (Fig. 5 in Finneran *et al.*, 2005). Beluga hearing threshold at 1 kHz and 3.5 kHz were estimated as 93 and 75 dB, respectively, from a composite audiogram of previous beluga hearing studies (Fig. 5 in Finneran *et al.*, 2005). The running threshold for detecting signal in noise was estimated as the maximum of the audiogram value for the species at that frequency and the 1/3 octave band level of the frequency. The 1/3 octave band level of the noise was chosen to approximate the detection threshold for a signal, as it roughly corresponds to the sound pressure spectrum level of the noise plus the critical ratio (CR) of signal to noise consistent with measurements for ringed seals and beluga in previous experiments. CR of ringed seal is apx. 17 dB re 1  $\mu Pa^2$  at 250 Hz (Sills *et al.*, 2015) and beluga apx. 10 dB re 1  $\mu Pa^2$  at 1 kHz (Erbe, 2008), so detection threshold of both are conservatively estimated using the 1/3<sup>rd</sup> octave band levels of the noise.

#### Listening space comparison with listening range reduction

Estimates of communication masking are reported here in units of LSR, which is a measure of change in effective listening area around an animal that would result from a change in relative noise levels within the frequency band of interest. This measure was selected because of its use in previous studies to evaluate communication masking in marine mammals (e.g. Pine *et al.*, 2019; Pine *et al.*, 2018) and because it reflects the nature of social communication for

many marine mammal species. An individual animal may be simultaneously acoustically communicating with or receiving acoustic signals from many other individuals or groups of animals within some area. An alternative measure of communication masking has been developed, which assesses only the reduction in effective range of communication between two animals. This is referred to as Listening Range Reduction (LRR; Pine et al., 2020). For example, a 3 dB increase in noise within some frequency band would result in estimation of a 37% reduction of LRR and 60% reduction of LSR. Table A.2.1 and Figure A.2.1 are included to facilitate comparisons of the LSR estimates presented in this report with estimates of LRR presented elsewhere.

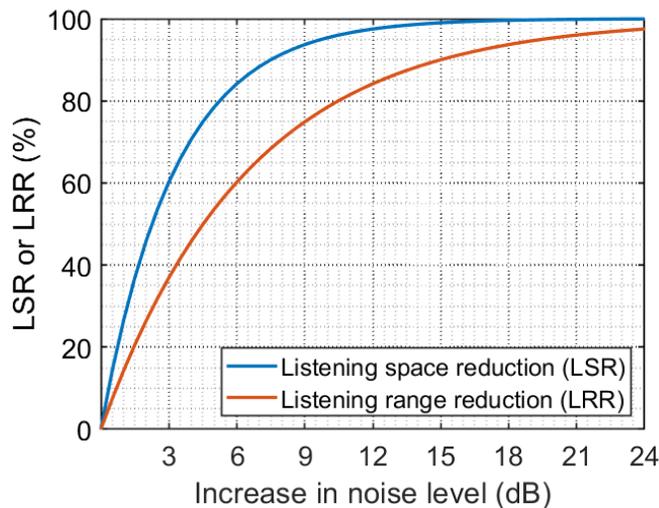


Figure A.2.1. Listening space reduction (LSR; red line) computed using Eqn. 1 is plotted with Listening Range Reduction (LRR; blue line) for relative increases in noise level ( $NL_1$  Eqn. 1) from 0 to 20 dB.

Table A.2.1 Comparison of estimated LRR and LSR as noise level increases in 3 dB increments, doubling the intensity of the noise level. Estimates are rounded to the nearest percent.

Increase in noise level (dB)	Listening Range Reduction (%)	Listening Space Reduction (%)
3	37	60
6	60	84
9	75	94
12	84	97
15	90	99
18	94	100
21	96	100
24	97	100
27	98	100
30	99	100

## RESULTS

### Estimated Listening Space Reduction

Listening Space Reduction (LSR) estimated for all ship types follows the typical patterns of received sound levels during ship transits. The proportion of LSR increases rapidly when received sound from the ship exceeds the reference noise level ( $NL_1$  in Eqn. 1), which was selected for each transit to represent the perceived background sound conditions for ringed seals at 250 Hz and for narwhals at 1 kHz and 3.5 kHz during the ship transit. LSR > 50% occurs at shorter distances from the bow than from the stern aspect of vessels. When background sound prior to a ship transit (*i.e.* pre-CPA minimum 1-min SPL for the frequency band) was above the median ship-excluded sound level and the estimated audibility threshold, defining  $NL_1$  as the 90<sup>th</sup> percentile of ambient noise helped to resolve a more distinct period of LSR resulting from the ship transit.

### *Bulk Carriers*

Listening space reduction (LSR) estimated for the Aug 1 and Sep 5, 2019 transits of bulk carrier Nordic Orion (Fig. A.2.2) demonstrates typical LSR patterns for this ship type at recording site PI. In both transits, pre-CPA SPL in the 1/3<sup>rd</sup> octave frequency bands (*i.e.* 250 Hz, 1 kHz, 3.5 kHz) was below the median background level. Noise-adjusted LSR was therefore estimated by defining  $NL_1$  (Eqn. 1) as the median background SPL for the 250 Hz and 3.5 kHz bands and as the threshold of the beluga audiogram for 1 kHz. Received ship noise in the 250 Hz 1/3<sup>rd</sup> octave band reached levels higher than the median background level during a period from about 1 h prior to CPA to 1 h after. Consequently, noise-adjusted LSR >50% was estimated to occur over a period of similar duration of 1.5 to 2 h. At 1 and 3.5 kHz, LSR >50% occurred over a duration of apx. 45-60 min and 30-40 min, respectively, about the CPA.

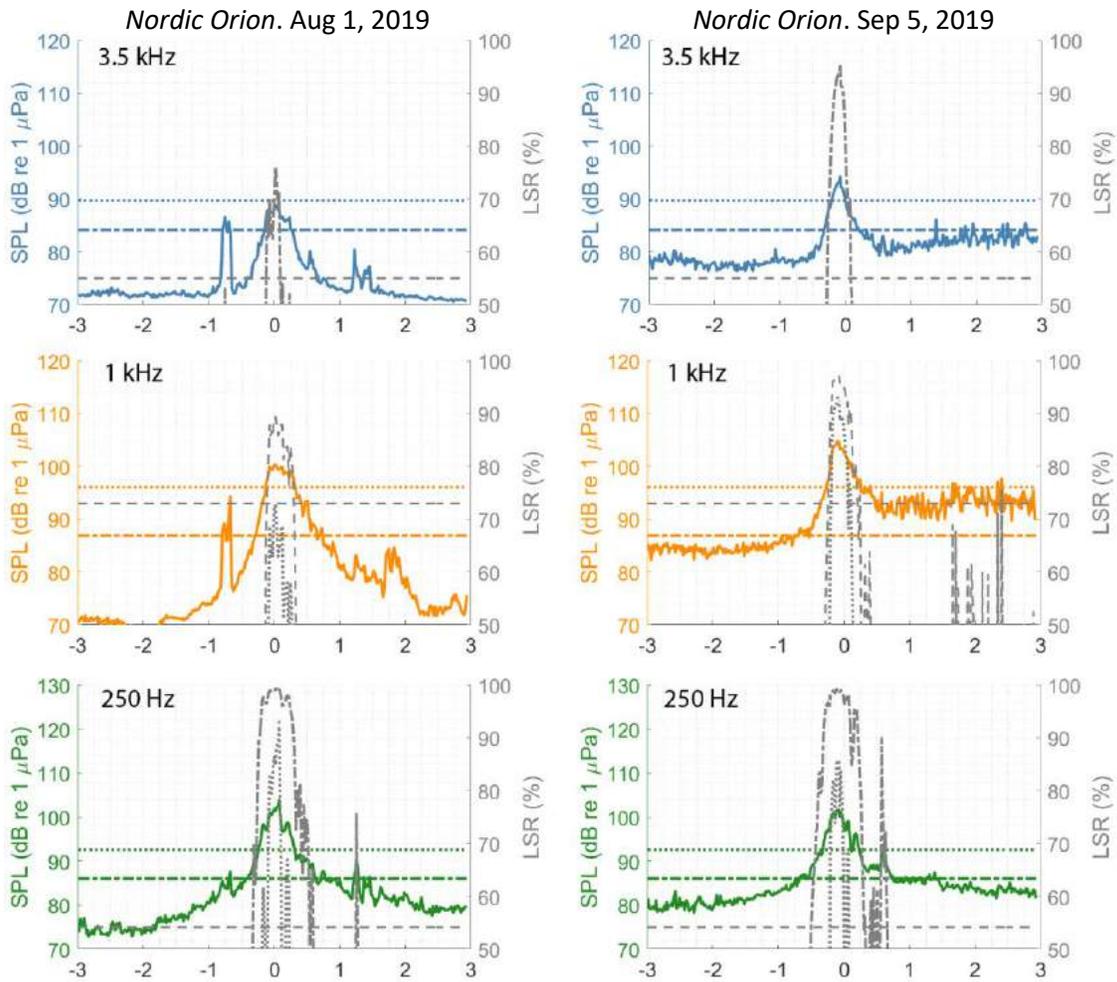


Figure A.2.2. Listening space reduction (LSR) for Bulk Carrier transit examples. LSR estimated for the 3.5 kHz (top; lt. blue), 1 kHz (middle; orange), and 250 Hz (bottom; green) 1/3rd octave bands for transits of the bulk carrier *Nordic Orion* on Aug 1 (left) and Sep 5, 2019 (right). Horizontal lines represent 90<sup>th</sup> (dotted, color) 50<sup>th</sup> (dash-dot, color) percentile of ship-excluded band levels and the assumed threshold of audibility (dashed, gray). Gray curves are LSR estimates relative to the median (dash-dot line) or 90<sup>th</sup> percentile (dotted line) ship-excluded noise level (dotted curve) of the estimated threshold of audibility (dashed line). Both 'noisy' and 'quiet' methods for determining LSR are plotted for comparison

Patterns in estimated LSR versus range were examined for a subset of 60 ore carrier ship transits (Fig. A.2.3) during which the nearest time to CPA of another ship transit was > 4 h to reduce effects of noise from other ships. Greater than 50% LSR occurred at longer ranges from the recorder in the 250 Hz band than in the 1 kHz or 3.5 kHz bands. For narwhal signals, 70% and 90% LSR was estimated to occur at median ranges of 10 and 3 km for 3.5 kHz and at 4 and 3 km for 1 kHz as a result of noise from transiting ore carriers. Ringed seal LSR 70% and 90% was estimated to occur at median ranges of 8 km and 3 km for 250 Hz signals.

#### *General Cargo*

Listening space reduction (LSR) estimated for the Aug 23 and 24, 2019 transits of general cargo vessels *Zelada Desgagnes* and *Sedna Desgagnes* (Fig. A.2.4) demonstrates typical LSR patterns for this ship type at recording site PI. Noise-adjusted LSR for the Aug 23 transit (Fig. A.2.4 left panels) was estimated by defining  $NL_1$  (Eqn. 1) as the median background SPL for the 250 Hz and 3.5 kHz bands and as the threshold of the beluga audiogram for 1 kHz. Received ship noise in the 250 Hz 1/3<sup>rd</sup> octave band reached levels higher than the median background level during a period from about 1 h prior to CPA to 1 h after. Consequently, LSR >50% was estimated to occur for ringed seals over a period of similar duration of 1.5 to 2 h. At 1 and 3.5 kHz, LSR >50% for narwhals occurred over a duration of apx. 45-60 min and 30-40 min, respectively, about the CPA.

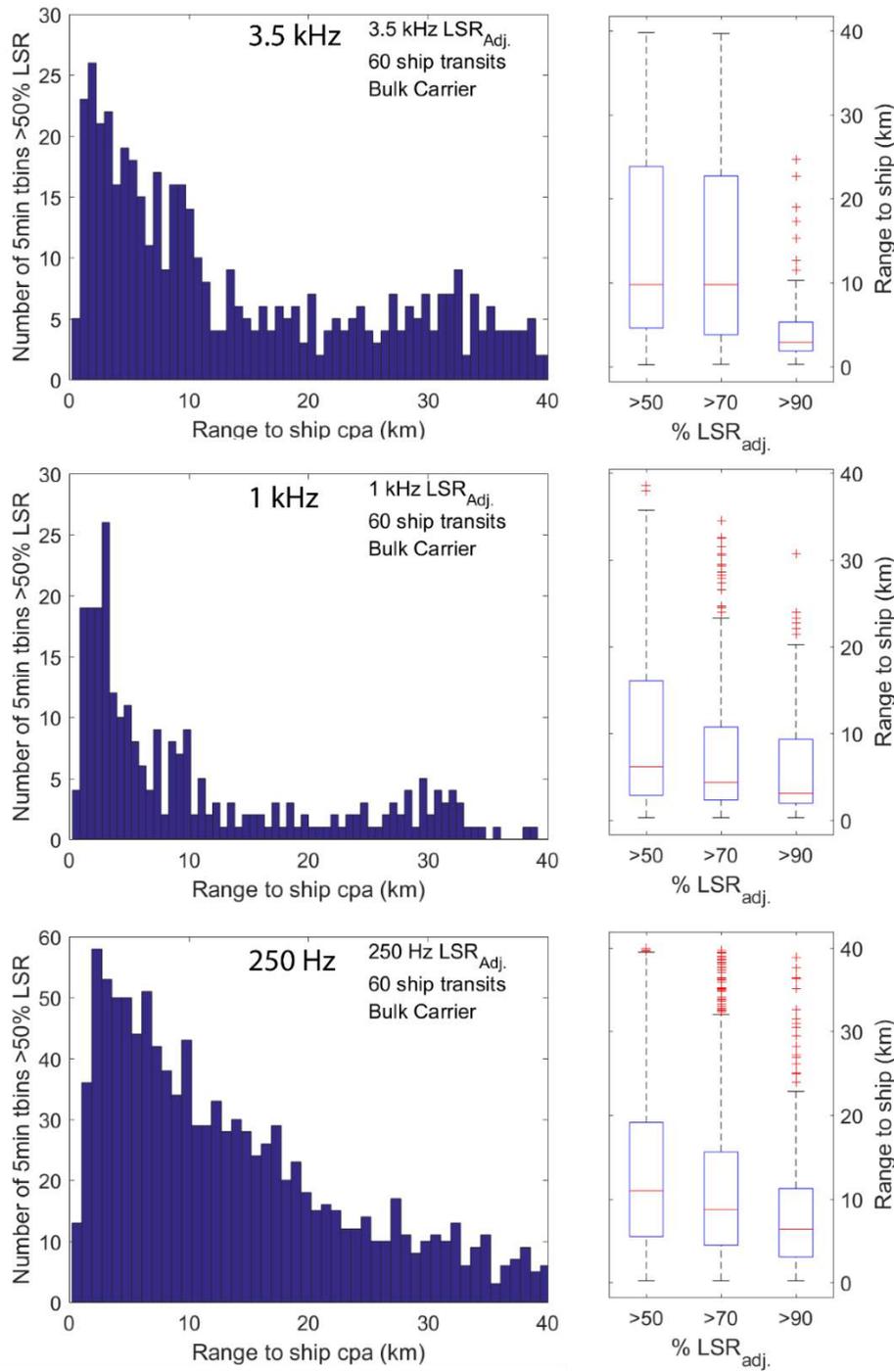


Figure A.2.3. Noise-adjusted listening space reduction (LSR) and range to ship estimated for all 5-min time bins with LSR > 50% in bulk carrier transits with no preceding ships (left panel histograms). Box plots show the 25<sup>th</sup> to 75<sup>th</sup> percentile data values (blue box), median (red line), and outliers removed (red plus sign).

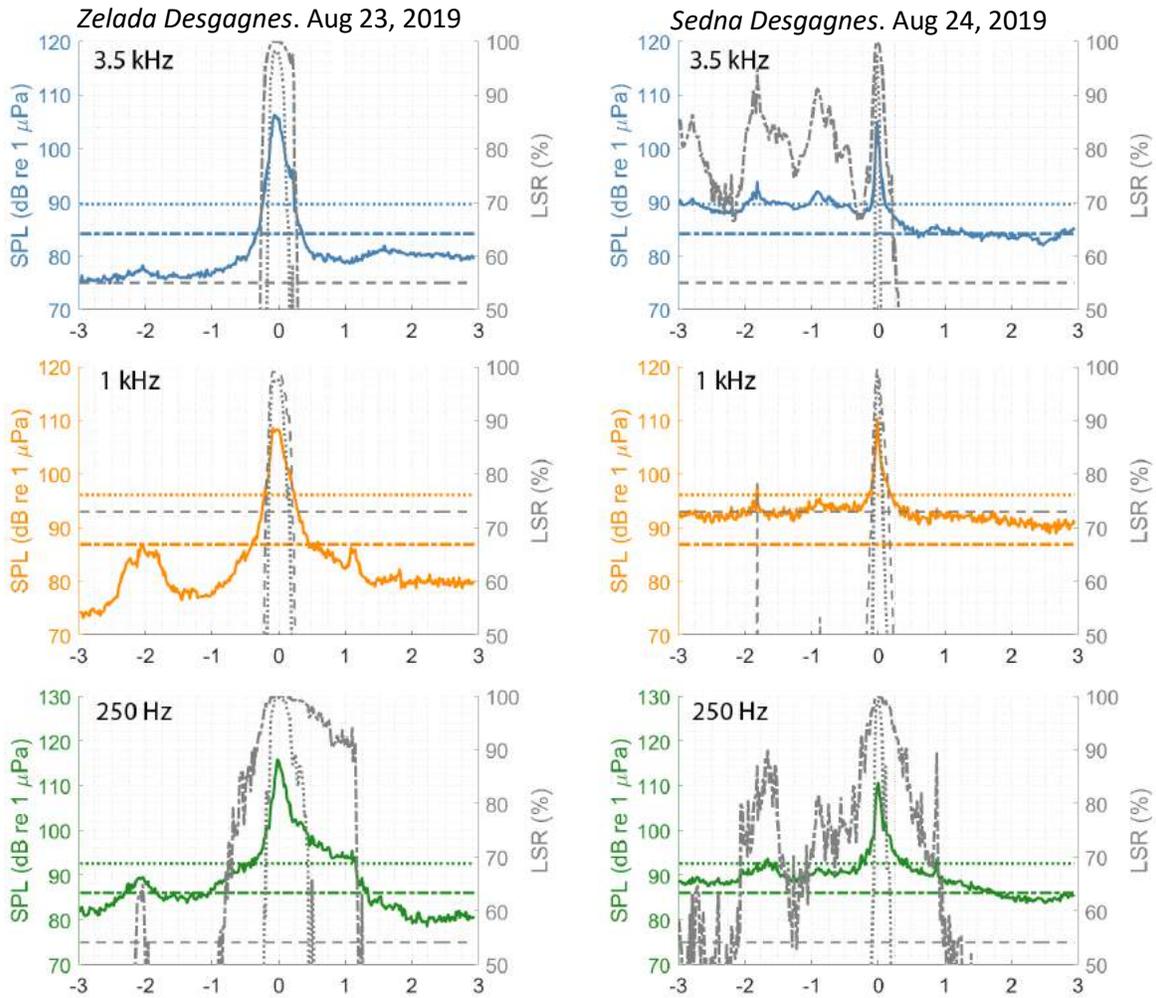


Figure A.2.4. LSR for General Cargo vessel transit examples. LSR estimated for example transits of *Zelada Desgagnes* (left) and *Sedna Desgagnes* (right) for the 3.5 kHz (top; blue), 1 kHz (middle; orange), and 250 Hz (bottom; green)  $1/3^{\text{rd}}$  octave bands for transits. Horizontal lines represent 90<sup>th</sup> (dotted, color) 50<sup>th</sup> (dash-dot, color) percentile of ship-excluded band levels and the assumed threshold of audibility (dashed, gray). Gray curves are LSR estimates relative to the median (dash-dot line) or 90<sup>th</sup> percentile (dotted line) ship-excluded noise level (dotted curve) of the estimated threshold of audibility (dashed line).

Patterns in estimated LSR versus range were examined for a subset of 6 general cargo ship transits (Fig. A.2.5) during which the nearest time to CPA of another ship transit was > 3 h to reduce effects of noise from other ships. Greater than 50% LSR occurred at longer ranges from the recorder in the 250 Hz band than in the 1 kHz or 3.5 kHz bands. For narwhal signals, 70% and 90% LSR was estimated to occur at median ranges of 7 and 2.5 km for 3.5 kHz and at 2.8 and 2.2 km for 1 kHz as a result of noise from transiting general cargo ships. Ringed seal LSR 70% and 90% was estimated to occur at median ranges of 9 km and 8 km for 250 Hz signals.

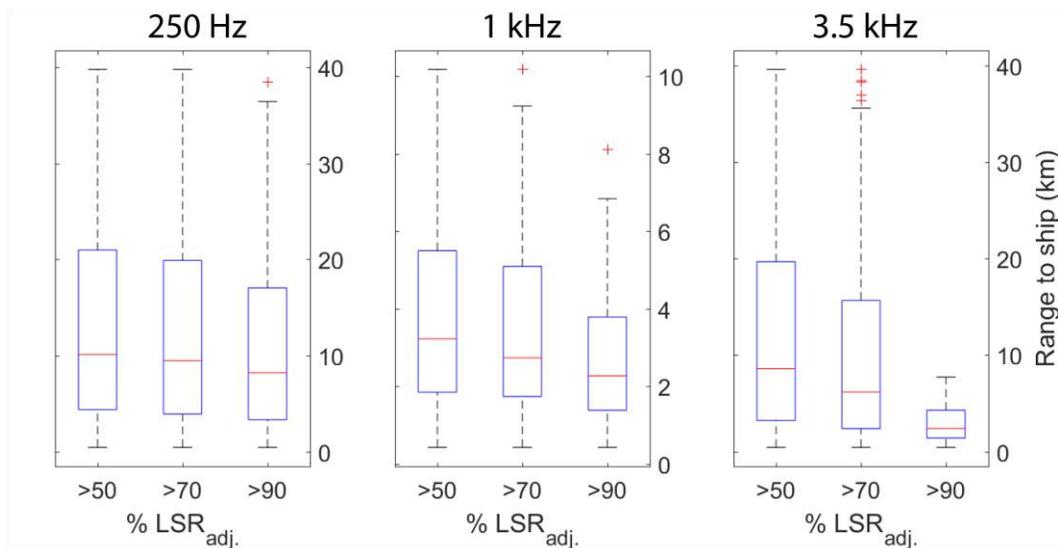


Figure A.2.5. Combined estimates of range from ship to receiver for LSR above 50, 70, and 90% from six transits of general cargo ships at site PI. Box plots show the 25<sup>th</sup> to 75<sup>th</sup> percentile data values (blue box), median (red line), and outliers removed (red plus sign)

*Fuel and chemical tanker*

Listening space reduction (LSR) estimated for the July 25 and Aug 22, 2019 transits of fuel and chemical tanker, *Sarah Desgagnes* (Fig. A.2.6) demonstrates typical LSR patterns for this ship type at recording site PI. Noise-adjusted LSR for the July 25 transit (Fig. A.2.6 left panels) was estimated by defining  $NL_1$  (Eqn. 1) as the median background SPL for the 250 Hz and 3.5 kHz bands and as the threshold of the beluga audiogram for 1 kHz. Received ship noise in the 250 Hz  $1/3^{\text{rd}}$  octave band reached levels higher than the median background level during a period from 1.25 h prior to CPA to 2.5 h after. LSR >50% was estimated to occur for ringed seals over a duration of approximately 3.5 h. At 1 and 3.5 kHz, LSR >50% for narwhals occurred over a duration of 45-60 min about the CPA.

Patterns in estimated LSR versus range were examined for a subset of 7 fuel and chemical tanker transits (Fig. A.2.7) during which the nearest time to CPA of another ship transit was > 1 h to reduce effects of noise from other ships. A shorter minimum time gap between tankers and other ships was necessary because tankers often passed within a few hours of another ship. Greater than 50% LSR occurred at longer ranges from the recorder in the 250 Hz band than in the 1 kHz or 3.5 kHz bands. 70% and 90% LSR was estimated to occur at median ranges of 2 and 1.5 km around 1 kHz and at 6 and 3 km around 3.5 kHz. Ringed seal LSR 70% and 90% was estimated to occur at median ranges of 15 km and 12 km for 250 Hz signals.

Sarah Desgagnes. Jul 25, 2019

Sarah Desgagnes. Aug 22, 2019

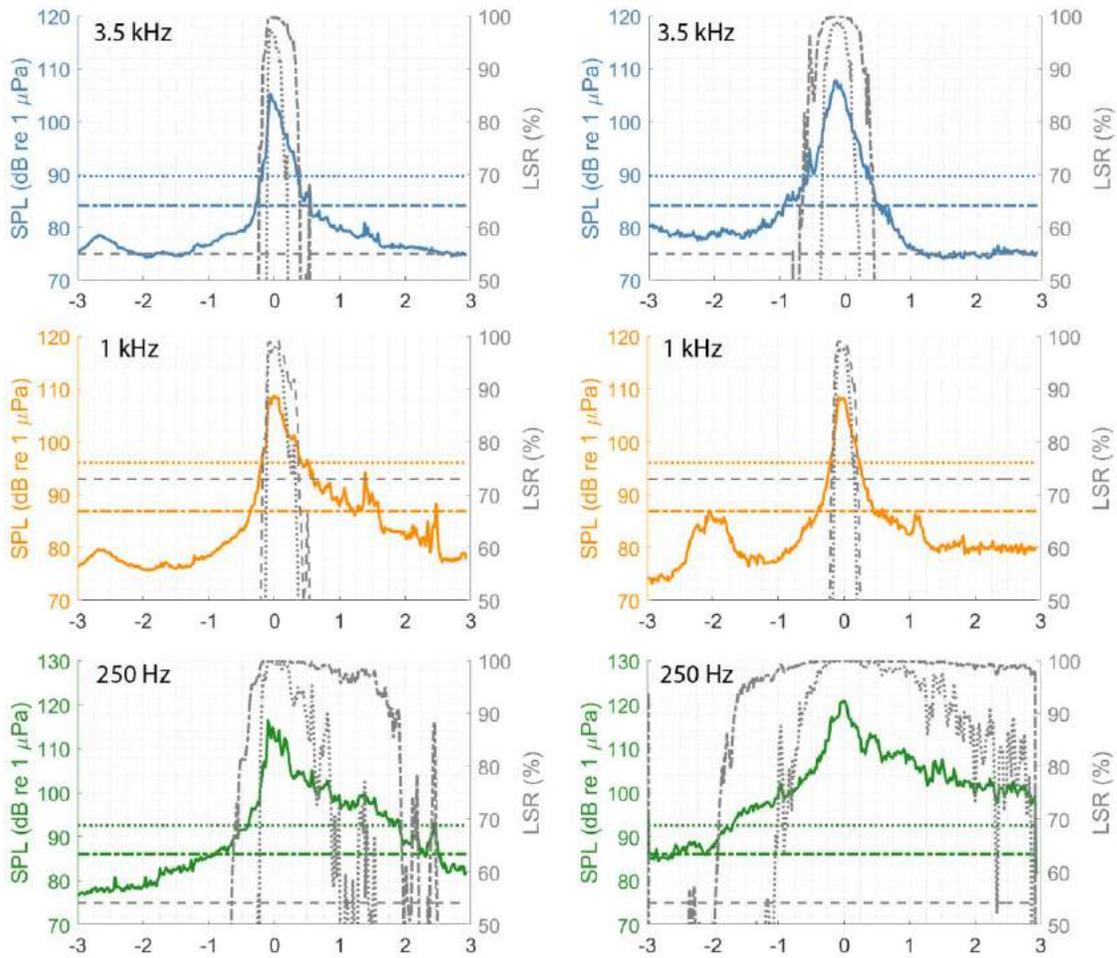


Figure A.2.6. LSR for Fuel and chemical tanker transit examples. LSR estimated for the 3.5 kHz (top; blue), 1 kHz (middle; orange), and 250 Hz (bottom; green) 1/3<sup>rd</sup> octave bands for transits of the fuel and chemical tanker, *Sarah Desgagnes* on July 25<sup>th</sup> (left) and August 22<sup>nd</sup>(right). Horizontal lines represents 90<sup>th</sup> (dotted, color) 50<sup>th</sup> (dash-dot, color) percentile of ship-excluded band levels and the assumed threshold of audibility (dashed, gray). Gray curves are LSR estimates relative to the median (dash-dot line) or 90<sup>th</sup> percentile (dotted line) ship-excluded noise level (dotted curve) of the estimated threshold of audibility (dashed line).

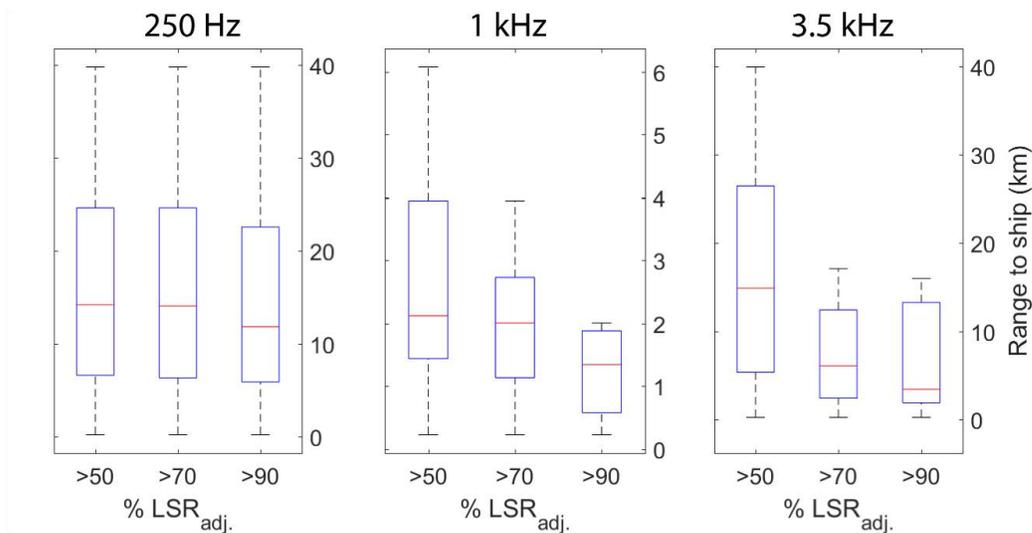


Figure A.2.7. Combined estimates of range from ship to receiver for LSR above 50, 70, and 90% from seven transits of fuel and chemical tanker ships at site PI. Box plots show the 25<sup>th</sup> to 75<sup>th</sup> percentile data values (blue box), median (red line), and outliers removed (red plus sign)

### Icebreaker

Listening space reduction (LSR) estimated for two transits of the icebreaker, *Botnica*, in October, 2018 and two transits in July, 2019. These transits were chosen to represent icebreaking activities in fall freeze-up and early summer break-up periods. The Oct 12 and 16<sup>th</sup>, 2019 transits of *Botnica* (Fig. A.2.8) demonstrate typical LSR patterns for this ship type at recording site PI. Noise-adjusted LSR for the Oct 12<sup>th</sup> transit (Fig. A.2.8 left panels) was estimated by defining  $NL_1$  (Eqn. 1) as the median background SPL for the 250 Hz, 90<sup>th</sup> percentile background SPL for the 3.5 kHz band, and the threshold of audibility for beluga at 1 kHz. Received ship sound in the 250 Hz 1/3<sup>rd</sup> octave band causes estimated ringed seal LSR > 50% during a period from 1 h prior to CPA to 2 h after. At 1 and 3.5 kHz, LSR >50% for narwhals occurred over a duration of 20-40 min about the CPA.

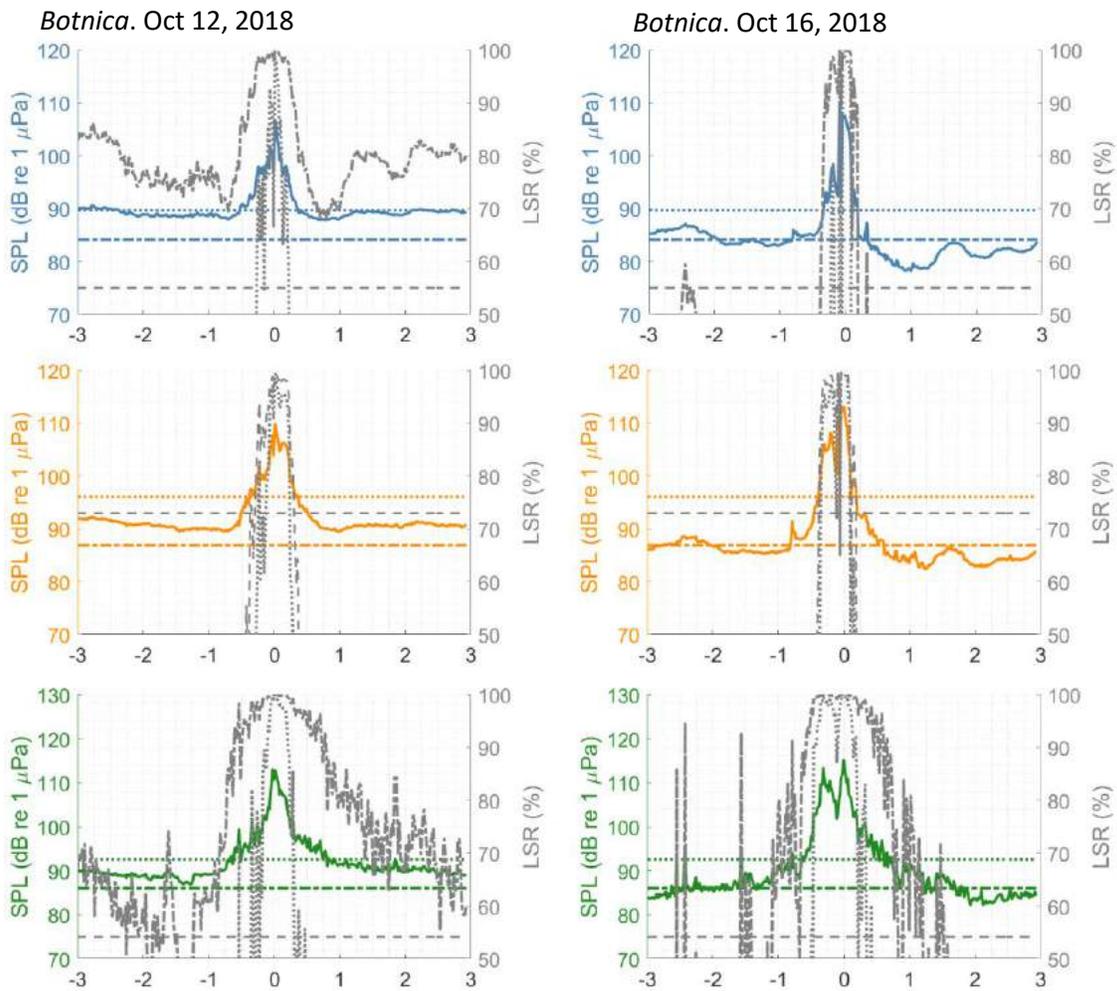


Figure A.2.8. LSR for example transits of the icebreaker, *Botnica*, during late open water/early freeze-up, 2018 for 3.5 kHz (top; lt. blue), 1 kHz (middle; orange), and 250 Hz (bottom; green) bands on October 12 (left) and Oct 16 (right), 2018. Horizontal lines represents 90th (dotted, color) 50th (dash-dot, color) percentile of ship-excluded band levels and the assumed threshold of audibility (dashed, gray). Gray curves are LSR estimates relative to the median (dash-dot line) or 90th percentile (dotted line) ship-excluded noise level (dotted curve) of the estimated threshold of audibility (dashed line).

The Jul 18<sup>th</sup> and 24<sup>th</sup>, 2019 transits of *Botnica* (Fig. A.2.8) demonstrate typical LSR patterns for this ship type at recording site PI during early summer. Noise-adjusted

LSR for the Jul 18<sup>th</sup> transit (Fig. A.2.8 left panels) was estimated by defining  $NL_1$  (Eqn. 1) as the median background SPL for the 250 Hz and 3.5 kHz bands and the threshold of audibility for beluga at 1 kHz. During this transit, *Botnica* escorted two bulk carriers and two tugs in convoy past the recording site at speed 8 knots (Figs. 30, 31). Received ship sound in the 250 Hz 1/3<sup>rd</sup> octave band resulted in estimated ringed seal LSR > 50% during a period from 2 h prior to CPA to >3 h after. At 1 and 3.5 kHz, LSR >50% for narwhals occurred over a duration of 1.75-2 h about the CPA. On Jul 24<sup>th</sup>, *Botnica* accompanied three bulk carrier ships in convoy past the recorder. Received levels throughout the transit were lower, in contrast to other transits for the icebreaker. For example, the 1 kHz band SPL did not exceed the assumed threshold of audibility for narwhal during the transit, although the CPA (4.3 km) and speed (8 kts) were comparable to other transits. Estimated LSR at 250 Hz was > 50% for 2 h and LSR at 3.5 kHz was > 50% for 15 min.

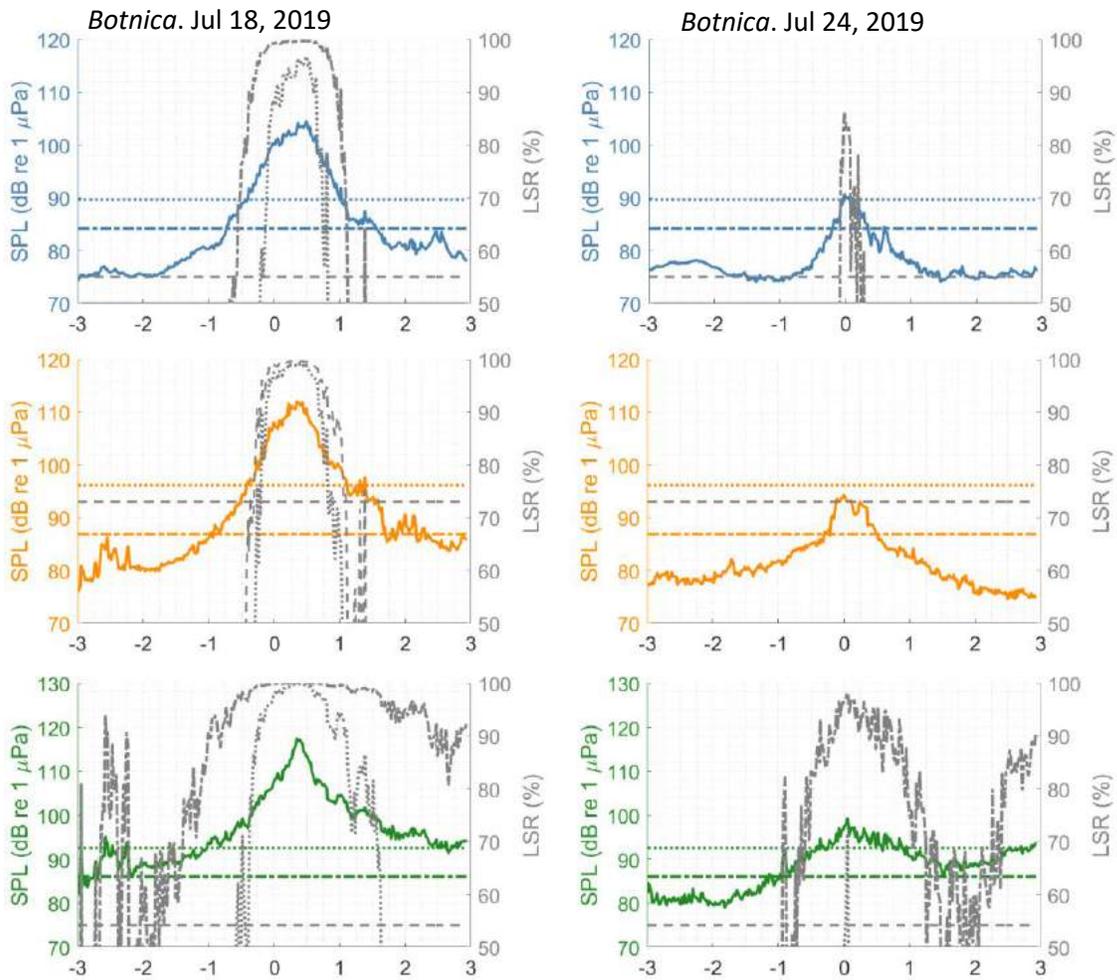


Figure A.2.9. LSR for example transits of the icebreaker Botnica during July, 2019 sea ice breakup for the 3.5 kHz (top; lt. blue), 1 kHz (middle; orange), and 250 Hz (bottom; green) frequency bands for transits of the icebreaker Botnica on July 18 (left) and 24 (right). Horizontal lines represents 90<sup>th</sup> (dotted, color) 50<sup>th</sup> (dash-dot, color) percentile of ship-excluded band levels and the assumed threshold of audibility (dashed, gray). Gray curves are LSR estimates relative to the median (dash-dot line) or 90<sup>th</sup> percentile (dotted line) ship-excluded noise level (dotted curve) of the estimated threshold of audibility (dashed line).

Patterns in estimated LSR versus range were examined for a subset of 23 icebreaker transits (Fig. A.2.10) during which the nearest time to CPA of another ship

transit was > 3 h to reduce effects of noise from other ships. Greater than 50% LSR occurred at longer ranges from the recorder in the 250 Hz band than in the 1 kHz or 3.5 kHz bands. For narwhal signals, 70% and 90% LSR was estimated to occur at median ranges of 8 and 4 km at 3.5 kHz and at 4.5 and 3 km for 1 kHz as a result of noise from the transiting icebreaker. Ringed seal LSR 70% and 90% was estimated to occur at median ranges of 12 km and 10 km for 250 Hz signals.

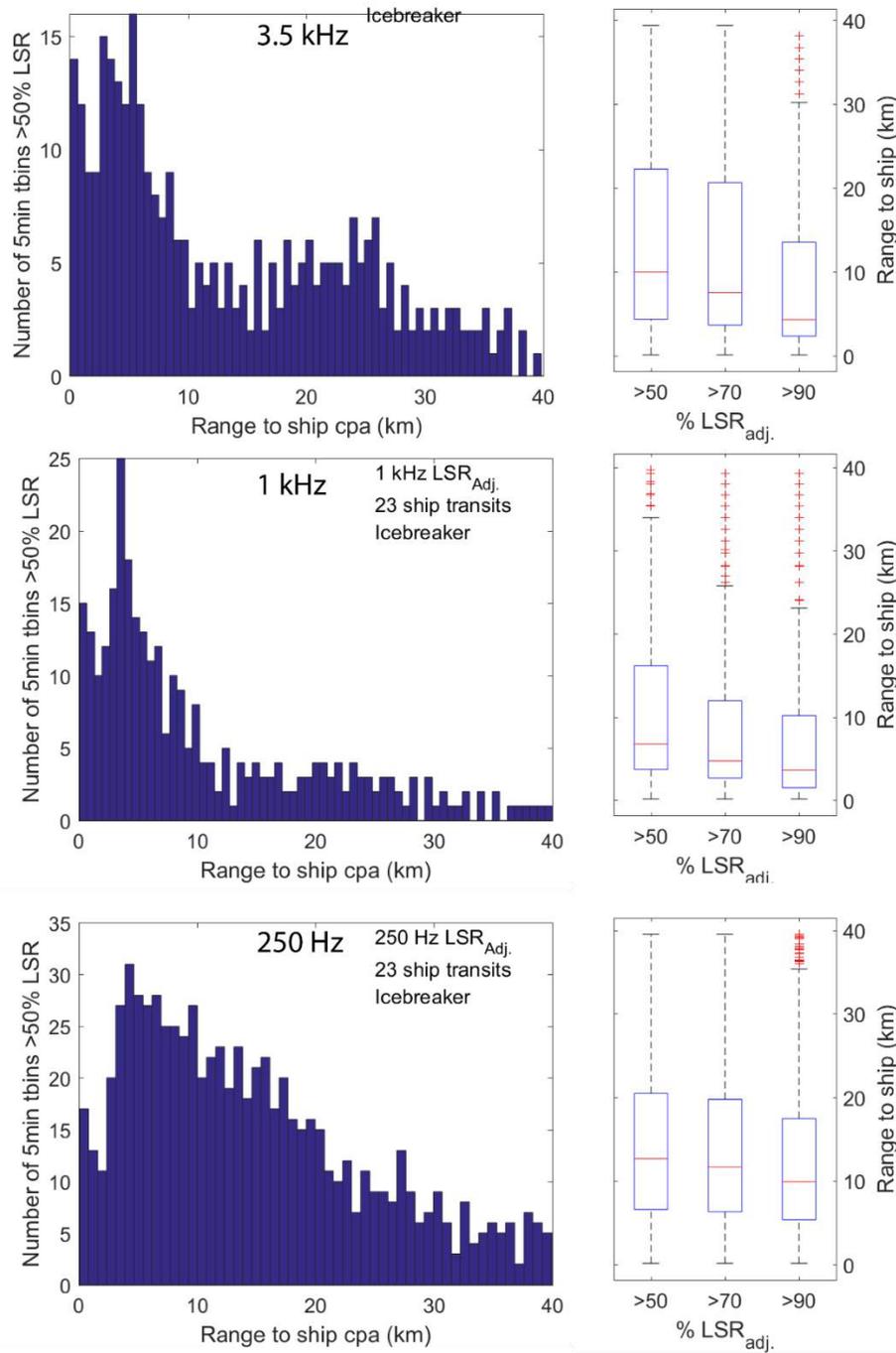


Figure A.2.10. Noise-adjusted listening space reduction (LSR) and minimum range to ship estimated for all 5-min time bins with LSR >50% in transits of the icebreaker Botnica past site PI. (left panel histograms). Box plots show the 25<sup>th</sup> to 75<sup>th</sup> percentile data values (blue box), median (red line), and outliers removed (red plus sign).

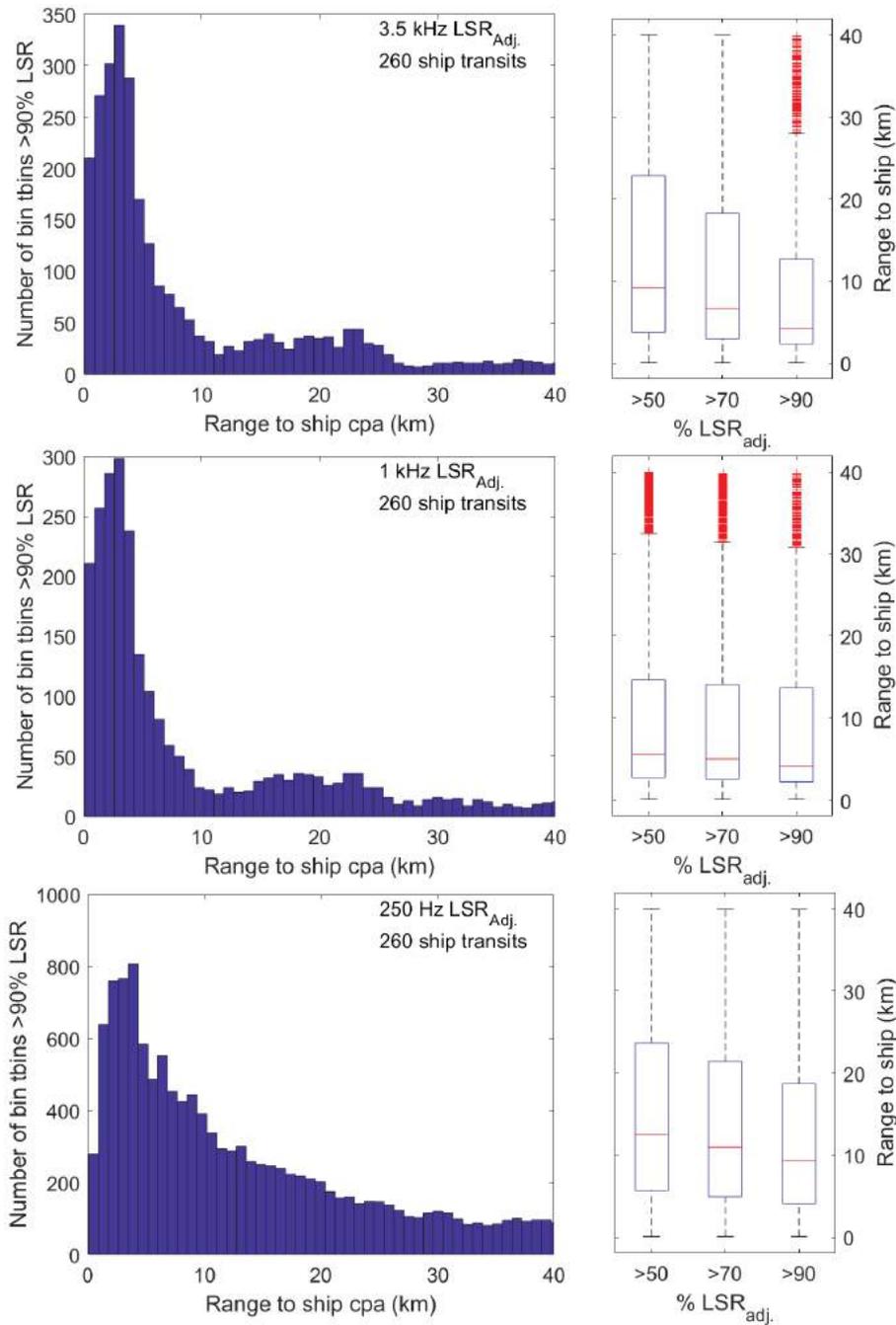


Figure A.2.11. Patterns in LSR for all ship transits past site PI. Left panels range to ship when LSR estimated >90% for 3.5 kHz (top), 1 kHz (middle) and 250 Hz (bottom). Right panels median (red line) 25<sup>th</sup> and 75<sup>th</sup> percentile (box bounds) range to ship for LSR >50, 70, and 90%.

## APPENDIX III. Preliminary description of narwhal social sounds in Milne Inlet, 2018-19

Description of narwhal (*Monodon monoceros*) social sounds in Milne Inlet, Eclipse Sound,  
Nunavut, 2018-19

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### INTRODUCTION

Narwhals (*Monodon monoceros*) are known to produce a variety of sounds to communicate, navigate and forage. These include high-frequency echolocation clicks (Miller et al., 1995; Rassmussen et al., 2015; Koblitz et al., 2016) and calls such as pulsed tones and whistles, mainly associated with communication and social behavior (Marcoux et al., 2011; Marcoux et al., 2012). Pulsed tones span frequencies usually from 500 Hz to 5 kHz (Marcoux et al. 2012) and their acoustic characteristics are variable in duration, bandwidth and tonal characteristics. They are distinguished from echolocation clicks produced by narwhals by their frequency content and pulse rates (Stafford et al., 2012). Tonal whistles have been described as narrow-band frequency modulated calls with a frequency range from 300 Hz to 18 kHz. Whistles are thought to have communication functions and might be a form of individual or group signature (Shapiro, 2006).

This report provides a preliminary description of underwater social communication sounds of narwhals recorded between October, 2018 and August, 2019 in Milne Inlet, a protected inlet of Eclipse Sound on north Baffin Island in the eastern Canadian Arctic.

## METHODS

Between late September and late August of 2018 – 19, a High-frequency Acoustic Recording Package (HARP; Wiggins and Hildebrand, 2007) recorded underwater sounds at a depth of 313m in the Milne Inlet of Eclipse Sound. The HARP recorded at a sampling rate of 200 kHz on a schedule of 25 min recording every 30 min. The hydrophone specifications and deployment location are given in the methods section of the main report.

The recordings were processed to create Long-Term spectral averages (LTSA's) for each disk data set (time average: 5s; frequency bin size: 100 Hz), that allowed for the manual search of acoustic events within the underwater recording. Analyses were conducted using the Triton program, based on MATLAB (MathWorks Inc; Natick, MA), to calculate and display long-term spectral averages (LTSA) and standard spectrograms, to perform audio playbacks, and to log call selected detections (Wiggins and Hildebrand, 2007). Two-hour long LTSA windows with a 0 to 20 kHz frequency resolution were visually scanned for the characteristic patterns of narwhal calls. The presence of likely calls was determined through the examination of 30-s spectrogram windows (4000 point FFT, Hanning windows, Overlap 90%). Spectrogram window length and other variables were adjusted as needed for the fine scale examination of detected individual calls. Start and end times of detected calls were logged, as-well as the descriptive features for each call. For pulsed calls, logged features included minimum and maximum frequencies and the frequency of peak energy. For whistle calls the frequency of the fundamental tone was logged at the start (initial frequency) and end (end frequency) of each call. Start and end time of each

analyzed call were also logged for determination of call duration. Measurements for each call were made manually from the spectrograms and entered into an excel sheet, from which characteristics were compiled for 117 whistle-type and 114 pulsed-type calls.

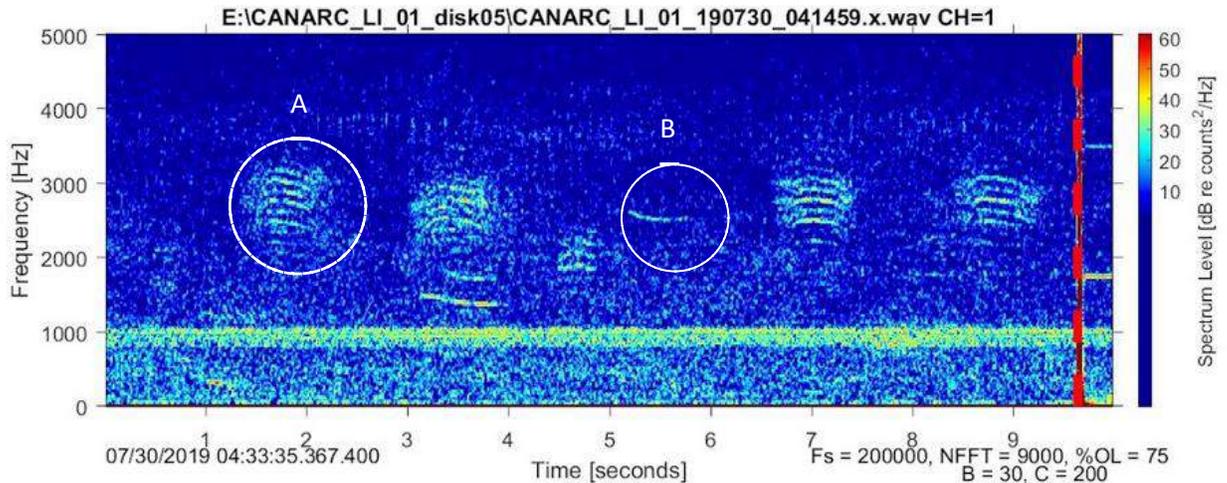


Figure A.3.1. Sample spectrogram showing a variety of narwhal pulsed calls (A) and whistles (B).

## RESULTS

Whistle and pulsed calls obtained from the visual scanning of <10kHz were used in the analysis (Fig. 1). The whistle frequencies averaged 2.7 kHz ranging from 689 Hz to 9776 kHz, lasting from 0.02 to 1.87s (Table 1). Whistles varied from narrow-band tonal signals with little frequency modulation to sounds that increased or decreased (Fig 2) frequency over time. The frequency at their peak for pulsed calls averaged 2.6 kHz ranging from 307 Hz to 10.6 kHz. Their minimum frequency ranged from 27 Hz to 8.8 kHz and averaging 1.5 kHz, while their maximum frequencies ranged from 213 Hz up to 55 kHz with an average frequency of 7.3 kHz (Table 2). The duration of the pulsed calls averaged 0.93s, ranging from 0.29 to 1.62s. Overall, pulsed calls

were observed to be highly variable in pulse rate, frequency and in the presence of tonal properties (Fig 3).

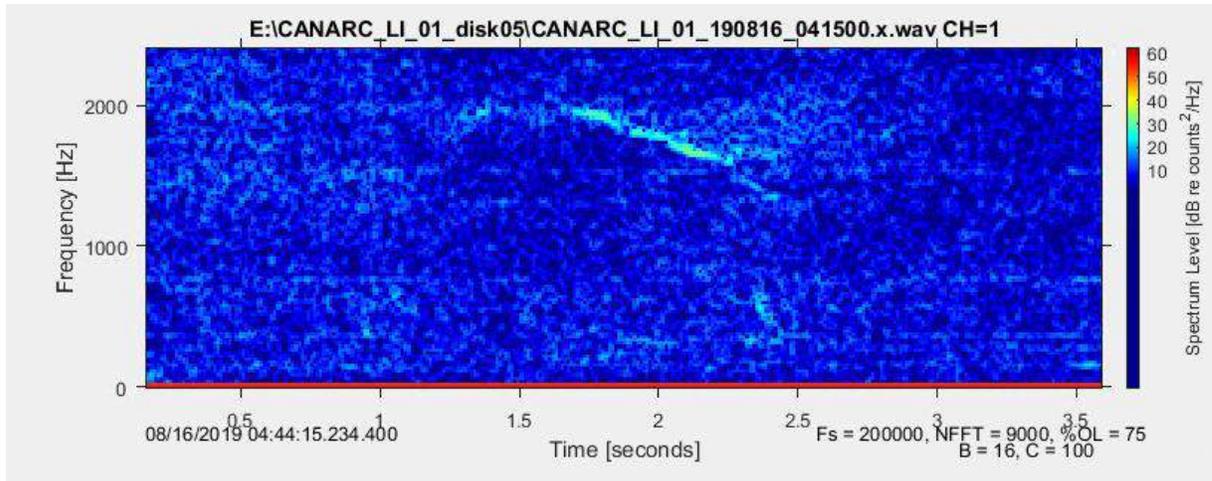


Figure A.3.2. Sample spectrogram showing a narwhal whistle of approximately 1s of duration and energy spanning frequencies below 2000 kHz.

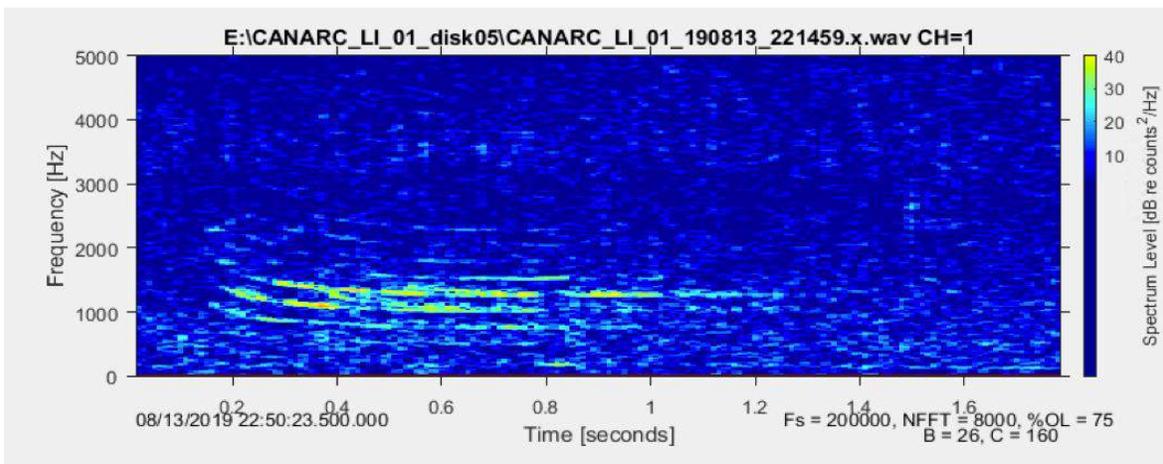


Figure A.3.3. Sample spectrogram showing a narwhal's pulsed call of approximately 1s of duration and energy spanning frequencies from 0.5 to 2.5 kHz

Table A.3.1. Descriptive statistics for 116 narwhal whistles.

	Initial frequency (Hz)	End frequency (Hz)
Mean	2759	2167
Minimum	689	647
Maximum	9776	9571
Standard Deviation	2388	2444
Coefficient of variation	86.57%	112.80%

Table A.3.2. Descriptive statistics for 114 pulsed calls. Peak frequency refers to frequency of the highest received sound pressure spectrum level for the call.

	Minimum frequency (Hz)	Peak frequency (Hz)	Max frequency (Hz)
Mean	1536	2683	7348
Minimum	27	307	213
Maximum	8822	10654	55079
Standard Deviation	1242	1430	10198
Coefficient of variation	80.88%	53.31%	138.78%

## DISCUSSION

These results present a preliminary overview of a selection of narwhal social sounds recorded in Milne Inlet during 2018-2019. The frequencies and characteristics described correspond to an analysis centered on a frequency range <10 kHz, which may have caused the missing of calls on the higher frequency end of the categories included. Note that for higher received levels, the recorded calls tend to have a broader frequency range. At lower received levels, the call frequencies tend to be lower and the frequency range narrower. This is expected, as absorption of sound in seawater is frequency-dependent. Higher frequencies are absorbed more strongly than lower frequencies (e.g. Browning and Mellen, 1987), so the received sound energy of narwhal calls is expected to occupy lower frequencies as the animals move farther or turn away from the receiver. This factor related to sound propagation and also the small sample size may explain some of the variability between detections, besides the possible occurring inter-call and inter-individual differences. While a bigger sample size is needed to conduct a comprehensive analysis, the goal of this study is to provide a preliminary overview of narwhal social sounds present on the data set that has been analyzed on the current report for ship noise and description of underwater soundscape.

## CONCLUSIONS

The acoustic detections described in this preliminary study indicate that Eclipse Sound narwhal emit a variety of sounds when in Milne Inlet. This analysis suggests that a portion of these calls have fundamental frequencies below 1000Hz and as low as <200 Hz and that whistle-type calls occupy frequencies below 4 kHz. In the relatively small sample of calls analyzed for this study, overlap has been observed to occur between the communication frequency range used by narwhal and the underwater radiated noise from ships transiting the Eclipse Sound

region. A larger sample size will help to determine the distribution of acoustic characteristics of in narwhal social sounds in this area. More substantial analyses of narwhal social communication signals in Eclipse Sound and Milne Inlet are needed to be able to fully document the acoustic behavior of the Eclipse Sound narwhal population and assess the possible masking of their acoustic signals by underwater ship noise in the region.

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