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Potential impacts of shipping noise on marine mammals in the western Canadian Arctic☆

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ABSTRACT

As the Arctic warms and sea ice decreases, increased shipping will lead to higher ambient noise levels in the Arctic Ocean. Arctic marine mammals are vulnerable to increased noise because they use sound to survive and likely evolved in a relatively quiet soundscape. We model vessel noise propagation in the proposed western Canadian Arctic shipping corridor in order to examine impacts on marine mammals and marine protected areas (MPAs). Our model predicts that loud vessels are audible underwater when > 100 km away, could affect marine mammal behaviour when within 2 km for icebreakers vessels, and as far as 52 km for tankers. This vessel noise could have substantial impacts on marine mammals during migration and in MPAs. We suggest that locating the corridor farther north, use of marine mammal observers on vessels, and the reduction of vessel speed would help to reduce this impact.

1. Introduction

Noise pollution is pervasive throughout marine environments (Merchant et al., 2014). Anthropogenic noise sources include resource exploration (e.g., seismic surveys) and extraction activities (e.g., drilling), construction and demolition (e.g., pile driving), military activities (e.g. sonar), and transportation (e.g., shipping). Shipping is the most widespread and continuous noise source of all of these sources (McDonald et al., 2006). It has been estimated that increased global shipping has led to an increase in ocean ambient noise levels off the coast of California by 2.5 to 3 dB re 1 μPa per decade from the 1960s to the 2000s (Andrew et al., 2002; McDonald et al., 2006) or even as high as 0.5 dB re 1 μPa per year (Ross, 2005). Changes in ambient noise levels like this can potentially affect all marine life, especially animals that rely on sound for predator/prey/conspecific detection, communication, or navigation. If animals evolved under specific ambient noise conditions, then changes to these conditions could alter the effectiveness of their auditory response or propagation of their vocalizations. A more direct effect of shipping is the impact of individual vessels on marine mammals. Individual vessels can have source levels close to 200 dB re 1 μPa at 1 m (Erbe and Farmer, 2000; Simard et al., 2016; Veirs et al., 2016). Levels this high can cause behavioural disturbance and mask other important acoustic signals (Erbe and Farmer, 2000), and can also increase stress levels (Rolland et al., 2012). If individual vessels are even louder or if multiple loud vessels are in the same area, vessel noise could cause temporary or permanent threshold shifts (TTS and PTS, respectively) or even injury (Southall et al., 2007). Noise pollution is such an important issue for marine life that policy makers have guidelines for projects that create noise (National Marine Fisheries Service, 2016; National Oceanic and Atmospheric Administration, 2016; Reeves et al., 2012).

The majority of the Arctic Ocean represents a unique and nearly pristine acoustic environment. Sea ice is present throughout much of the Arctic Ocean for most of the year and shipping is restricted mainly to the open ice season, typically between August and October. The combination of sea ice and reduced shipping makes the Arctic a particularly quiet environment. Ice typically dampens the effect of other noise-making factors, such as increased wind speed (Insley et al., 2017; Kinda et al., 2013; Roth et al., 2012). Since vessels can only access Arctic waters for a short period each year, they currently have relatively little impact on the year-round acoustic environment. Moreover, most shipping through the Arctic is currently limited to providing services to local communities rather than as a route for long-distance transportation, although the Northern Sea Route along the coast of Russia is

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already used for some long distance transport (Zhang et al., 2016). However, the rapid decrease in sea ice caused by climate change is expected to make many shipping routes through the Arctic viable by 2050 (Stephenson et al., 2011), and shipping has been increasing in the Arctic in recent history (Pizzolato et al., 2016). Although viability of the Northwest Passage through the Canadian Arctic is estimated to take longer than other shipping routes (Stephenson et al., 2011), Canadian policy makers are still planning for increased shipping traffic by proposing shipping corridors through the Canadian Arctic (Dawson et al., 2016). Unfortunately, the preliminary shipping corridors were identified based on historical average vessel routes traveling through the Canadian Arctic, and do not consider important environmental factors, such as core use areas by marine mammals, fish, or sea birds (Oceans North Canada, 2016). In addition, the potential acoustic impacts have not been assessed for the proposed shipping corridor, which are an important aspect of shipping impacts. There is an urgent need to assess the impacts of shipping on the Arctic before major increases in noise levels occur (Moore et al., 2012).

For this study, we examine the acoustic impacts of shipping in the western Canadian Arctic by modelling the propagation of noise from ships, and compare received noise levels to sound levels that are audible to marine mammals and are known to affect their behaviour. We model acoustic propagation from a ship that we recorded near Sachs Harbour, Northwest Territories, as well as from a tanker vessel from a different site that might be expected to represent future shipping in the Arctic. We specifically apply this model to the proposed shipping corridor (Dawson et al., 2016) through the eastern Beaufort Sea and Amundsen Gulf (see Fig. 1). This geographic area is home to two year-round resident seal species (bearded seals, *Erignathus barbatus*; and ringed seals, *Pusa hispida*) and two seasonally resident cetacean species (bowhead whales, *Balaena mysticetus*; and beluga whales, *Delphinapterus leucas*). Bowhead whales are listed as Special Concern in Canada (COSEWIC, 2009), and beluga whales are considered Near Threatened globally (IUCN, 2012). The Department of Fisheries and Oceans Canada created a management plan for the Bering-Chukchi-Beaufort population of bowhead whales in Canada (Fisheries and Oceans Canada, 2014), which lists underwater noise as the greatest threat to this population. The management plan suggests that if shipping does increase in the Beaufort Sea, that lower speed limits for vessels could be enforced in known congregation areas, or shipping routes could be developed that avoid important areas for bowheads. The current shipping corridor does not avoid important areas for bowhead whales and does not include recommendations for speed limits.

The Canadian Beaufort Sea and Amundsen Gulf also have two marine protected areas (MPAs), the Tarium Niryutait Marine Protected Area (TNMPA), located in the Mackenzie River Delta near the communities of Aklavik, Inuvik, and Tuktoyaktuk, and the Anguniaqvia Niqiqyuam Marine Protected Area (ANMPA), located at Darnley Bay near the community of Paulatuk. The TNMPA is specifically focussed on preserving important feeding/congregating habitat for beluga whales, whereas the ANMPA is focused on preserving habitat for a more diverse species assemblage including Arctic char, cod, beluga whales, ringed and bearded seals, polar bears, and a variety of sea birds. The TNMPA management plan (Fisheries and Oceans Canada, 2013) recognizes the impacts of noise on belugas, and suggests that commercial vessels follow the Canadian Coast Guard buoys that demarcate the community supply routes. Vessels are still allowed to travel through the TNMPA; however, suggestions are provided for reducing noise. The ANMPA was officially designated in November 2016 and does not currently have a management plan.

Given that no legislation or management plan in the Canadian Beaufort Sea or Amundsen Gulf effectively addresses the acoustic impacts of shipping, this study provides useful basic information for policy makers about the acoustic impacts of shipping on marine mammals in this region. Two other studies have modelled the effects of ship noise on marine mammals in the Beaufort Sea: Erbe and Farmer (2000) modelled the zones of impact for beluga whales around icebreakers while icebreaking, and Ellison et al. (2016) modelled the acoustic impact of multiple simultaneous industrial activities, including vessel noise, on bowhead whales. Both of these studies focused on very specific aspects of shipping. In contrast, we offer a wider geographic perspective on vessels traveling along the proposed shipping corridor through the Canadian Beaufort Sea.

2. Methods

2.1. Estimating vessel source levels

We used acoustic data from hydrophones near Sachs Harbour, Northwest Territories, to estimate source levels of vessels in Arctic waters. We collected acoustic data using Wildlife Acoustics (Maynard, Maryland, USA) SM3M bioacoustics recorders fitted with a low noise HTI 92-WB hydrophone (High Tech, Inc., Gulfport, Mississippi, USA; sensitivity between −175 and −165 dB re 1 V μPa^{-1} in the range of analysis). We deployed recorders between 2014 and 2016: one between July and August 2014, one between May and August 2015 along with a second recorder between July and August 2015, and one from August 2015 to July 2016. Only our deployment from August 2015 to July 2016 recorded any large vessels. We deployed this recorder from 20 August 2015 to 8 July 2016 roughly 8 km southwest of Sachs Harbour (71°55.621′N, 125°23.447′W), anchored at a depth of 23.5 m (water depth = 28.5 m), recording on a duty cycle of 5 min recording followed by 30 min off, 48 kHz sampling rate at a 16 bit resolution, and +18 dB of gain.

We used Automated Identification System (AIS) vessel data collected via exactEarth's (Ontario, Canada) satellite network to determine which vessels were within 100 km of our hydrophone, and then manually examined spectrograms of the acoustic data to determine when we could detect vessels based on characteristic horizontal banding (continuous energy at specific frequencies). We expanded this radius beyond 100 km when vessels were still being detected at the 100 km radius. While eight vessels passed within the 100 km radius when we had hydrophones deployed, we only detected signals from two of these vessels, which spent much more time close to our hydrophone than the other vessels. These two vessels were the CCGS Amundsen (Canadian Coast Guard icebreaker and research vessel, detected between 30 August and 18 September 2015) and the HMCS Saskatoon (Royal Canadian Navy Kingston-class maritime coastal defence vessel, detected between 22 and 25 August 2015). The other vessels noted within the AIS dataset that were within the 100 km radius but were not acoustically detected were four tug boats, an icebreaker, and a pleasure craft. For each vessel, we obtained a time series of GPS coordinates, distance to our hydrophone, and speed of travel over ground.

We processed all recordings in Matlab to quantify the underwater acoustic signals. We measured power spectral densities (PSD) between 10 Hz and 24 kHz, computed from fast Fourier transforms (FFTs) of 1 s of data in 1 Hz bins overlapped by 0.5 s (120 averages/min) using a Hanning window. From these PSDs, we calculated sound pressure level (SPL) in 1/3-octave bands between 63 Hz and 20 kHz, and broadband SPL over this same range. For the two vessels that we acoustically detected, we extracted the spectra which corresponded to the vessel's closest point of approach (5 min recording). We calculated source level for the spectrum based on transmission loss with a mix of spherical and cylindrical spreading, while factoring in frequency-dependent attenuation and loss due to depth (adapted from Pine et al., 2014):

$$SL = RL + 15log_{10}RO + 10log_{10}\frac{R}{RO} + 0.04 + 10log_{10}\frac{d}{dO} + \propto \tag{1}$$

where *SL* is source level, *RL* is received level, *R* is the range of the vessel, *RO* is the range at which geometric spreading switches from spherical to cylindrical, *d* is depth of the recorder, *dO* is depth of the source, and *α* is frequency-dependent attenuation. The subsequent noise

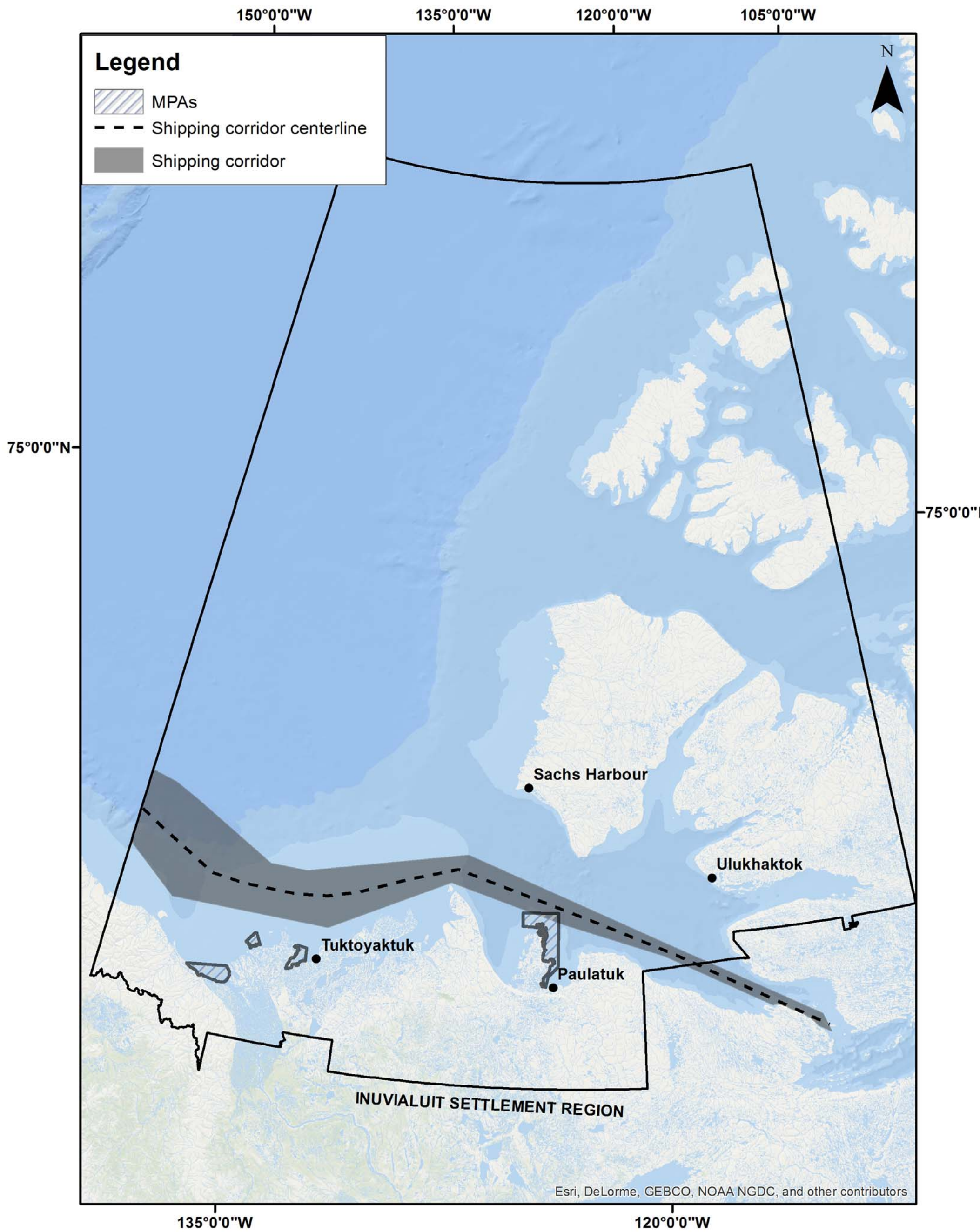

Fig. 1. Study area map showing the Tarium Niryutait Marine Protected Area (TNMPA), the Anguniaqvia Niqiqyuam Marine Protected Area (ANMPA), and the proposed shipping corridor through the eastern Beaufort Sea and Amundsen Gulf in the western Canadian Arctic.

modelling was carried out on these source levels.

To determine the impact of wind speed on ambient noise levels and to determine audibility thresholds (see Modelling the acoustic footprint of shipping), we matched broadband SPLs between 10 Hz and 24 kHz with wind speed data obtained from the Environment Canada weather station at Sachs Harbour (Environment Canada, 2016), and determined the impact of wind speed on SPL when no ships were within 100 km of our recorders between 20 August and 31 October 2015 using a simple linear regression model (method described in Insley et al., 2017), and used this relationship to estimate the audibility threshold during calm (wind speed = 0 km/h) and windy conditions (wind speed = 50 km/h).

2.2. Modelling the acoustic footprint of shipping

We modelled the acoustic footprint of two large vessels that might travel through Arctic waters: the CCGS Amundsen and the Awanuia. The CCGS Amundsen is a Canadian Coast Guard ice-breaking vessel (length = 98 m, draft = 7.4 m) that is used mainly for research, and is often in the western Canadian Arctic during the summer. The Awanuia is a medium-sized tanker vessel (length = 80 m, draft = 6.3 m) that represents one type of vessel that will likely use the Northwest Passage once it is ice-free. We obtained the source level spectra for the Awanuia from a recording in New Zealand coastal waters using the same method as for the CCGS Amundsen. The Awanuia was recorded using a SoundTrap model 202 ST autonomous recorder (Ocean Instruments, Auckland, New Zealand). The recorder was anchored at a depth of 17 m and recorded the Awanuia when it was 257 m away from the recorder.

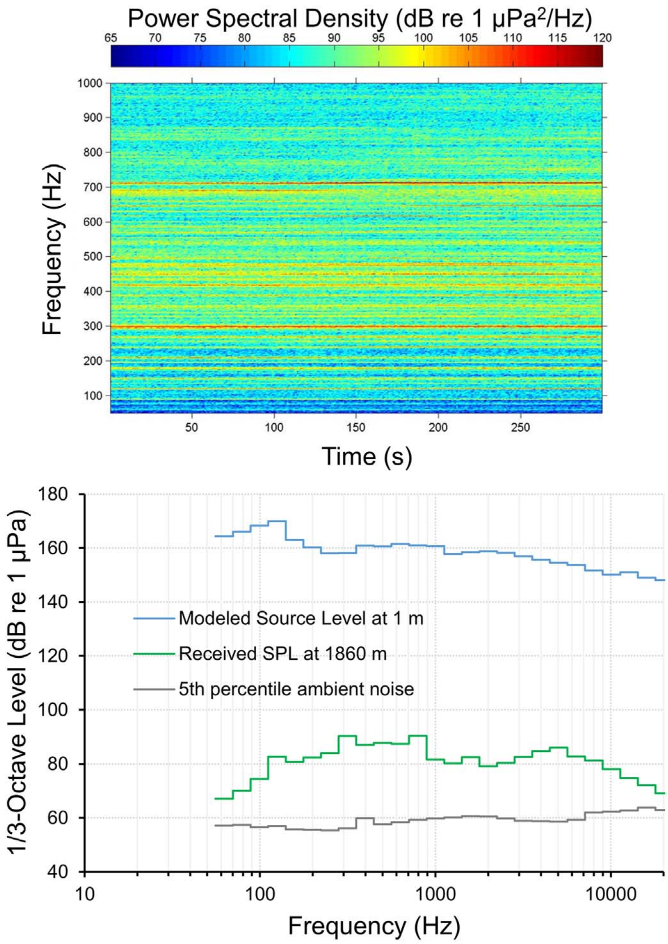

Fig. 2. Spectrogram at the closest point of approach for the CCGS Amundsen near Sachs Harbour, Northwest Territories (top, distance = 1.86 km), and its corresponding 1/3-octave spectra along with the estimated source level spectra and 5th percentile ambient noise levels (bottom).

We modelled sound propagating from each vessel traveling along the shipping corridor near both the ANMPA and TNMPA using a coupled normal modes model for a range-dependent environment (for frequencies between 50 Hz and 1.5 kHz) (Jensen et al., 2011), and a Bellhop Gaussian ray trace model (for frequencies between 1.5 and 24 kHz) (Jensen et al., 2011) in the modelling software dBSea (dBSea Ltd., UK). We estimated the sound field spreading from each vessel traveling along the center and the northern and southern edges of the proposed shipping corridor, and calculated this sound field every 10 km along the corridor. We used bathymetry data obtained from the International Bathymetric Chart of the Arctic Ocean (3rd edition) with 500 m resolution (Jakobsson et al., 2012), and an averaged sound speed profile based on conductivity, temperature, and depth (CTD) data collected on ArcticNet Cruise 1103 (available in the Polar Data Catalogue: www.polardata.ca).

We assessed the model output to determine the area around the vessel's route that exceeded sound levels that affect marine mammal behaviour, and also sound levels that are expected to be audible under windy conditions (wind speed = 50 km/h) and calm conditions (wind speed = 0 km/h) at our site. The National Oceanic and Atmospheric Administration (2016) (NOAA) set a behavioural disturbance threshold for all marine mammal species at 120 dB re 1 μPa. Southall et al. (2007) also reviewed multiple studies of both bowhead and beluga whales, and determined that levels at 100 dB would cause some observable disturbance to behaviour, while levels as high as 140 dB re 1 μPa would cause more severe behavioural disturbance. No studies have been published that measured behavioural disturbance caused by noise in either bearded or ringed seals, but Southall et al. (2007) did estimate that the average sound level for behavioural disturbance in seals (as a class) was around 140 dB re 1 μPa. We used 120 dB re 1 μPa as our value for behavioural disturbance because it is the value used by the NOAA, and it is intermediate to Southall et al.'s (2007) range of values. These acoustic behavioural thresholds are context-dependent, and likely change depending on the state of the animal and whether it is acclimated to anthropogenic noise (Ellison et al., 2012; Gomez et al., 2016). However, in the absence of both population-specific data on acoustic behavioural thresholds and even data on how individual animals react to noise, the NOAA threshold of 120 dB re 1 μPa is a good starting point for assessing the effects of anthropogenic noise on marine mammals. We also note that SPL alone may not provide an adequate indicator for behavioural disturbance (Southall et al., 2007; Gomez et al., 2016), but it is a reasonable starting point. We did not assess the possibility of either TTS or PTS because the cumulative 24 h sound exposure levels from both ships that we modelled were below the levels that cause either TTS or PTS according to the National Marine Fisheries Service (2016).

A reasonable estimate for a signal audibility threshold is just above background noise levels (Erbe, 2002). Although audiograms do exist for beluga whales (e.g., Erbe et al., 2016) and ringed seals (e.g., Sills et al., 2015), there are no audiograms for bowhead whales or bearded seals. Audiograms for marine mammals generally demonstrate peak hearing ability around 10 kHz (Erbe et al., 2016); this value should be lower for mysticete whales (such as bowhead whales) because most of their vocalizations are at lower frequencies. We use background noise levels to estimate audibility since audiograms are only available for two of the four species at our study site, and we wanted the model output to be generalizable to any species in the region. Noise caused by wind and sea state is the greatest contributor to ambient noise levels near our study site in the Canadian Arctic during the ice-free season (Insley et al., 2017), therefore we calculated the effect of wind on ambient noise levels in the absence of ships (see method above in Estimating vessel source levels) and found ambient noise levels with no wind to be 90 dB re 1 μPa, and ambient noise levels with medium-high wind (wind speed = 50 km/h) at 110 dB re 1 μPa. Ambient noise levels at this site are generally much quieter than in more temperate regions (Insley et al., 2017), and tend to peak between 100 and 1000 Hz. We used these two levels as metrics of audibility under calm and windy conditions.

3. Results

3.1. Estimating vessel source levels

We detected the CCGS Amundsen when it was 121.5 km away from our hydrophone, and calculated the source level when it was 1.86 km away (Fig. 2) (broadband source level = 176 dB re 1 μPa at 1 m, received level = 98 dB re 1 μPa).

We detected the HMCS Saskatoon when it was 139.5 km away from our hydrophone, and at its closest point of approach, it was 3.18 km away (broadband received level = 89 dB re 1 μPa). Much of the noise from the Saskatoon was masked by wind-related noise (average ambient noise in absence of wind = 90 dB re 1 μPa), therefore we did not calculate its source level.

Increased wind speed led to increased ambient noise levels (slope = 0.39 ± 0.02 dB re 1 μPa/km/h), which equated to a broadband SPL of 90 dB re 1 μPa in calm conditions (wind speed = 0 km/h) and 110 dB re 1 μPa in windy conditions (wind speed = 50 km/h). This was comparable with the impact of wind on noise levels in other studies, including Ross (1976) (0.23 dB re 1 μPa/km/h), McDonald et al. (2006) (0.18 to 0.43 dB/km/h), and Roth et al. (2012) (0.14 to 0.28 dB re 1 μPa/km/h).

Table 1
Areas within two MPAs in the western Canadian Arctic (ANMPA and TNMPA) that would be affected by ships traveling along the southern edge (S), center (C), or northern edge (N) of the proposed shipping corridor. Areas refer to the area within the MPA where sound pressure levels would reach minimal thresholds affecting behaviour (SPL = 120 dB re 1 μPa), or where vessels would be audible under windy conditions (wind speed = 50 km/h, SPL = 110 dB re 1 μPa) or calm conditions (wind speed = 0 km/h, SPL = 90 dB re 1 μPa). We calculated these levels for two vessels: the CCGS Amundsen (top panel), and the Awanuia (bottom panel). Percent represents the percent of the MPA that is affected.

	Behaviour	Audibility – windy	Audibility – calm
CCGS Amundsen			
ANMPA – S	37 km^2 (2%)	881 km^2 (37%)	2006 km^2 (85%)
ANMPA – C	0 km^2	800 km^2 (34%)	2000 km^2 (85%)
ANMPA – N	0 km^2	801 km^2 (34%)	1993 km^2 (84%)
TNMPA – S	0 km^2	0 km^2	247 km^2 (14%)
TNMPA – C	0 km^2	0 km^2	113 km^2 (6%)
TNMPA – N	0 km^2	0 km^2	92 km^2 (5%)
Awanuia			
ANMPA – S	382 km^2 (16%)	1349 km^2 (57%)	2011 km^2 (85%)
ANMPA – C	266 km^2 (11%)	1472 km^2 (62%)	2023 km^2 (86%)
ANMPA – N	202 km^2 (9%)	1532 km^2 (65%)	2011 km^2 (85%)
TNMPA – S	0 km^2	0 km^2	401 km^2 (22%)
TNMPA – C	0 km^2	0 km^2	251 km^2 (14%)
TNMPA – N	0 km^2	0 km^2	378 km^2 (21%)

3.2. Modelling the acoustic footprint of shipping

The CCGS Amundsen (source level = 176 dB re 1 μPa at 1 m; Fig. 2) traveling along the southern edge of the shipping corridor near the ANMPA would exceed the behavioural disturbance threshold in 37 km^2 (2%) of the MPA, and would be audible under windy conditions in 881 km^2 (37%) and 2006 km^2 (85%) under calm conditions within the MPA (Table 1, Fig. 4F). Traveling along the center of the corridor near the ANMPA, the Amundsen would not exceed the behavioural disturbance threshold in the MPA, but would be audible in 800 km^2 (34%) under windy conditions and 2000 km^2 (85%) under calm conditions (Table 1, Fig. 4E). Along the northern edge of the shipping corridor, the Amundsen would not exceed the behavioural disturbance threshold in the MPA, but would be audible in 801 km^2 (34%) under windy conditions and 1993 km^2 (84%) under calm conditions (Table 1, Fig. 4D). The Amundsen traveling along any part of the shipping corridor near the TNMPA would not exceed the behavioural disturbance threshold in the MPA, nor would it be audible within the MPA under windy conditions; however, it would be audible under calm conditions in 247 km^2 (14%), 113 km^2 (6%), and 92 km^2 (5%) when traveling the southern edge, center, and northern edge, respectively (Table 1, Fig. 4A–C).

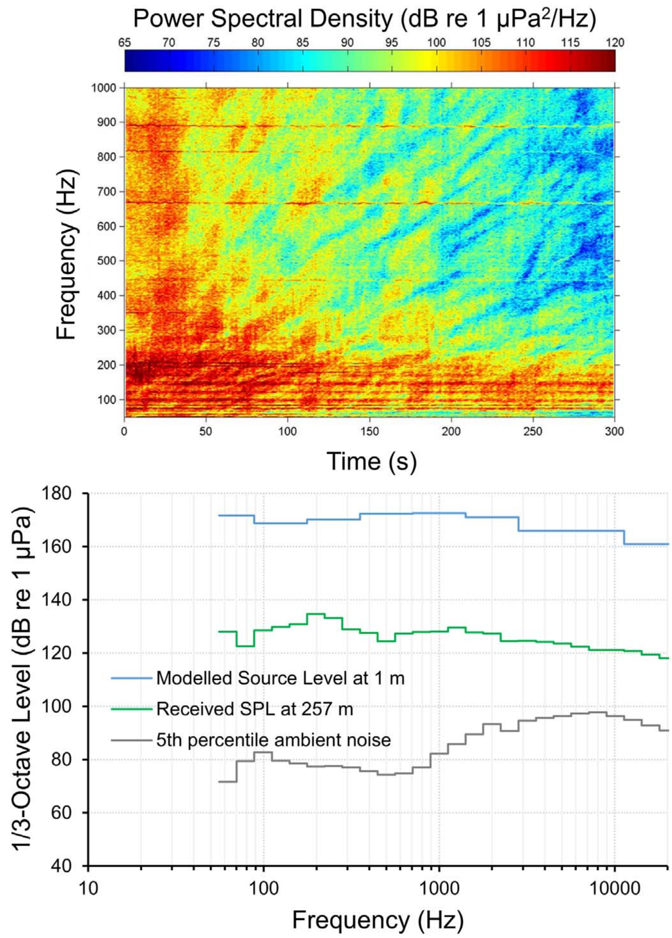

Fig. 3. Spectrogram at the closest point of approach for the Awanuia in New Zealand (top, distance = 257 m), and its corresponding 1/3-octave spectra along with the estimated source level spectra and 5th percentile ambient noise levels (bottom).

Table 2
Mean propagation distances ± SE from the source location towards the mainland and towards the open ocean for ships traveling along the southern edge (S), center (C), or northern edge (N) of the proposed shipping corridor through the western Canadian Arctic. Distances refer to the distances at which sound levels exceed the behavioural disturbance threshold (SPL = 120 dB re 1 μPa), or where vessels would be audible under windy conditions (wind speed = 50 km/h, SPL = 110 dB re 1 μPa). We do not include distances for calm conditions (wind speed = 0 km/h, SPL = 90 dB re 1 μPa) because the geographic area for our modelling space was too small to reach these distances. Calculated for two vessels: the CCGS Amundsen (top panel), and the Awanuia (bottom panel). The rows refer to the path that the vessel is traveling along, either in front of the ANMPA or TNMPA. Distance from the source to the shore is identical for both vessels. Note that there was no variation in behavioural threshold for the Amundsen on any path.

	Behaviour		Audibility – windy		Distance to shore	
	Mainland	Sea	Mainland	Sea	Mainland	Sea
CCGS Amundsen						
ANMPA – S	2.0	2.0	21.0 ± 3.3	103.6 ± 5.0	66.8 ± 10.0	110.5 ± 5.7
ANMPA – C	2.0	2.0	35.0 ± 2.8	88.5 ± 4.4	81.5 ± 9.0	98.0 ± 9.3
ANMPA – N	2.0	2.0	55.0 ± 4.6	72.8 ± 4.7	106.8 ± 9.8	71.8 ± 5.2
TNMPA – S	2.0	2.0	16.4 ± 1.3	20.4 ± 1.0	45.3 ± 5.0	NA
TNMPA – C	2.0	2.0	15.9 ± 1.3	21.2 ± 1.1	59.5 ± 6.8	NA
TNMPA – N	2.0	2.0	43.7 ± 0.9	68.0 ± 9.8	97.0 ± 16.5	NA
Awanuia						
ANMPA – S	10.4 ± 1.7	37.1 ± 0.8	28.7 ± 6.0	106.2 ± 5.5	66.8 ± 10.0	110.5 ± 5.7
ANMPA – C	25.8 ± 1.2	47.1 ± 0.5	47.8 ± 6.3	90.9 ± 4.6	81.5 ± 9.0	98.0 ± 9.3
ANMPA – N	41.4 ± 2.4	51.9 ± 0.4	69.4 ± ± 8.2	74.5 ± 5.8	106.8 ± 9.8	71.8 ± 5.2
TNMPA – S	10.5 ± 1.9	12.2 ± 1.5	43.3 ± 0.2	71.5 ± 3.2	45.3 ± 5.0	NA
TNMPA – C	10.6 ± 1.1	10.1 ± 1.7	30.0 ± 1.6	134.2 ± 12.6	59.5 ± 6.8	NA
TNMPA – N	12.7 ± 0.5	14.9 ± 2.6	60.0 ± 2.8	NA	97.0 ± 16.5	NA

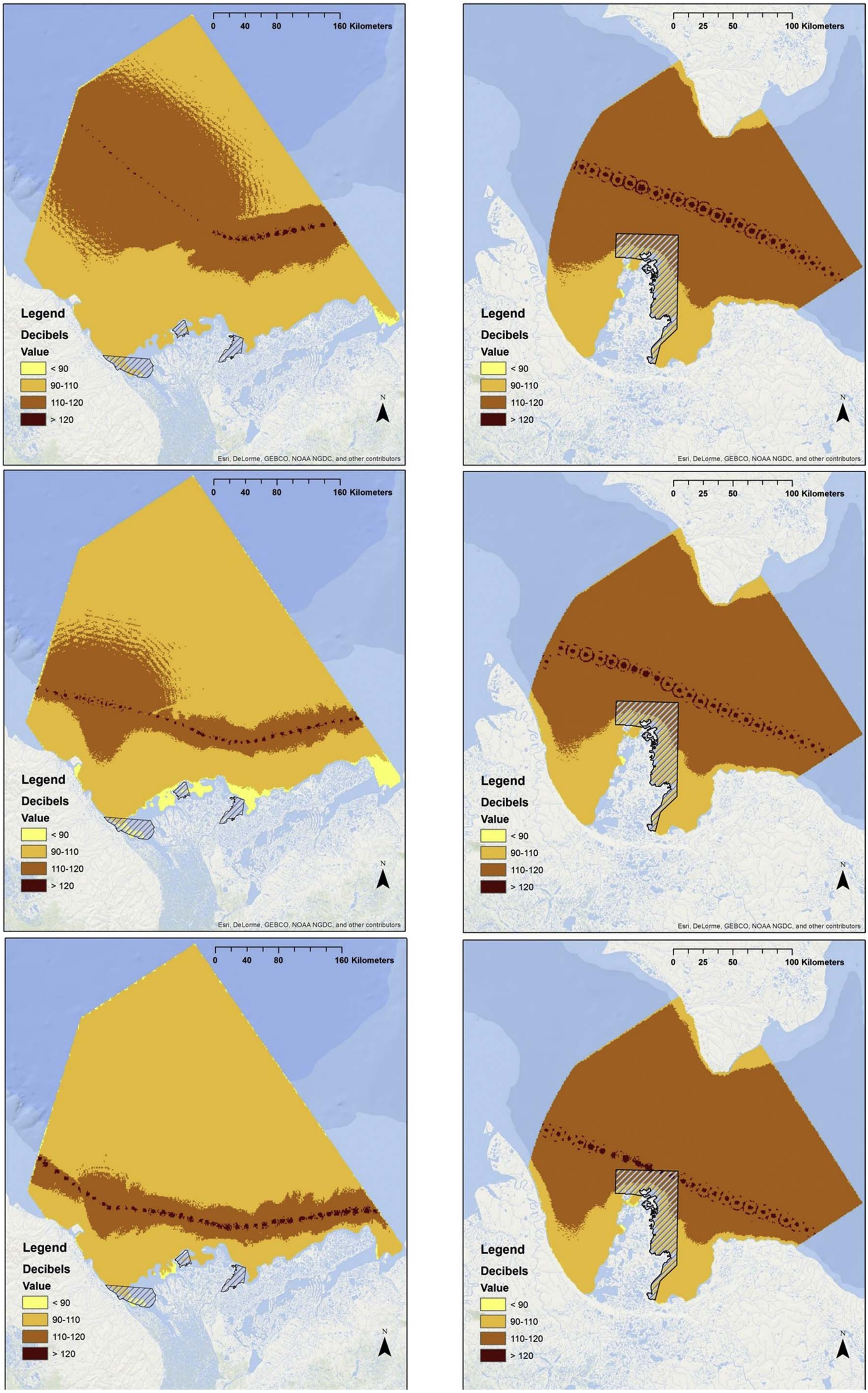

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Fig. 4. Potential acoustic impacts of shipping noise from the CCGS Amundsen (source level = 176 dB re 1 μPa at 1 m) traveling along a proposed shipping corridor through the eastern Beaufort Sea and Amundsen Gulf in front of the Tarium Niryutait Marine Protected Area (A–C) and the Anguniaqvia Niqiqyuam Marine Protected Area (D–F) when ships are traveling along the northern edge (A, D), center (B, E), and southern edge (C, F) of the proposed shipping corridor. Yellow, orange, and brown colours represent the geographic space that was modelled. The darkest colour represents sound levels affecting behaviour of marine mammals (> 120 dB re 1 μPa), dark orange represent sound levels that are audible under winder conditions (wind speed = 50 km/h, SPL > 110 dB re 1 μPa), light orange represents sound levels that are audible under calm conditions (wind speed = 0 km/h, SPL > 90 dB re 1 μPa), and yellow represents sound levels below 90 dB re 1 μPa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

When traveling along the corridor near the ANMPA and the TNMPA, the Amundsen would exceed the behavioural threshold when marine mammals are within 2.0 km of the vessel regardless of where the vessel is within the corridor (Table 2). The Amundsen would exceed the audibility threshold under windy conditions at distances between 16 and 55.0 km for marine mammals towards the mainland, and between 20 and 104 km for marine mammals on the open ocean side of the corridor (Table 2). Audibility thresholds under calm conditions go as far as the shoreline and farther than the space that we modelled out to sea for the Amundsen traveling any part of the corridor near both the ANMPA and TNMPA.

The Awanuia (source level = 184 dB re 1 μPa at 1 m; Fig. 3) traveling along the southern edge of the shipping corridor near the ANMPA would exceed the behavioural disturbance threshold in 382 km^2 (16%) of the MPA, and would be audible under windy conditions in 1349 km^2 (57%) and 2011 km^2 (85%) under calm conditions within the MPA (Table 1, Fig. 5F). Traveling along the center of the corridor near the ANMPA, the Awanuia would exceed the behavioural disturbance threshold in 266 km^2 (11%) of the MPA, and would be audible in 1472 km^2 (62%) under windy conditions, and 2023 km^2 (86%) under calm conditions (Table 1, Fig. 5E). Along the northern edge of the shipping corridor, the Awanuia would exceed the behavioural disturbance threshold in 202 km^2 (9%) of the MPA, and would be audible in 1532 km^2 (65%) under windy conditions, and 2011 km^2 (85%) under calm conditions (Table 1, Fig. 5D). The Awaniua traveling along any part of the shipping corridor near the TNMPA would not exceed the behavioural disturbance threshold in the MPA, nor would it be audible within the MPA under windy conditions; however, it would be audible under calm conditions in 401 km^2 (22%), 251 km^2 (14%), and 378 km^2 (21%) when traveling the southern edge, center, and northern edge, respectively (Table 1, Fig. 5A–C).

The Awanuia traveling along the corridor near both the ANMPA and TNMPA would exceed the behavioural disturbance thresholds at distances between 10 and 41 km for marine mammals towards the mainland, and between 10 and 52 km for marine mammals towards the open ocean (Table 2). The Awanuia would surpass the audibility threshold under windy conditions between 29 and 80 km for marine mammals towards the mainland, and between 72 and 134 km for marine mammals towards the open ocean (Table 2). Audibility thresholds under calm conditions go as far as the shoreline and farther than the space that we modelled out to sea for the Awanuia traveling any part of the corridor near both the ANMPA and TNMPA.

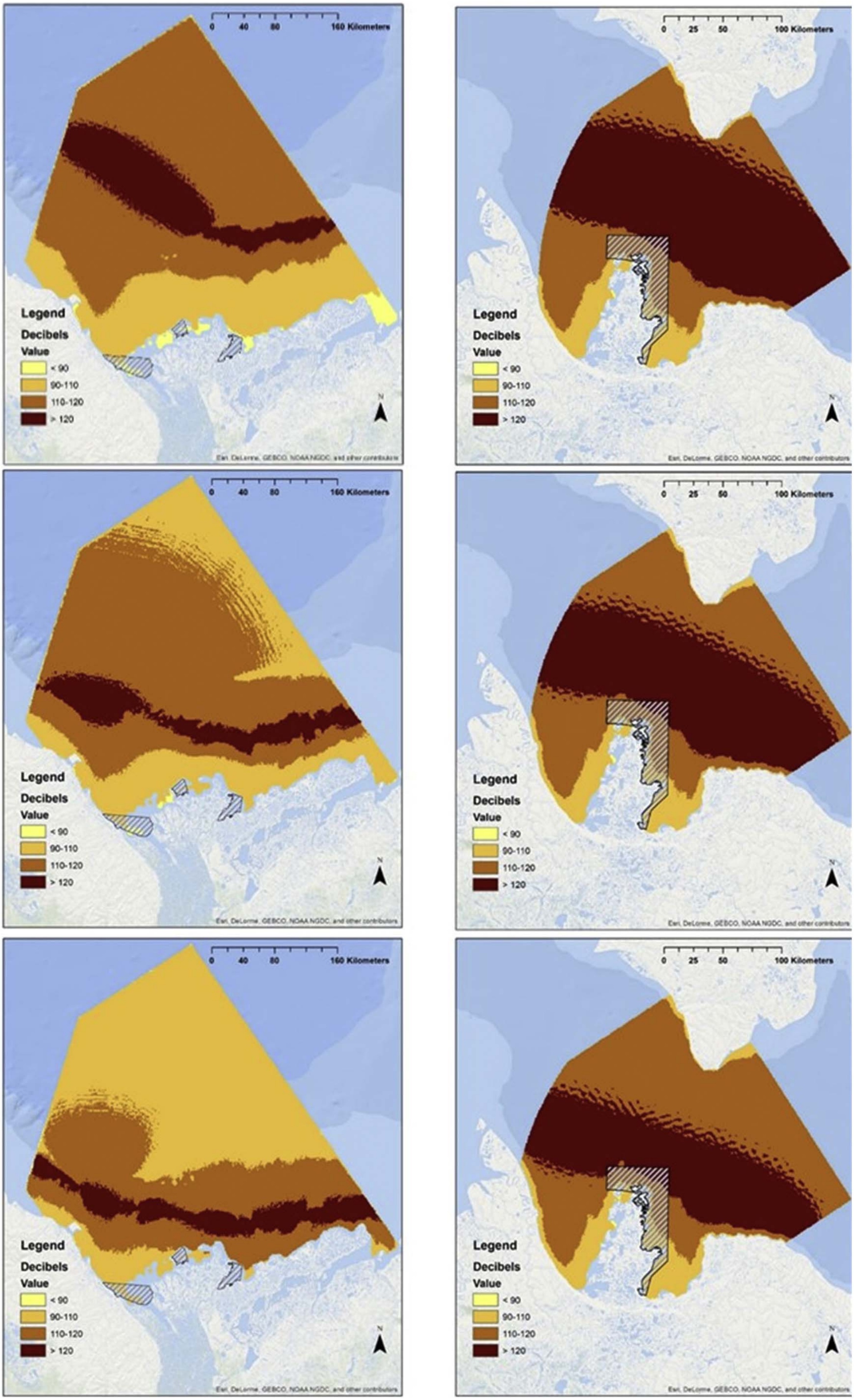
4. Discussion

Our results demonstrated that vessels traveling through the Canadian Arctic may be audible over 100 km from the vessel under quiet conditions, which we documented with two vessels traveling near our site and with the output from our acoustic propagation model. This highlights how quiet the Arctic soundscape is, and also necessitates a warning that any increase in anthropogenic noise, whether via increased shipping or industrial activity, will have large impacts on the Arctic soundscape, with unknown implications for the animals that live there. Our acoustic propagation model predicts that vessels traveling along the proposed shipping corridor can create sound levels exceeding the behavioural disturbance threshold in the ANMPA but not in the TNMPA, and as expected, louder vessels will affect larger areas than quieter vessels. Vessels were predicted to be audible under calm conditions in both MPAs and along the entire shoreline of the mainland, and throughout much of the ANMPA under windy conditions. Vessels traveling along the southern edge of the shipping corridor were predicted to have greater impacts on both MPAs, especially since this route travels through the ANMPA. Shifting vessel traffic towards the northern edge of the shipping corridor might remove the behavioural disturbance from the ANMPA for many vessels like the Amundsen, and might decrease the impact for loud vessels like the Awanuia, decreasing the impacted area from 16% of the ANMPA down to 9% (a reduction of 180 km^2; Table 1).

The autumn migration of both bowhead and beluga whales tends to follow the mainland coast from the Amundsen Gulf towards Alaska (Citta et al., 2015; Fissel et al., 2013; Harwood et al., 2017). Data on migration routes is too coarse to accurately describe overlap between migration and the primary shipping corridor, but the shipping corridor roughly follows the migration route of both species, and ships traveling this route would likely encounter large numbers of both species. The shipping period (currently August through October; Halliday, *personal observation*) also overlaps significantly with the fall migration of whales (Fissel et al., 2013). The primary shipping route also goes through important bowhead feeding areas (Citta et al., 2015; Harwood et al., 2017). Given the wide migration path of both species, it would be difficult for any shipping corridor to entirely avoid the migration, although avoiding known areas of congregation is critical. For these reasons, we recommend that vessels traveling the corridor during the migration should have marine mammal observers onboard and greatly reduce speed when marine mammals, especially bowhead whales, are encountered, as well as avoiding known congregation areas.

Erbe and Farmer (2000) used a similar model to estimate zones of impact for beluga whales around an icebreaker undergoing various icebreaking activities in the Beaufort Sea, but used different criteria than we did to measure disturbance and audibility. In this prior work, the measure of audibility was based on an audiogram for beluga whales rather than ambient noise levels, and behavioural disturbance was based on results from one playback experiment with beluga whales in the Beaufort Sea, which set the behaviour disturbance threshold at 81 dB re 1 μPa at the 5 kHz 1/3 octave band. Their results estimated that belugas would be disturbed by the vessel in this scenario when 35 km away in shallow water or 48 km away when on the surface in deep water, and that the vessel would be audible when 41 km away in shallow water or 54 km in deep water. Our model shows similar trends, although we used vessels with much lower source levels. Propagation towards deep water leads to farther propagation distances than towards shallow water. For example, vessel noise could be audible under windy conditions as much as 134 km from the vessel towards the open ocean, but only as far as 106 km towards the shore (Table 2). However, as predicted by our model, these critical distances are not constant through space (Figs. 4, 5), and are greatly affected by local bathymetry and stratification of the water column. If the shipping corridor is going to take the effects of acoustic propagation into account, then detailed acoustic modelling will need to be performed along the entire shipping corridor.

The source levels that we used in our model are typical for both types of vessels that we modelled, and should therefore be representative of similar vessels traveling through the Arctic. The CCGS Amundsen is a Canadian Coast Guard ice breaker vessel and research vessel, and we recorded its source level at 176 dB re 1 μPa at 1 m, and the Awanuia is a tanker ship with a recorded source level of 184 dB re 1 μPa at 1 m. Veirs et al. (2016) measured source levels on over 2800 ships, and found that the average source level for all vessels was 173 dB



(caption on next page)

Fig. 5. Potential acoustic impacts of shipping noise from the Awanuia (source level = 184 dB re 1 μPa at 1 m) traveling along a proposed shipping corridor through the eastern Beaufort Sea and Amundsen Gulf in front of the Tarium Niryutait Marine Protected Area (A–C) and the Anguniaqvia Niqiqyuam Marine Protected Area (D–F) when ships are traveling along the northern edge (A, D), center (B, E), and southern edge (C, F) of the proposed shipping corridor. Yellow, orange, and brown colours represent the geographic space that was modelled. The darkest colour represents sound levels affecting behaviour of marine mammals (> 120 dB re 1 μPa), dark orange represent sound levels that are audible under winder conditions (wind speed = 50 km/h, SPL > 110 dB re 1 μPa), light orange represents sound levels that are audible under calm conditions (wind speed = 0 km/h, SPL > 90 dB re 1 μPa), and yellow represents sound levels below 90 dB re 1 μPa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

re 1 μPa at 1 m, 174 dB re 1 μPa at 1 m for tankers, and 167 dB re 1 μPa at 1 m for research vessels. Simard et al. (2016) measured source levels from 255 ships, and found the average to be much higher (197 dB re 1 μPa at 1 m). Pine et al. (2016) measured source levels between 159 and 198 dB re 1 μPa at 1 m. The most relevant recorded source levels are those by other studies from the Arctic: Erbe and Farmer (2000) measured an ice breaker ship in the Beaufort Sea with source levels between 192 and 197 dB re 1 μPa at 1 m when it was actively breaking ice; other vessels in the Arctic will likely have similar source levels to those in temperate waters. Overall, the source levels that we measured were much lower than those measured by Erbe and Farmer (2000) and Simard et al. (2016), but were slightly higher than the averages measured by Veirs et al. (2016), and intermediate within those recorded by Pine et al. (2016). With these source levels in mind, we can consider our calculations to be conservative estimates of areas impacted.

While the model that we are using is based on previously published methods that have been tested in the field (Jensen et al., 2011), any model can be considered a representation of the real world, and without testing the model's predictions in the real world, it is impossible to test the accuracy and precision of the model's predictions. Due to the sparse number of ships at our hydrophone deployments, it is not currently possible for us to test the predictions of the model; however, we are in the process of deploying more hydrophones throughout the region, and plan to test the model predictions once we have a larger sample size of ships transiting the shipping corridor. The largest issues with this model are likely the quality of the environmental data (i.e. bathymetry, sediment, and CTD) that we are using to inform the model. Data for CTD and sediment type are especially sparse in the region, and higher resolution data would improve the accuracy of the model predictions.

4.1. Management recommendations

Ship noise is only briefly mentioned in the management plan for the TNMPA (Fisheries and Oceans Canada, 2013), but there is currently no specific policy for reducing the impacts of this noise, and the ANMPA does not currently have a management plan. Our model demonstrates that ship noise from vessels traveling along the primary shipping corridor has the potential to affect the behaviour of marine mammals in the ANMPA, but likely not in the TNMPA. However, vessels can potentially be audible in both MPAs, and this may still cause disturbance to animals in those MPAs (e.g. Erbe and Farmer, 2000; Southall et al., 2007). Management plans for both MPAs should therefore include guidelines for vessels traveling through the MPA that will reduce the impact of vessel noise on marine mammals. Moreover, areas just north and east of the TNMPA (Tuktoyaktuk Peninsula and Cape Bathurst) are important for both bowhead (Citta et al., 2015; Harwood et al., 2017, 2010) and beluga whales (Harwood et al., 1996; Richard et al., 2001), so vessel management reducing impacts in the TNMPA and ANMPA may also benefit whales outside of the MPAs. Vessel management could also focus specifically on important marine mammal areas outside of the MPAs; the corridor currently goes very close to Cape Bathurst, which may be an area of increased risk for bowhead whales. Possibilities include generally reducing vessel speed (Ross, 1976), equipping each vessel with a marine mammal observer, and reducing speed when marine mammals are observed. Vessels that do not need to travel through the MPA should be redirected to a different shipping corridor that is farther away from the mainland. The northern edge of the proposed shipping corridor (central Amundsen Gulf) is at least far enough away from the MPAs so that vessels traveling along this route would not be expected to affect the behaviour of marine mammals in either of the MPAs, or would at least decrease levels in the ANMPA for loud vessels like the Anawuia. Moving the corridor farther north may also reduce impacts for whale core use areas near Cape Bathurst and the Tuktoyaktuk Peninsula because it will also move vessels farther away from those sites.

Any vessel management plan should also take the economic impact for vessels into consideration, because measures that are too costly are more likely to fail. For example, while we think that including marine mammal observers on each vessel is an excellent tool for minimizing ship strikes, it also means that it would be necessary to hire a marine mammal observer for each vessel transiting through the region, which would add a significant cost to operations. Similarly, moving the corridor or imposing speed restrictions will add time to voyages, which will again increase the cost.

5. Conclusion

In conclusion, noise from vessels can propagate long distances in the quiet waters of the Arctic. The shipping corridor through the Canadian Arctic should not simply focus on navigation, but also take ecological considerations into account, including the impacts of noise on areas surrounding the corridor. Future work should continue to monitor the acoustic impacts of shipping in the Arctic, and conduct a detailed analysis of the impacts of shipping along the entire shipping corridor.

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