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Assessing potential perception of shipping noise by marine mammals in an arctic inlet[a)]

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ABSTRACT:
Shipping is increasing in Arctic regions, exposing marine mammals to increased underwater noise. Noise analyses often use unweighted broadband sound pressure levels (SPL) to assess noise impacts, but this does not account for the animals' hearing abilities at different frequencies. In 2018 and 2019, noise levels were recorded at five and three sites, respectively, along a shipping route in an inlet of Northern Baffin Island, Canada. Broadband SPLs (10 Hz–25 kHz), unweighted and with auditory weighing functions from three marine mammal groups, were compared between times ore carriers (travelling < 9 knots) were present or absent. Clearly audible distances of shipping noise and exposure durations were estimated for each weighting function relative to vessel direction, orientation, and year. Auditory weighting functions had significant effects on the potential perception of shipping noise. Bowhead whales (*Balaena mysticetus*) experienced similar SPLs to unweighted levels. Narwhals (*Monodon monoceros*) and ringed seals (*Pusa hispida*) experienced lower SPLs. Narwhals were unlikely to clearly perceive shipping noise unless ships were in close proximity (<3 km) and ambient noise levels were low. Detectability propagation models of presumed noise exposure from shipping must be based on the hearing sensitivities of each species group when assessing noise impacts on marine mammals.
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I. INTRODUCTION

The focus of this paper is to characterize underwater shipping noise levels as they would be perceived by marine mammals along an active shipping route in an Arctic inlet, and estimate the amplitude increase, range of detection (i.e., audible range), and exposure duration of shipping noise. The analyses take the hearing sensitivity at different frequencies of the marine mammal species in the area into account. There has been rising concern over the last several decades that globally increasing underwater noise levels from anthropogenic activities can result in harmful effects on marine life (Weilgart, 2007). Marine mammals rely heavily on underwater acoustics for supporting important life functions (Nowacek *et al.*, 2007). Anthropogenic noise pollution can mask animal communication, cause temporary or permanent hearing loss, and/or result in changes in animal behavior (Bejder *et al.*, 2006; Nowacek *et al.*, 2007; McDonald *et al.*, 2012; Blair *et al.*, 2016; Erbe *et al.*, 2016; Gabriele *et al.*, 2018; Blackwell and Thode, 2021; Heide-Jørgensen *et al.*, 2021; Kochanowicz *et al.*, 2021). As global marine shipping levels have increased over the last few decades, low frequency shipping noise has increased globally (McDonald *et al.*, 2006; Andrew *et al.*, 2011; Miksis-Olds *et al.*, 2018). Shipping noise is also entering formerly pristine acoustic environments such as the Arctic. Northern waterways are becoming more accessible due to rapid sea ice decline, leading to an increase in the amount of ship traffic (Pizzolato *et al.*, 2016). It is expected that shipping traffic in the Arctic will continue to increase as climate change advances (Aulanier *et al.*, 2017), thus potentially exposing previously naive marine mammal populations to new sources of underwater noise.

Marine mammals that regularly frequent the fjords and inlets of the Eastern Canadian Arctic during the ice-free summer months, when shipping may occur, include narwhals (*Monodon monoceros*), belugas (*Delphinapterus leucas)*, bowhead whales (*Eubalaena mysticetus*), ringed seals (*Pusa hispida*), and bearded seals (*Erignathus barbatus*). Inuit communities in the Arctic are highly dependent on hunting these marine mammals for subsistence and cultural purposes. Many of these species are presently facing increasing threats to their populations from climate change due to decreased sea ice cover and from increased predation from killer whales (*Orcinus orca;* Higdon *et al.*, 2012; Lefort *et al.*, 2020). With the introduction of shipping in recent years, concerns have been raised regarding the sensitivity of narwhal and ringed seal to shipping noise in Arctic inlets (Jason Prno Consulting Services Ltd., 2017; Oolayou, 2016; Qikiqtani Inuit Association, 2018, 2019;

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ERM Consultants Canada Ltd., 2019; Kochanowicz *et al.*, 2021). Given the value of marine mammals in the high Arctic region, it is important to better understand the potential acoustic impacts of shipping noise on arctic marine mammal species to better inform future management initiatives for the region.

The impact of an anthropogenic sound source on a marine mammal depends on various factors. Varying sources of anthropogenic sounds with different spectral profiles can have differing effects. Impulsive sound sources from Mid-Frequency Active Sonar (MFAS) and seismic exploration surveys are associated with risk of temporary and permanent hearing loss, communication masking, behavioral responses, and in some cases fatal strandings (Southall *et al.*, 2019; Heide-Jørgensen *et al.*, 2021). Non-impulsive sounds, such as those generated by shipping, have been associated with physiological stress, behavioral disturbances, and communication masking; however, due to the chronic nature of this noise, its impacts are more difficult to assess (Rolland *et al.*, 2012; Southall *et al.*, 2019).

Animals are not equally sensitive to noise across all frequencies. Identical unweighted noise exposure will not be equally perceived by animals with different hearing abilities. Marine mammals have varied frequency ranges of calls and vocalizations, which range from subsonic (i.e., blue whales, *Balaenoptera musculus*) to ultrasonic (i.e., porpoises) (Kyhn *et al.*, 2013; McDonald *et al.*, 2001). Assuming that the marine mammals can hear the calls that they make, this wide vocalization range is expected to be reflected in their hearing abilities. For species that have been held in captivity (i.e., dolphins, porpoises, phocids), hearing measurements have been obtained (Klishin *et al.*, 2000; Kastelein *et al.*, 2002; Sills *et al.*, 2015). Very little is known about baleen whale hearing abilities although an estimated audiogram has been proposed (Southall *et al.*, 2019).

Auditory weighting functions are mathematical functions used to emphasize the frequencies of higher sensitivity for humans and other animals and de-emphasize frequencies of lower sensitivity (Houser *et al.*, 2017). The weighting function effectively changes the unweighted SPLs perceived to those that would be experienced by the listener based on their hearing sensitivity (audiogram) across the frequency range. To varying degrees depending on the listener, the lower and higher frequencies are reduced in amplitude. The A-weighting is an example of an equal loudness curve (similar to a hearing curve or audiogram) developed to express the relative loudness of sounds in air as perceived by the human ear and is commonly used to assess impacts of environmental noise (Vos, 2003). The application of weighting functions has been identified as an important tool in assessing noise impacts for humans and their use has been extended to animals as well (Houser *et al.*, 2017). For marine mammals, generalized hearing weighting functions have been developed for several different functional hearing groups based on the audiograms of representative species (National Marine Fisheries Service, 2018; Southall *et al.*, 2019). Weighting functions have seen use calculating weighted Sound Exposure Levels (SEL), which could be used to assess the potential for the onset of temporary (TTS) or permanent threshold shifts (PTS) for the different marine mammal functional hearing groups (Southall *et al.*, 2019).

Once an auditory weighting function has been applied to estimate the likely perceived amplitude of a signal at that frequency or frequency range, it will also be necessary to determine if the signal is likely to be detected. Natural and anthropogenic noises can mask signals that would be clearly audible in quiet surroundings. Metrics such as the critical ratio have been used to estimate the detectability of vocalizations over masking noise (measured in 1 Hz wide bands; Sills *et al.*, 2020). It will be important to determine the signal-to-noise ratios and use data from laboratory measurements of hearing abilities of captive marine mammals to estimate audibility of natural and anthropogenic sounds in nature. There is, however, an absence of literature that provides a clear standardized method for estimating detectability of real-world sounds for marine mammals.

Despite the development of marine mammal weighting functions, many of today's environmental assessments still apply unweighted broadband sound pressure level (SPL) as a common metric for evaluating acoustic impacts of industrial noise on marine mammals (Kochanowicz *et al.*, 2021). Unweighted broadband levels do not account for an animal's frequency-dependent hearing abilities and may misrepresent the noise levels that are actually perceived by the animal. Audiogram data are not available for every species; however, the generic frequency-weighting functions developed by Southall *et al.* (2019) can approximately account for the diverse hearing abilities of marine mammal groups. The present study has applied auditory weighting functions to measured *in situ* underwater noise levels along and near an active commercial shipping lane in the Canadian Arctic. The intent of this study was to present an example of underwater ambient and shipping noise in an Arctic inlet and assess the influence of auditory weighting functions on the likely perceived SPLs associated with ore carrier (bulk carrier) transits in the area. The study evaluates the potential degree of shipping noise exposure for narwhal and other marine mammal species that frequent the area using a novel approach for determining the detectability of shipping noise in a real–world setting.

II. METHODS

A. Study area

This study took place in Milne Inlet; a large inlet in Northern Baffin Island in the Qikqtaaluk region of Nunavut, Canada (72.066°N, 80.476°W). Milne Inlet extends from Eclipse Sound in the North to Assomption Harbor (Milne Port) in the south (Fig. 1). This study took place in central Milne Inlet, ranging from the south end of Stephen's Island past the entrance of Koluktoo Bay, and toward Milne Port, covering an area of ~133 km^2 (Fig. 1). Koluktoo Bay is a historically significant summering ground for narwhal with animals returning every open-water season, aggregating in

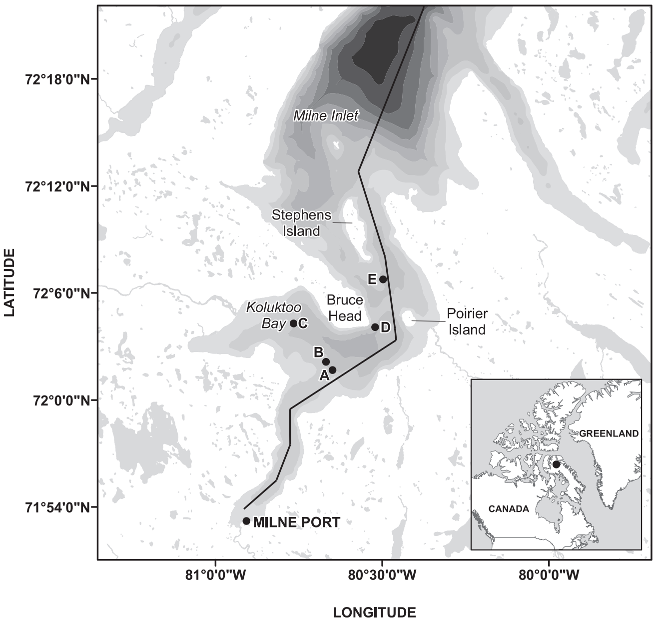

FIG. 1. Map of the study area (with 100 m bathymetry contours) covering Milne Inlet/Koluktoo Bay and showing the locations of underwater recorders deployed in 2018 (A–E) and 2019 (A, C, D) and the nominal shipping route (black line).

the hundreds and possibly thousands (Marcoux *et al.*, 2009). The area is a traditional hunting ground for local Inuit during summer who access these waters in small outboard hunting vessels. There are several hunting camps in the area, the majority of which are located on the west side of Milne Inlet (Ootova, 2019).

A port belonging to Baffinland Iron Mines Corporation is located at the south end of Milne Inlet. The Milne Port facility exports iron ore extracted from the Mary River mine site located 100 km south of the port. Marine export of the iron ore only occurs during the ice-free shipping season which extends between July and October. The shipping route passes by the entrance to Koluktoo Bay and continues north into Eclipse Sound (Fig. 1) and past Pond Inlet towards Baffin Bay. It takes ∼23 h for a typical ore carrier to be filled, and so the study area typically experiences two ship transits a day: one departing from port (Northbound), and the other entering port (Southbound). The study area in Milne Inlet was selected due to its proximity to the nominal shipping lane and its overlap with a well-established narwhal calving ground in Koluktoo Bay. An observation platform set up on the cliff of Bruce Head Peninsula provides an excellent vantage point of the study area allowing for detailed behavioral observations of narwhal in close proximity to the shipping route.

B. Data collection

Since the mine began operations in 2015, monitoring programs have been implemented to assess potential effects of shipping on the local marine wildlife and evaluate the effectiveness of mitigation measures introduced to avoid and/or minimize any adverse effects (Kim and Conrad, 2016; Smith *et al.*, 2015; Smith *et al.*, 2016; Smith *et al.*, 2017; Frouin-Mouy *et al.*, 2019; Frouin-Mouy *et al.*, 2020; Golder Associates Ltd., 2020a,b). Environmental monitoring included a passive acoustic monitoring program to measure ambient and shipping noise levels at several locations along the shipping corridor during the open-water shipping season. JASCO Applied Sciences (JASCO) deployed Autonomous Multichannel Acoustic Recorders (AMARs) at five locations in Milne Inlet in 2018 (A–E) from 4th August to 28th September (Table I), and at three locations in Milne Inlet in 2019 (A, C, and D) from 5th August to 28th September (Table I, Fig. 1), tallying 55 and 54 days of recording each year, respectively. Each AMAR was fitted with an M36-V35-100 omnidirectional hydrophone (GeoSpectrum Technologies Inc., –165 ± 3 dB re 1 V/μPa sensitivity). All devices were calibrated to within 1 dB using a pistonphone calibrator (prior to deployment and after retrieval in the field) and recorded continuously at a 64 kHz sampling rate with a 6 dB gain (Table I). For each minute of recording, 1/3 octave bands between 10 Hz and 25 kHz were obtained. Details of the individual recording locations, durations, and depths are provided in Table I.

C. AIS Ship tracking data

Forty-six bulk carriers, most with multiple transits, were used to transport iron ore from the port at the head of Milne Inlet. Their gross tonnage was 40 423 ± 5839, lengths 221 ± 16 m and widths 32 ± 2 m [means ± standard deviation (SD); Marinetraffic, 2020]. The maximum permitted speed for Project vessels in Milne Inlet was 16.7 km/h (9 knots). AIS ship tracking data were used to track the positions of ships along the shipping route during the study

TABLE I. List of autonomous recorder deployments in 2018 and 2019 with year, name, location (general and latitude/longitude), and depths.

Year	Deployment Date	Retrieval Date	Recorder Name	Location	Deployment Latitude/Longitude	Deployment Depth (m)
2018	Aug 4	Sep 28	AMAR 1	A	72.03/−80.65	209
2018	Aug 4	Sep 28	AMAR 2	B	72.04/−80.67	205
2018	Aug 4	Sep 28	AMAR 3	C	72.07/−80.76	201
2018	Aug 4	Sep 28	AMAR 4	D	72.07/−80.52	225
2018	Aug 4	Sep 28	AMAR 5	E	72.11/−80.49	245
2019	Aug 5	Sep 28	AMAR 1	A	72.03/−80.65	190
2019	Aug 5	Sep 28	AMAR 2	C	72.07/−80.76	202.5
2019	Aug 5	Sep 28	AMAR 3	D	72.07/−80.21	223.5

period. An AIS shore-based receiver station was deployed during the shipping season from July to October in both 2018 and 2019. Located on a cliff near Bruce Head, the AIS system had an uninterrupted view of the shipping route in Milne Inlet. The shore-based data were merged with satellite-based data from exactEarth (2020) for both the 2018 and 2019 recording periods to fill in data gaps when the shore-based receiver was inactive. The influence of hunting vessels and other small motorboats on local underwater sound levels was not assessed in the present study as no AIS ship tracking information was available for these vessels.

D. Auditory weighting functions

The marine mammal species present in the study area belong to three distinct functional hearing groups (Southall *et al.*, 2019). The weighting function of each marine mammal group was used to transform the unweighted (linear) SPL of each 1/3 octave band with a dB reduction corresponding to the hearing groups' auditory sensitivity (Southall *et al.*, 2019). For this study, the high-frequency cetacean (HFC) weighting function was applied to the recordings to simulate the hearing of narwhal, the low-frequency cetacean (LFC) weighting function was applied to noise recordings to simulate the hearing sensitivity of bowhead whale and for phocid carnivores in water (PCW) the weighting function was applied to simulate hearing for ringed and bearded seal. While audiograms do exist for these two phocid species, the PCW weighting function was selected to represent both species (Sills *et al.*, 2015; Sills *et al.*, 2020). All weighting functions were applied to the unweighted 1/3 octave levels from 10 Hz to 25kHz.

E. Broadband measurements

Broadband SPLs (dB re 1 μPa) were calculated using the 1/3 octave band levels from 10 Hz to 25 kHz (unweighted and weighted) to provide a standardized measurement (Richardson *et al.*, 1995). Since shipping noise is variable and dominates in the frequencies below 1 kHz (Arveson and Vendittis, 2000), the 10 Hz–25 kHz frequency range for measuring broadband SPL was considered to be appropriate for this study. Broadband SPL was calculated for every minute of recording for the unweighted noise levels and with the HFC, LFC, and PCW weightings applied. This provided four different broadband SPL measurements for every minute of recording, one representing raw (unfiltered) noise levels, and three based on the weighting functions of the three hearing groups of interest.

F. AIS analysis

Characteristics of ship transits (direction, heading, speed) were defined in the AIS data (Extracted from exactEarth, 2020) depending on their general direction and location relative to the recorders. The analysis was limited to ore carriers (bulk carriers) which constituted the majority of shipping traffic in Milne Inlet. An ore carrier was considered northbound if it was departing from Milne Port and southbound if it was heading to Milne Port from the north. Northbound transits were typically ore-laden vessels although this was not always the case. Southbound transits were generally unladen/empty vessels. For AMAR locations A, D, and E (along or close to the shipping route), the deployment latitude was used to determine if the ship was north or south of the AMAR. For AMARs B and C, since the recording sites were located perpendicular to the ore carrier transit direction from AMAR A, ship locations were categorized as either north or south of AMAR A. Based on this information, it could be determined if the ship was moving towards the recorder or away from it. The AIS data were often collected at a resolution of seconds and as a result did not offer the same temporal resolution as the minute-by-minute noise levels. To account for this, the AIS data were reorganized to have one AIS entry per minute. In the case where there were multiple entries within a one-minute interval, the entry with the closest distance to the recorder was used. This was done to ensure that the vessel's closest point of approach within the minute was measured.

G. Interpolation of ship presence

There were sporadic gaps in the AIS data coverage caused by breaks in satellite coverage and differing ship transponder configurations. These gaps generally did not last longer than a few minutes but did contribute to uncertainty of a ship's location, especially in cases where the vessel may have changed speed, as in slowing down when approaching the port or speeding up when departing. Along with vessel location data, time brackets were used to interpolate vessel presence or absence and more accurately determine the presence of shipping noise. Time samples in the acoustic record were classified as containing vessel noise if there was an AIS entry for a ship transiting within 15 km of AMAR A and within 15 min (either side) of a given recording min with an AIS location $\leq$15 km from AMAR A. Conversely, they were classified as having no shipping noise present if no AIS entries were present for ships transiting within 15 km of AMAR A and within 60 min (either side) of an AIS location $\leq$15 km from AMAR A. The time interval between the 15-min and 60-min brackets was associated with low certainty in terms of ship presence/absence and was therefore excluded from the broadband SPL comparisons. A 15 km distance was used as this distance accounted for all possible locations from which a ship would have line of sight to one of the acoustic recorders.

H. Statistical analysis

Statistical analysis of the data were conducted in R using the "*stats*" package and the RStudio interface (R Core Team, 2021; RStudio Team, 2021). Significant increases in noise level were based on detection thresholds that were $\geq$3 dB above the ambient noise level. There is an absence of literature, which clearly describes how detectability should be estimated for marine mammals in studies of real-world sounds in the absence of psychophysical measurements. For this study, detectability was estimated using a defined detection threshold. The detection threshold was defined as an acoustic signal correctly detected 50% of the time (e.g., Sills *et al.*, 2015). Under controlled laboratory settings, detection thresholds of marine mammals have been examined under conditions in which the subject is actively listening for a known signal that occurs within a short period of time. Detection levels measured under laboratory conditions for both unmasked (often with noise levels below a 0 Sea State) and masked conditions are not close to certainty until they are at least ≥3 dB above the 50% detection threshold (Sills *et al.*, 2015; Sills *et al.*, 2020; Kastelein *et al.*, 2021). Even with highly trained subjects, the 50% detection levels often have a measurement accuracy of a few dB (e.g., Kastelein *et al.*, 2021). Assuming that a signal is detectable if the amplitude is only 3 dB above the ambient or anthropogenic noise level is a very conservative value. As a result, a difference in mean broadband SPL in the presence of ships was considered biologically significant if the effect size (signal-to-noise ratio) exceeded 3 dB.

1. Broadband SPL comparisons

To assess if vessel presence in the area significantly contributed to noise levels, unweighted and weighted broadband SPLs were compared between times when ships were interpolated to be present versus times when ships were absent at each location in 2018 and 2019. The effect of vessel presence on broadband SPL was tested with a Welch's t-test (Bonferroni corrected), which compared broadband SPL for different recording locations, weighting functions, and recording years. This resulted in 32 separate t-tests, which were all testing the detectability of ship presence. The t-tests require the assumption of normality and independence of the data (Sawilowsky and Blair, 1992). Linear, LFC, and PCW broadband SPLs had relatively normal distributions; however, the HFC broadband SPLs were left-skewed. T-tests can be robust to deviations in normality with large sample sizes. Due to the large number of broadband SPL measures in the recordings ($n \geq 77\,758$ min per recorder per year), the results inferred from these t-tests can still be interpreted as valid differences/non-differences. The designation of a ≥3 dB SPL increase in shipping noise over ambient levels as being a biologically significant threshold level (i.e., the minimum SPL increase likely to be clearly detectable by marine mammals) was required. This was because of the variability in the ambient noise SPLs. Boxplots were used for exploratory analysis of unweighted and weighted broadband SPLs for the 2018 and 2019 deployment periods.

2. Estimated duration and distance of shipping noise exposure

The distance at which shipping noise would increase the broadband SPL by ≥3 dB above ambient was examined and used to calculate the time during transits that the shipping noise would be detectable by marine mammals. This was done for each weighting function, recording year, and vessel direction (Northbound/Southbound transits) at two recorder locations along the shipping route (AMAR A) and in Koluktoo Bay (AMAR C). Analysis was limited to recording minutes with AIS data available. The vessel distances were rounded to the nearest 0.5 km and vectorized so that locations south of the recorder were a negative value, and locations north of the recorder were positive. Since AMAR C was perpendicular to the shipping route at AMAR A, the distance to AMAR A was used to assess the vessel's approximate closest approach to AMAR C. AMAR C was ∼6 km from AMAR A, and the closest point of approach for ore carriers was typically the same distance. The ambient level in this analysis was defined as the noise level when a vessel was 15 km north or south of the AMAR, as at this distance ore carriers were well beyond line of sight from the recorder, and best represent the ambient levels close to the time of a vessel transit. The ≥3 dB increase in noise level criteria was required to enable calculations of meaningful audible distances and exposure durations for shipping noise. Once the audible distances were determined, the mean speed of the ore carriers was used to calculate the noise exposure duration. Boxplots were used to show the general trends of broadband SPL across a vessel transit.

A linear regression model was fitted for each weighting function in R using the "*lm*" function. The models were created to determine the distances (both north and south of the recorders) at which the noise generated by the shipping was estimated to become clearly audible (≥3 dB over ambient) for each functional hearing group at both recording locations and in both years. The distance at which the shipping noise became clearly detectable when transiting towards the recorder was noted, as was the distance that the ship was no longer clearly detectable when it was transiting away from the recorder. The sum of the distances with significantly higher SPLs was used with the average vessel speed in the area (13.7 km/h) to calculate the estimated duration of noise exposure of a vessel passage for each hearing group.

III. RESULTS

A. Broadband SPL as a function of ship presence

Differences in the SPLs of 1/3 octave bands were observed with the application of different weighting functions. The effect of each weighting function on ambient (ships absent) 1/3 octave band SPLs can be seen in Fig. 2.

Of the 32 comparisons across all recording sites in 2018 and 2019 (inclusive of weighted and unweighted categories), 30 had statistically significant higher broadband SPLs during periods of ship exposure compared to non-exposure ($p < 0.00125$ using Bonferroni corrected t-test comparisons, $n = 20\,976$–$22\,765$ for ships present, $n = 46\,341$–$47\,199$ for ships absent; Table II; Figs. 3 and 4). This relative increase in underwater sound levels due to shipping was considered to be biologically significant (≥3 dB change above ambient) in fewer than half the recordings (15 of 32) depending on year and location. In the absence of ships, all five recording sites had similar SPLs to one another in their respective year (Table II).

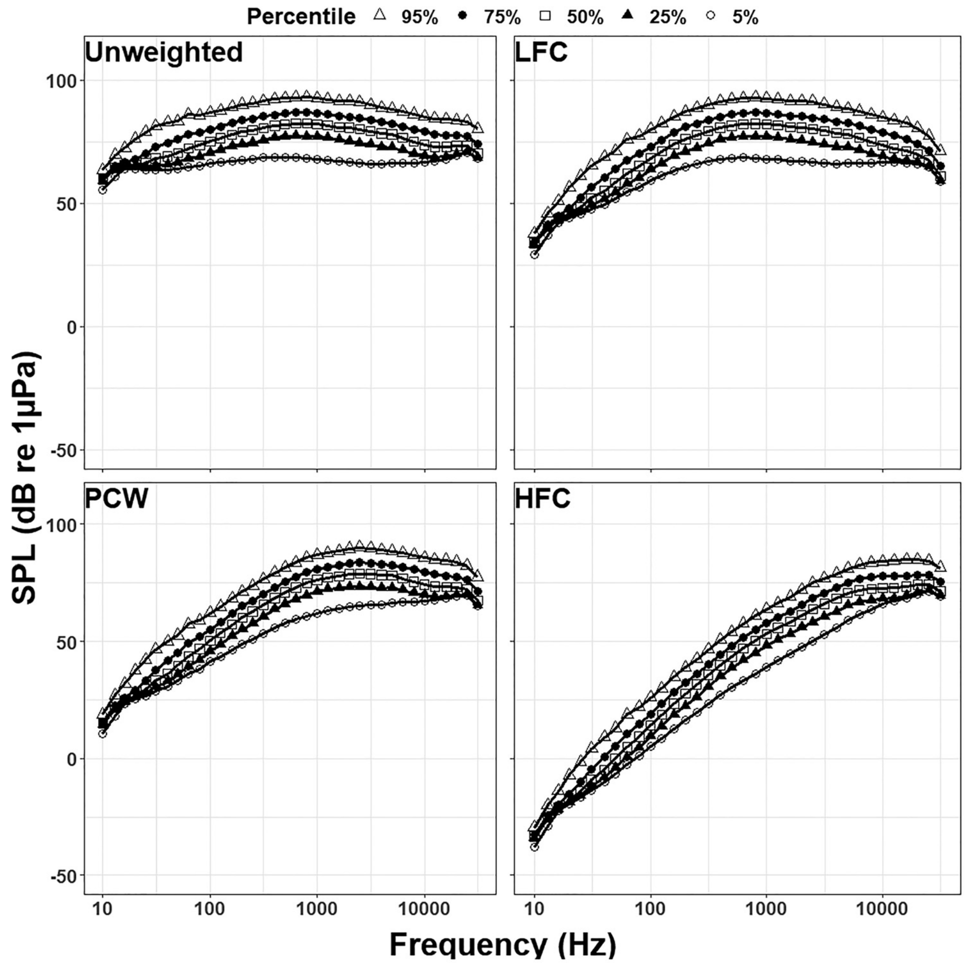

FIG. 2. The 5th, 25th, 50th, 75th, and 95th percentiles for one 1/3 octave bands (x axis scaled to $\log_{10}$) for unweighted and weighted (LFC, PCW, and HFC) broadband SPL (from 10 Hz to 25 kHz) for periods with ships absent at AMAR A in 2018. A similar plot for 2019 presented in Supplementary Fig. S1(footnote 1).

HFC weighted SPLs showed no biologically significant increases in noise levels when ships were present at any of the recording sites in 2018 and 2019 (Table II, Figs. 3 and 4). LFC weighted SPLs on the other hand were the most similar to unweighted broadband levels. Potential biologically significant increases in noise levels (from 3 to 7 dB) were observed at all recording sites in 2018 when ships were present as compared to when they were absent. However, they were only significantly higher at AMAR A in 2019 (Table II, Figs. 3 and 4). PCW weighted SPLs saw ∼3 dB increases in noise levels when ships were present for recording sites AMAR D and AMAR E during 2018 only, with increases being less pronounced than those observed for LFC and unweighted SPLs, but higher than those observed for HFC (Table II, Fig. 4). Of all recording sites, AMAR C located deep in Koluktoo Bay consistently had the lowest mean increases in underwater noise level during periods when ships were present. At this site, only LFC and unweighted SPLs had significant increases in noise levels during ship exposure periods, and only during 2018 (Table II, Figs. 3 and 4). It is important to note, however, that the SPL measurements when ships were present reflect mean levels and thus include times when ships were up to 15 km away from the recorder and the noise levels would be close to the ambient levels. When ore carriers were closer to the recorders, the SPLs would be much higher than the mean levels for a short duration; details of which are further explored in the next section.

Differences in broadband SPL increases were observed between the two recording years. In 2018, unweighted broadband SPLs were higher at all recording sites when ships were present (increases of 7–10 dB at AMARs A, B, D, and E, and an increase in 4 dB at AMAR C) (Table II, Fig. 3). In 2019, time-mean, unweighted broadband SPLs increased by more than 3 dB at 2 of the 3 recording sites when ships were present (AMARs A and C) (Table II, Fig. 4). The increase at AMAR D was only slightly less than 3 dB. Overall, during periods when ships were absent, unweighted broadband SPLs were 7.2, 7.6, and 8.1 dB higher in 2019 than 2018 at AMARs A, C, and D respectively (Table II). The mean unweighted broadband SPL when ships were absent ranged from 92 to 95 dB re 1 μPa in 2018 and increased at the same locations from 101 to 103 dB re 1 μPa in 2019 (Table II), indicating that there was an increase in the background ambient levels between years that did not originate from shipping. Wind speeds were not

TABLE II. T-test results for comparisons of mean broadband noise levels for ship exposure vs non-exposure periods. SPL increases greater than 3 dB are shown in bold ($P < 0.00125$ following Bonferroni correction).

Weighting	Year	Location	t	df	p-value	Vessel Absent Mean (dB re 1 μPa)	Vessel Present Mean (dB re 1 μPa)
Unweighted	**2018**	**A**	**−107.4**	**30 368**	**<0.0001**	**94.2**	**102.5**
Unweighted	**2018**	**B**	**−100.4**	**30 974**	**<0.0001**	**93.5**	**100.9**
Unweighted	**2018**	**C**	**−70.7**	**38 917**	**<0.0001**	**95.0**	**99.6**
Unweighted	**2018**	**D**	**−119.5**	**29 858**	**<0.0001**	**93.8**	**102.8**
Unweighted	**2018**	**E**	**−126.8**	**29 670**	**<0.0001**	**92.0**	**102.1**
LFC	**2018**	**A**	**−83.0**	**33 214**	**<0.0001**	**92.9**	**98.8**
LFC	**2018**	**B**	**−77.0**	**33 224**	**<0.0001**	**92.2**	**97.6**
LFC	**2018**	**C**	**−46.2**	**41 137**	**<0.0001**	**93.8**	**96.8**
LFC	**2018**	**D**	**−96.7**	**32 157**	**<0.0001**	**92.7**	**99.5**
LFC	**2018**	**E**	**−101.5**	**32 630**	**<0.0001**	**90.7**	**98.4**
PCW	2018	A	−39.0	35 876	<0.0001	89.5	91.9
PCW	2018	B	−36.2	35 512	<0.0001	88.4	90.7
PCW	2018	C	−6.4	43 399	<0.0001	90.4	90.7
PCW	**2018**	**D**	**−49.7**	**35 697**	**<0.0001**	**90.2**	**93.2**
PCW	**2018**	**E**	**−57.6**	**35 229**	**<0.0001**	**88.1**	**91.7**
HFC	2018	A	−6.8	39 651	<0.0001	84.2	84.6
HFC	2018	B	1.2	41 552	0.227	83.3	83.3
HFC	2018	C	22.3	46 502	<0.0001	85.4	84.4
HFC	2018	D	−12.6	38 278	<0.0001	85.6	86.3
HFC	2018	E	−19.6	36 749	<0.0001	84.0	85.0
Unweighted	**2019**	**A**	**−95.0**	**32 892**	**<0.0001**	**101.4**	**108.2**
Unweighted	**2019**	**C**	**−70.6**	**37 151**	**<0.0001**	**102.6**	**106.3**
Unweighted	2019	D	−37.7	41 345	<0.0001	101.9	104.5
LFC	**2019**	**A**	**−76.7**	**35 942**	**<0.0001**	**99.9**	**105.1**
LFC	2019	C	−53.9	38 768	<0.0001	101.0	103.8
LFC	2019	D	−30.2	43 692	<0.0001	100.3	102.3
PCW	2019	A	−39.6	40 715	<0.0001	97.1	99.8
PCW	2019	C	−25.9	42 695	<0.0001	97.9	99.3
PCW	2019	D	−47.5	40 626	<0.0001	96.9	100.1
HFC	2019	A	−9.52	41 031	<0.0001	92.6	93.7
HFC	2019	C	−10.2	41 849	<0.0001	92.7	93.5
HFC	2019	D	−2.36	42 110	0.01823	92.2	92.4

measured but are possibly responsible for the increased underwater noise levels in 2019 (Sweeney, 2021).

B. Broadband SPL as a function of ship distance

Overall, distances at which shipping noise levels remained potentially audible to marine mammals were higher for unweighted and LFC weighted SPLs compared to PCW and HFC weighted SPLs (Fig. 5, Tables III and IV). This was the case at both AMAR A and AMAR C (Figs. 5 and 6). Sample sizes ranged from 5065 to 7038 recording minutes for each recording location, recording year, and vessel direction. Equivalent plots for northbound and southbound transits sampled in 2018 and 2019 are presented in the supplementary materials (Figs. S2 to S7).[1] For all weighting scenarios, the audible range for shipping noise was slightly higher for northbound ore carriers than southbound ore carriers (Tables III and IV). Shipping noise was least audible at the Koluktoo Bay recording site (AMAR C). At this location, shipping noise was undetectable over ambient noise for HFC weighted SPLs at all approach distances along the shipping route and in both sampling years (2018 vs 2019). Similarly, shipping noise was undetectable over ambient noise for PCW weighted SPLs at all approach distances along the shipping route for recordings collected at AMAR C in 2019 (Table IV). Similar to the comparisons of ship presence and absence, shipping noise was less detectable at distance in 2019 compared to 2018 due to higher ambient noise levels in the study area that year. Underwater noise was also less detectable at distance for southbound carriers than for northbound carriers. For example, applying HFC weighting to broadband shipping noise recorded at AMAR A in 2019, southbound vessel transits were not audible over ambient conditions at any distance from the recorder despite the recorder being situated along the nominal shipping route (Table IV, Fig. 1). Higher ambient noise levels in 2019 resulted in acoustic masking of shipping noise generated by southbound carriers for the HFC group.

The estimated durations of vessel acoustic exposure during an ore carrier transit were highest for baleen whales in 2018 (e.g., bowhead whale, LFC) at 32–35 min per vessel transit for an animal located along the shipping route

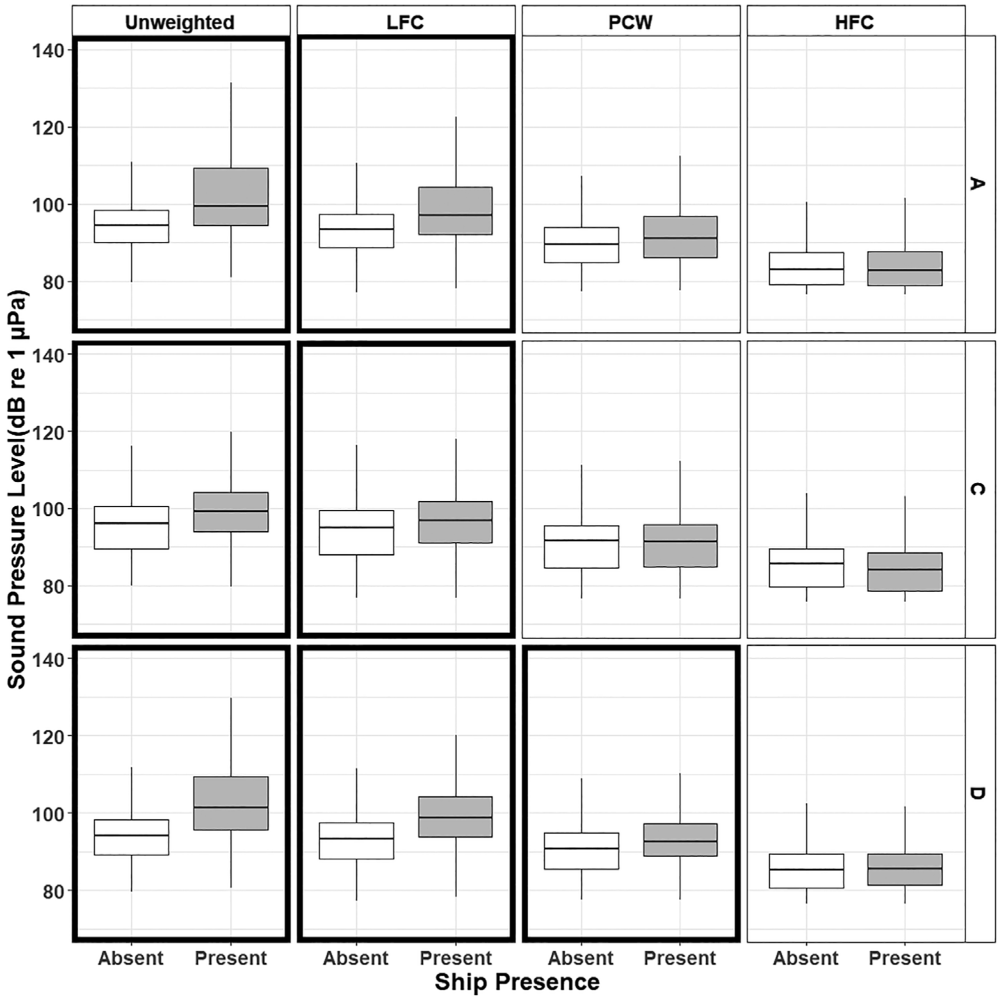

FIG. 3. Unweighted and weighted broadband SPLs (showing 5th, 25th, 50th, 75th, and 95th percentiles) during periods of ship presence (gray) and ship absence (white) for underwater recordings collected in 2018 near Bruce Head (AMAR A, C, and D). Bolded panels indicate ≥ 3 dB increases in mean broadband SPL during ship exposure periods.

(AMAR A). These values were similar to unweighted ship exposure durations in the same year (Table III), suggesting that the LFC group (i.e., baleen whales) would be able to hear the broadband noise emitted by ships over the longest distances. In Koluktoo Bay (AMAR C), the estimated duration of vessel exposure for the LFC group ranged from 16 to 21 min in 2018 with northbound vessels associated with longer exposure durations than southbound vessels. In 2019 these durations were lowered to 16–30 min at AMAR A and 2–21 min at AMAR C (Table IV). Phocid carnivores in water (PCW; e.g., ringed seal) would have experienced vessel exposure durations in 2018 ranging from 28 to 31 min at AMAR A and 8–16 min at AMAR C, similar to the LFC group. In 2019, vessel exposure durations for the PCW group were much lower, ranging from 3 to 6 min at AMAR A to 0 min at AMAR C. Following application of the HFC weighting function, the estimated vessel exposure durations for the HFC group (e.g., narwhal) located on the shipping lane (AMAR A) were 5–9 min in 2018 and 0–3 min in 2019. For the HFC group located in Koluktoo Bay (AMAR C), the vessel exposure period would be 0 min, given that shipping noise levels would not be clearly detectable over ambient sound levels in this area.

IV. DISCUSSION

Obtaining samples of natural and anthropogenic noises at multiple recording locations and at different times of the year is important to advance our understanding of the Arctic underwater soundscape. Underwater noise from natural and anthropogenic sources will influence, and in some cases limit, acoustical communication, predator detection, navigation, and related behavioral processes of marine mammals. The data presented herein identify the ranges of frequencies and amplitudes of noise in a sheltered Arctic inlet and indicate how the amplitudes of such sounds are likely to be perceived by the marine mammals in this area during summer. Applying auditory weighting functions can result in substantially lower perceived levels than unweighted sound levels for some species, especially at low frequencies. Comparing the hearing abilities of a listener to the spectral distribution of a noise source is required as a first step in assessing

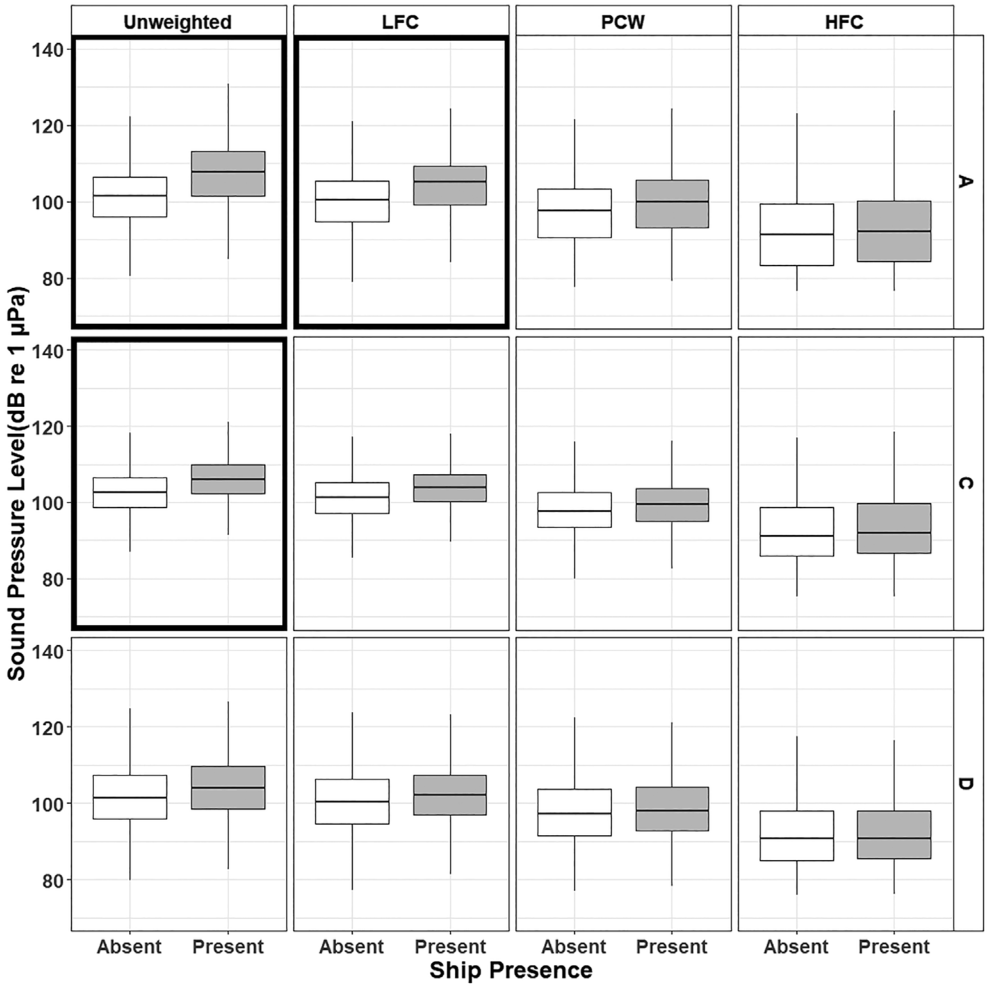

FIG. 4. Unweighted and weighted broadband SPLs (showing 5th, 25th, 50th, 75th, and 95th percentiles) during periods of ship presence (gray) and ship absence (white) for underwater recordings collected in 2019 near Bruce Head (AMAR A, C, and D). Bolded panels indicate ≥ 3 dB increases in mean broadband SPL during ship exposure periods.

potential detrimental aspects of anthropogenic underwater noise. These data and concepts are useful in support of environmental impact assessments and may help develop mitigation measures that aim to minimize adverse impacts on marine mammals due to anthropogenic noise exposure.

The use of the weighting functions in this study demonstrates the importance of considering the hearing capabilities of resident marine mammal species when assessing impacts of anthropogenic noise. Unweighted broadband SPL is a commonly used metric to assess behavioral effects from anthropogenic noise exposure in marine mammals (Erbe *et al.*, 2012; Erbe *et al.*, 2018; Jones, 2021; Kochanowicz *et al.*, 2021); however, this metric can misrepresent perceived noise exposure as it does not account for an animal's hearing abilities (Southall *et al.*, 2019). When the hearing capabilities of a marine mammal do not overlap with peak frequencies of a noise source of concern, the perceived levels are significantly lower than the unweighted levels, as observed in this study. Weighting functions (including the marine mammal weighting functions from Southall *et al.*, 2019) have been used in several marine wildlife studies relative to anthropogenic noise (McQuinn *et al.*, 2011; Owen *et al.*, 2021; Heide-Jørgensen *et al.*, 2021). Their use provides a more accurate representation of potential marine mammal exposure to anthropogenic noise than unweighted levels (Tougaard and Dähne, 2017; Lucke *et al.*, 2020), and their wider use in acoustic-based behavioral studies is recommended.

For narrow bandwidth sounds of 1/3 octave or less, the detectability of a vocalization or other important signals will be limited by the background noise within the same frequency band and thus will be independent of the auditory weighting function values. That is, measures of the signal-to-noise ratio (dB without a specific reference value) will be similarly influenced by the auditory weighting at that frequency. The perception of absolute amplitude measures (dB re 1 μPa), however, will be influenced by auditory weighting, thus it will be necessary to apply the auditory weighting function to approximate the signal detection threshold of the listener. Signal detection by nature is influenced by a multitude of factors, including the absolute sensitivity of the listener, the direction of the sound source, the separation of

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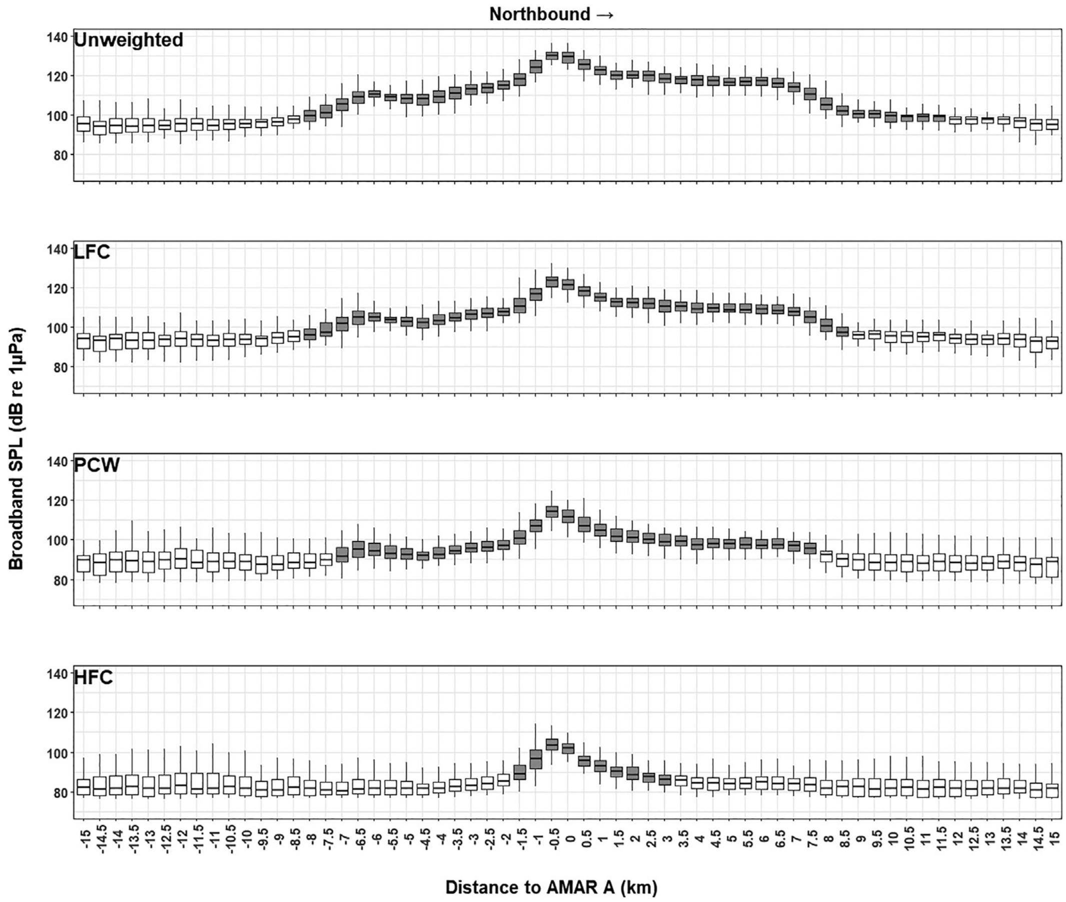

FIG. 5. Broadband SPLs (showing 5th, 25th, 50th, 75th, and 95th percentiles) relative to distance from AMAR A (recorder on shipping lane) for northbound transits in recordings collected in 2018. Shaded boxes indicate SPL increases ≥ 3 dB above the ambient level.

directions of the signal and masking noises, the degree of frequency overlap, amplitude differences between the signal and masking noise, and variation in the amplitude of masking noise (Zwicker and Fastl, 2007). Variation in the amplitude of the masking sound can result in less masking than that of a constant amplitude noise (termed masking release; Kastelein *et al.*, 2021). Local geography and topography can also be a significant factor in the propagation of a

TABLE III. Audible (ship detection) range limits and ship exposure durations (based on weighted and unweighted broadband SPLs) following exposure to northbound and southbound vessels near Bruce Head (AMAR A and AMAR C) during the 2018 open water season. The ship speed used in the calculations was 7.4 knots (13.7 km/h).

Weighting	AMAR location	Vessel direction	Mean audible range (bow facing) (km)	Mean audible range (stern facing) (km)	Estimated exposure duration (min per one-way transit)
Unweighted	A	North	−7.5	9.5	36.4
		South	9	−7	34.3
Unweighted	C	North	−5.5	9.5	32.1
		South	5	−3	17.1
LFC	A	North	−8	8.5	35.4
		South	8.5	−6.5	32.1
LFC	C	North	−5	5	21.4
		South	4.5	−3	16.1
PCW	A	North	−7	7.5	31.1
		South	7.5	−6	28.9
PCW	C	North	−3.5	4	16.1
		South	3	−1	8.6
HFC	A	North	−1.5	3	9.6
		South	1.5	−1	5.4
HFC	C	North	0	0	0
		South	0	0	0

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TABLE IV. Same as Table III except for 2019.

Weighting	Amar location	Vessel direction	Mean audible range (km; bow facing)	Mean audible range (km; stern facing)	Estimated Exposure duration (min per one-way transit)
Unweighted	A	North	−7	8	32.1
		South	7.5	−5.5	27.9
Unweighted	C	North	−3	8.5	24.6
		South	3.5	−2.5	12.9
LFC	A	North	−6.5	7.5	30.0
		South	2	−5.5	16.0
LFC	C	North	−2.5	7.5	21.4
		South	0	−1	2.1
PCW	A	North	−1.5	1.5	6.4
		South	1	−0.5	3.2
PCW	C	North	0	0	0
		South	0	0	0
HFC	A	North	−1	0.5	3.21
		South	0	0	0
HFC	C	North	0	0	0
		South	0	0	0

masking sound in real world scenarios, as seen in this study. Detection thresholds are typically defined as signal levels correctly detected 50% of the time and these measures are made in laboratory sessions in which the subject is actively listening for a familiar signal (e.g., Sills *et al.*, 2015; Sills *et al.*, 2020). A critical ratio is defined as the threshold level of a pure tone relative to the level of a masking noise. The ratio is the number of dB between the amplitude of the tone

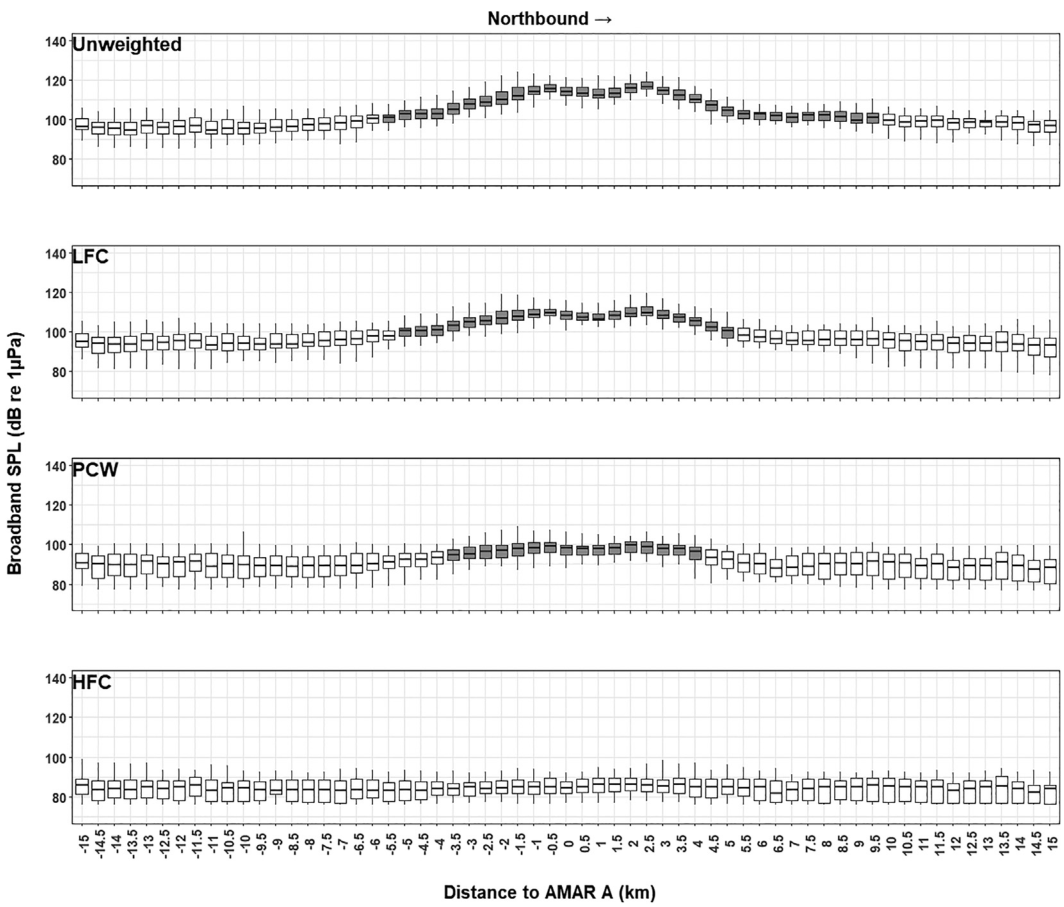

FIG. 6. Broadband SPLs (showing 5th, 25th, 50th, 75th, and 95th percentiles) at AMAR C (recorder in Koluktoo Bay) relative to the distances along the shipping route from AMAR A for northbound transits in recordings collected in 2018. Shaded boxes indicate SPL increases ≥ 3 dB above the ambient level. AMAR C is located 6 km away from AMAR A (Fig. 1).

and the spectrum level (noise amplitude in a 1 Hz wideband) of the masking noise (e.g., Sills *et al.*, 2020). Critical ratios can be used to estimate the detectability of a tonal vocalization masked by a broadband noise. When the signal has a wide bandwidth (i.e., ≥1/3 octave), it is estimated to become detectable when it has the same sound energy as the masking noise, both measured using a 1/3 octave bandwidth. For broadband shipping noises, the vessel noise will be detectable whenever it is at, or above, the ambient noise level. That is, once the signal-to-noise ratio of the signal (shipping noise in this context) and the ambient noise exceeds 3 dB, detection will be possible.

The 3 dB above ambient noise level criterion for the detection of the shipping noise adopted in this study was selected as a practical measure that reflected the uncertainty associated with the 50% threshold detection level and the variation in both the ambient and shipping noise levels. Undoubtedly, there will have been times when ambient noise levels were momentarily lower and/or the ore carrier noises were momentarily higher when marine mammals in the study area would have detected shipping noises at greater distances than modelled here. Conversely, there will also have been times when shipping noises were not detected when ambient noise levels were momentarily higher and/or shipping noises were momentarily lower. For practical reasons, the noise levels were measured over 1 min durations. If the measurement duration had been shorter than 1 min, there likely would have been a greater proportion of higher and lower amplitudes in the noise level distribution associated with very short duration, higher amplitude sounds of both the ambient noise and ore carrier noise. When this occurred, the detection ranges of the shipping noise would be slightly shorter or longer than that of the calculated means. Overall, the detection range and duration values clearly show the differences in the perception of ore carrier noises by the three marine mammal hearing groups and the importance of applying the auditory weighting functions to the unweighted noise levels.

Although the use of unweighted broadband SPL demonstrated significant increases during periods when ships were present, this was not the case for narwhal (or other toothed whales in the study area) following the application of the HFC weighting function. Ships would generally be inaudible to toothed whales located in or near the shipping lane until they were less than 3 km from the animal. For toothed whales occurring in Koluktoo Bay (represented by AMAR C, 6 km away from the nominal shipping route), ships would not be clearly detectable above background noise levels. The high frequency hearing specialization of toothed whales (e.g., narwhal and beluga) results in their lower sensitivity to frequencies below 1 kHz, where noise from shipping dominates (Arveson and Vendittis, 2000). Veirs *et al.* (2016) examined shipping noise in Southern Resident Killer Whale (SRKW) core habitat, finding a 5–13 dB increase above ambient conditions in the 10 to 40 kHz frequency range. This relative increase in amplitude would allow killer whales to perceive ships up to ∼3 km away from the source vessel (Veirs *et al.*, 2016), which is a similar range to that observed in this study. Heide-Jørgensen *et al.* (2021), assessing impacts and response from narwhals to a seismic vessel in East Greenland found that when surveying was inactive, HF weighted SPLs flattened out to ambient levels at distances of 2.5–3.5 kilometers from the vessel. The present results demonstrate that shipping noise impacts on narwhal and other toothed whales are likely negligible at distances beyond several kilometers from the shipping lane as shipping noise at these distances would largely be inaudible to the HFC group. However, shipping noise would be detectable in close proximity to vessels (<3 km) at levels capable of resulting in the behavioral disturbance. The limited ability of narwhal to perceive shipping noise should be considered when assessing their vulnerability to increasing ship traffic in the Arctic, including the Northwest Passage. These results are of particular importance, as narwhal occur in high densities in Milne Inlet during the summer months, including along the nominal shipping route which overlaps with established calving grounds and refuge areas for this species (Marcoux *et al.*, 2009).

In areas of heavy ship traffic, shipping noise can contribute significantly to noise audible to toothed whales (Hermannsen *et al.*, 2014; Cominelli *et al.*, 2018). Ship traffic in Milne Inlet is much lower than other industrialized areas with transits occurring up to twice a day, compared to up to three transits per hour in the Salish Sea near Vancouver, British Columbia, Canada (Erbe *et al.*, 2012). Sound levels in Milne Inlet differ from open water conditions due to its enclosed geography, which prevents the propagation of outside noise from entering the inlet. This phenomenon was also observed by Jones (2021) in Milne Inlet.

Avoidance behavior has been reported by harbor porpoises and SRKW within close range of commercial shipping lanes (Williams *et al.*, 2014; Oakley *et al.*, 2017). It is possible narwhal may exhibit a similar response at close distances to ships. Narwhal tagged in Tremblay Sound did show some evidence of localized, short-term avoidance behavior when very close (<1 km) to an ore carrier, and changes in certain dive behaviors when an ore carrier was between 1 and 5 km away (Golder Associates Ltd., 2020a). Narwhal and beluga have also exhibited avoidance behavior in the presence of icebreaking vessels (Finley and Davis, 1984). Since icebreaking generates significantly higher noise emissions including in the higher frequency band, these cases are not directly comparable (Cosens and Duek, 1993; Arveson and Vendittis, 2000; Erbe and Farmer, 2000). Similarly, the responses seen by narwhals at distances up to 11 km away from a seismic vessel in Heide-Jørgensen *et al.* (2021) also involved additional vessel-borne noise sources such as airguns and multibeam echosounders which were not present on the vessels in this study.

Baleen whales are considered to be at particular risk to shipping noise due to an overlap between their low frequency hearing range and shipping dominated frequencies (Arveson and Vendittis, 2000; Tougaard and Beedholm, 2019). In this study, the LFC group (e.g., bowhead whales) were likely to experience the highest increases in broadband SPL when ships were present. Based on the LFC hearing group weighting, bowhead whales are likely capable of detecting shipping noise ∼9.5 km away and were the only marine mammal hearing group capable of clearly perceiving shipping noise over background noise levels in 2019, based on the overall higher ambient noise levels that year. The audible ranges identified for the LFC group in the present study were shorter than the distances for which bowhead whales have been observed reacting to icebreaking (10–30 km; National Research Council, 1994). The lower ranges reported in this study may be partly explained by the enclosed geographical nature of the inlet in which headlands may impede long-range sound transmission in the study area. It should be noted that there is a lack of hearing data for baleen whales and their hearing abilities are poorly understood as a result (Southall *et al.*, 2019). The actual noise perception by bowhead whales may differ from the LFC weighing function. If ship traffic in Milne Inlet increases as part of further mining development, the potential for acoustic disturbance effects is likely to be more prominent for the LFC group (e.g., bowhead whales) than for species belonging to the other marine mammal hearing groups.

Phocid carnivores in water (PCW) (e.g., ringed seal) potentially perceive shipping noise to a lesser degree than LFC, but more acutely than HFC. Broadband SPLs of shipping noise as perceived by the PCW group were shown to be only slightly (∼3–6 dB) higher than ambient noise levels along the shipping route, and only for the recordings collected in 2018. Based on PCW weighting, ringed seals are likely capable of detecting shipping noise up to 7.5 km away, under quiet ambient conditions. In general, evidence of reactions by seals to vessel sound is scarce; the limited data suggest that seals are fairly tolerant of vessel sound or nearby activity, and are known to return to areas of previous disturbance (Richardson *et al.*, 1995). Harbor seals (*Phoca vitulina*) hauled out on land have been shown to move into the water in response to vessel sounds, particularly during the pupping period (Reijnders, 1981; Mathews *et al.*, 2016). This species has also been observed returning to haul out sites within an hour of being displaced into the water as a result of vessel disturbance (Bowles and Stewart, 1980; Osborn, 1985). Other studies report habituation of harbor and gray (*Halichoerus grypus*) seals to repeated vessel approaches in high traffic areas (Bonner, 1982; Johnson *et al.*, 1989). However, a recent study found that satellite-tagged gray and harbor seals changed their underwater behavior in the presence of loud shipping noise (Mikkelsen *et al.*, 2019). Ringed and bearded seals may exhibit similar responses at close ranges to ships in this study area.

Sound exposure level (SEL) is a measurement of cumulative noise over time that can be used to assess the onset of temporary (TTS) or permanent (PTS) hearing threshold shifts (Southall *et al.*, 2019, Martin *et al.*, 2019). These metrics were not explored in this study, however, weighted SELs calculated by Sweeney (2021) from shipping transits in this study area were not sufficient to cause the onset of TTS or PTS in narwhal, bowhead whale, or ringed seal (or other phocid species).

During ship exposure events, the average unweighted broadband SPL increased by 7–10 dB along the shipping route. Ore carriers and other large commercial vessels can increase average broadband SPL by 20–30 dB above ambient levels (Arveson and Vendittis, 2000; McKenna *et al.*, 2012; Jansen and De Jong, 2017). Source levels for bulk carrier vessel types typically range between 183 and 187 dB re 1 μPa at 1 m (McKenna *et al.*, 2012; Jansen and De Jong, 2017). Broadband SPL increases recorded in this study were lower than that reported in the above literature. Ore carriers were restricted to transit below 9 knots in this enclosed inlet, which may also explain why the observed noise levels are less than those reported in Arveson and Vendittis (2000).

Vessel slowdown areas have been shown to reduce shipping noise in marine mammal habitat, even though it leads to longer vessel transit times (Pine *et al.*, 2018; Joy *et al.*, 2019). Higher speeds are associated with increased propeller cavitation, which contributes more noise in the higher frequency bands (Arveson and Vendittis, 2000). It is estimated that shipping noise levels increase by 1 dB for every additional knot of speed (Veirs *et al.*, 2016). Speed was not found to significantly impact broadband SPL, unweighted or weighted, in the study area (Sweeney, 2021), likely a result of the previously mentioned speed restrictions. The lack of shipping operating at higher speeds may help to explain the lower broadband SPLs compared to other studies (Arveson and Vendittis, 2000; McKenna *et al.*, 2012; Jansen and De Jong, 2017). This suggests that speed restrictions are an effective strategy for mitigating noise from shipping in Milne Inlet.

Two other factors that were also shown to influence broadband SPL from ore carrier transits were travel direction and ship load (Arveson and Vendittis, 2000). Audible ranges were higher when ore carriers were heading away from a recorder and when the ships were deeper in the water after being loaded with ore. These differences occurred as expected.

The increased ambient levels in 2019, compared to 2018, had a large effect on the broadband SPL increases when ships were present. Sweeney (2021) found that the ambient levels in 2019 were also unusually high compared to 2014 and 2015. The lower SPL increases, shorter audible ranges, and shorter estimated durations of shipping noise exposure in 2019, relative to 2018, were a consequence of the increased ambient SPLs, and not a change in shipping noise levels. The higher ambient SPLs in 2019 masked some of the lower amplitude shipping noises. Wind speed has a strong effect on ambient SPL above 100 Hz, even in areas with heavy shipping traffic (Kinda *et al.*, 2017; Erbe *et al.*, 2021). Other contributions to ambient noise can come from ice noises and the production of biological sounds (Urick, 1983; Stafford *et al.*, 2018; Halliday *et al.*, 2020; Southall *et al.*, 2020), although these sources are unlikely to be occurring frequently enough to explain the increases in ambient levels in 2019. It is possible that increased average wind speeds contributed to the variability in ambient levels between 2018 and 2019; however, detailed meteorological data were not available for the specific study area during the respective recording periods. Future studies should record meteorological data, including wind speed, to further investigate this relationship.

Ambient noise levels are increasing in many regions in the Arctic due to decreased sea ice cover and higher exposure to wind noise (Southall *et al.*, 2020). These studies have mostly occurred in open water environments such as the Bering Sea (Southall *et al.*, 2020), but as climate change leads to extended and stormier ice-free seasons in these inlets, increases in the ambient levels may also affect the acoustic habitats of marine mammals in Milne Inlet. High ambient levels limited the contribution of weighted noise from ore carriers at some locations in this study area, particularly in areas located further away from the shipping route, such as Koluktoo Bay. This masking of the noise of distant vessels may reduce the exposure of marine mammals to shipping noise, and consequently any potential behavioural responses. It is, however, likely that some marine mammals are capable of detecting lower levels of shipping noise during brief periods when dips in ambient noise amplitudes occur and thus would be aware of ship presence during these periods.

Although small vessels can contribute significantly to underwater ambient noise levels (Hermannsen *et al.*, 2019), the contribution of noise from non-AIS vessels could not be quantified in this study. Their contribution to the soundscape, however, may be significant as hunters using outboard motorboats were a common occurrence during the study period. The presence of outboard engines is of particular biological importance for Arctic marine mammals as it indicates the potential presence of hunters (i.e., predation cue).

This study does not address weighted broadband SPLs close to a ship or any possible behavioral reactions as a consequence of hearing shipping sounds by marine mammals. The determination of the noise exposure durations associated with individual ore carrier transits will provide some guidance in predicting an increase in the noise levels and duty cycles should the numbers of large vessels in Milne Inlet increase in future years. Restricting access into Koluktoo Bay by all large vessels would provide the narwhals with an acoustic reserve where they would only experience low level and short duration exposures to the noise of ships during their passage across the mouth of the bay.

The results outlined in this study provide important information regarding the potential impacts of shipping on Arctic marine mammals that can help inform policymakers and stakeholders when making decisions about the future of shipping in the Arctic. This study has also shown that the use of auditory weighting function adjustments (Southall *et al.*, 2019) can provide a more realistic approximation of the noise levels perceived by marine mammals when exposed to shipping. Weighted noise levels from shipping (i.e., sound levels perceived by the different hearing groups) can differ significantly from unweighted noise levels. Thus, the use of unweighted broadband SPL to assess the biological and ecological impact of anthropogenic noise is not appropriate. The hearing sensitivities of different marine mammal hearing groups must be considered for a more accurate assessment of potential noise impacts on local species.

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[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0009956 for a percentile figure for AMAR A in 2019, broadband over distance figures for southbound vessels in 2018 for AMAR A and C, and for both northbound and southbound vessels in 2019 for AMAR A and C.

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