Assessing vessel slowdown as an option for reducing acoustic masking for marine mammals and fish of the western Canadian Arctic.

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ABSTRACT:

Vessel slow-down may be an alternative mitigation option in regions where re-routing shipping corridors to avoid important marine mammal habitat is not possible. We investigated the potential relief in masking from a 10 knot speed reduction of container and cruise ships. Based on ambient sound measurements and real shipping noise data, the percentage reduction in the available listening space for marine mammals and fish as a container or cruise ship passes under varying speeds and ambient sound conditions was estimated. The mitigation effect from slower vessels, in terms of masking, was not equal between ambient sound conditions, species or vessel-type. At short distances from vessels, the available listening space, relative to ambient noise conditions, was reduced most for bearded and ringed seals, followed by bowhead whales, beluga whales and then Arctic cod. Vessel slowdown through sensitive habitat could be an effective mitigation strategy for reducing the extent of auditory masking.

Key Words: Underwater sound, noise, shipping, marine mammal, fish, listening space, masking.

INTRODUCTION:

The presence of sea ice has effectively preserved the western Canadian Arctic's natural underwater soundscape by making it inaccessible to most commercial shipping. Shipping through the Northwest Passage in the western Canadian Arctic has remained low, although shipping in the Arctic has recently increased(Eguíluz, Fernández-gracia, Irigoien, & Duarte, 2016). Marine life in the western Canadian Arctic has therefore had little exposure to the anthropogenic noise pollution commonly reported at lower latitudes(Ahonen et al., 2017;

Bazile Kinda, Simard, Gervaise, Mars, & Fortier, 2013; Insley, Halliday, & de Jong, 2017; Roth, Hildebrand, Wiggins, & Ross, 2012)). However, the presence of sea ice has been declining (a trend that is expected to continue) and thus the region is becoming more accessible for shipping(Eguíluz et al., 2016; Miller & Ruiz, 2014; Ware, Berge, Jelmert, Olsen, & Alsos, 2016). As a consequence, increased interactions with marine mammals and fish are expected(Laidre et al., 2015; Wilson et al., 2017).

Vessel transits through the Northwest Passage have increased from four per year in the 1980s to 20-30 between 2009 and 2013(NWT, 2015). The vast majority of these transits occurred through the southern routes (11% of all vessel transits being passenger ships; 1% being container ships), with only 8% of the total traffic transiting north of Banks or Victoria Islands(NWT, 2015). Those numbers are likely to increase as the extent of summer sea-ice continues to decrease ((Smith & Stephenson, 2013)). Marine fauna in this region will therefore be exposed to increased vessel traffic noise(Moore et al., 2012). There is a growing concern that increased acoustic masking from these exposures will lead to adverse ecological effects (Erbe, Reichmuth, Cunningham, Lucke, & Dooling, 2016; Slabbekoorn et al., 2010).

Marine mammals and fish use sound for critical life processes. Auditory masking (the interference of a biologically-important signal by an invasive noise source that prevents the receiver from perceiving that signal(Erbe, 2008)) is arguably the most pervasive impact of vessel noise(Erbe et al., 2016). The western Canadian Arctic is important habitat for a number of marine mammal and fish species. Previous research has shown the distribution of marine mammals around the Beaufort Sea to vary and several known core-habitats have been identified(Citta et al., 2015; Harwood et al., 2017; Hauser et al., 2017). Bowhead whales (*Balaena mysticetus*) migrate from the North Pacific and along the Canadian mainland coastline, forming summer core habitat areas in the western Canadian Arctic(Harwood et al., 2017). Summer core habitat areas for beluga whales (*Delphinapterus leucas*) include the Tuktoyaktuk Peninsula, Amundsen Gulf near Ulukhaktok and Viscount-Melville Sound (for males)(Hauser, Laidre, Suydam, & Richard, 2014). While ringed and bearded seals (*Pusa hispida, Erignathus barbatus*, respectively) occur throughout the eastern Beaufort Sea region, ringed seals show high concentrations near the Hamlet of Ulukhaktok(Hartwig, 2009; Harwood, Smith, Melling, Alikamik, & Kingsley, 2014). A range of fish species also occur, including the polar cod (*Arctogadus glacialis*) and Arctic cod (*Boreogadus saida*)(Hartwig, 2009). Audiograms of marine mammals and fish show that hearing ranges overlap with those of vessel noise, making these animals vulnerable to auditory masking. Vocalisations of these species often occur in the same frequency range as vessel noise(Stafford, Castellote, Guerra, & Berchok, 2017; Stanley, Van Parijs, & Hatch, 2017), thereby making them impacted by masking. Vocalisations from bowhead whales vary in complexity and frequency range(Cummings & Holliday, 1987; Stafford et al., 2017; Tervo, Christoffersen, Parks, Møbjerg Kristensen, & Teglberg Madsen, 2011). Their songs (being reproductive advertisement calls) are complex and broadband, ranging between ~30 Hz and 5 kHz, while their vocalisations for group cohesion, socialising and navigating are simpler and below 500 Hz(Stafford et al., 2017). Beluga whale vocalisations are highly variable, with tonal sounds ranging between 400 Hz and 20 kHz and echolocation clicks ranging between 20 and 160 kHz(Stafford et al., 2017). Bearded seals also emit several different call types below 5 kHz, such as trills, moans, ascents and sweeps(Frouin-Mouy, Mouy, Martin, & Hannay, 2016). Ringed seals produce yelps, barks and growls between 50 and 4 kHz(Mizuguchi, Tsunokawa, Kawamoto, & Kohshima, 2016), and arctic cod calls have been described as short (approximately 289 ms) grunts consisting of 6-12 pulses under 250 Hz(Riera, Rountree, Pine, & Juanes, n.d.). Vessel noise is very broadband(McKenna, Ross, Wiggins, & Hildebrand, 2012), ranging in frequencies below 10 Hz to over 60 kHz, depending on the type of vessel. Much of the noise from vessels is below 5 kHz and so overlaps substantially with the primary vocalisations of the marine mammals and fish within the western Canadian Arctic. Since the source levels of large commercial vessels can be high, and because this noise can propagate over large distances, vessel noise can potentially mask vocalisations over large areas.

An effective method for assessing auditory masking in marine mammals and fish is to estimate the change in radius, due to increased anthropogenic masking noise levels, of the volume of ocean centred on a vocalising animal, within which communication with conspecifics is possible (e.g.(Christopher W. Clark et al., 2009; Janik, 2000; Stanley et al., 2017)). This volume of ocean is referred to as the animal's communication space. The sonar equation is used to quantify communication space, but its applicability depends on understanding the receiver's auditory filters and the call structure at its source. Detection thresholds and critical ratios, auditory gain functions and call source levels across multiple spectra – all of which change between species and contexts(Erbe et al., 2016) – are also required inputs for the sonar equation(Christopher W. Clark et al., 2009). Unfortunately, these inputs are often unknown or are highly variable for many species, particularly for mysticete cetaceans. The calculation of communication space is therefore difficult as several assumptions or approximations are often required.

An alternative approach is to consider masking from the perspective of the listener. Increased masking noise, such as due to a passing vessel, will reduce the volume of ocean within which the listener can detect biologically-important sounds(Barber, Crooks, & Fristrup, 2010; Matthews, Schlesinger, & Hannay, 2016). This volume is referred to as the listening space. Marine mammals and fish listen for changes in background sounds to detect approaching predators/danger, to find prey and to locate mates for breeding(Au & Hastings, 2008; Bradbury & Vehrencamp, 2000; C.W. Clark, 1990). For example, mysticetes, including bowhead whales, sing to attract mates(Payne & McVay, 1971; Tervo et al., 2011), odontocete cetaceans vocalise to maintain group cohesion, socialise, find prey and to solicit aid when in danger(Castellote et al., 2014), and fish vocalise during spawning(Slabbekoorn et al., 2010). Changes to the size of the listening space, due to a passing vessel can be calculated without knowledge of several of the parameters required to calculate communication space. The relative amount of listening space reduction requires knowledge of the frequency-dependent propagation loss of the call, the change in masking noise levels and the species' audiogram(Barber et al., 2010; Matthews et al., 2016). Thus, this method can serve as a potentially efficient technique that can either replace (when species-specific data are unknown) or supplement generalised communication space assessments(Matthews et al., 2016).

The issue of masking has been widely discussed and recognised, with the International Maritime Organisation (IMO) adopting guidelines to reduce underwater noise from commercial ships(IMO, 2014) and the marine industry trialling mitigation strategies to reduce noise effects on sensitive marine life(Chion et al., 2017; Constantine et al., 2015; POAL, 2015; POV, 2017). Management of marine shipping has been discussed in an Arctic context by the Arctic Council(ArcticCouncil, 2015), with modification of vessel operations through areas of high marine mammal densities and vessel slowdowns being suggested as possible measures to mitigate vessel noise effects(ArcticCouncil, 2015; Chion et al., 2017; Huntington et al., 2015). Vessel slowdown is becoming increasingly attractive in areas where re-routing shipping corridors is not possible, particularly as it can also reduce the risk of ship strike(Chion et al., 2017; Constantine et al., 2015). Furthermore, slowing vessels reduces emitted noise levels and consequently decreases masking for marine mammals and fish(Putland, Merchant, Farcas, & Radford, 2017). These management strategies will become more important over the next 30 years as the number of vessels, particularly container vessels and cruise ships, transiting the Northwest Passage increases. It is important to understand the effectiveness of slowing vessels for reducing masking. We investigated the potential relief in masking from a 10 knot speed reduction for container and cruise ships (given their expected increases in the Northwest Passage in future years), under varying ambient sound conditions. The potential benefit of vessel slowdown within the western Canadian Arctic is demonstrated and quantified by assessing the percentage change in listening space of marine mammals and fish by slowing container and cruise ships by 10 knots from their normal operating speeds.

METHODS AND MATERIALS:

Study Areas

Noise levels produced by container and cruise ships were predicted for an unmitigated (baseline) speed of 25 knots and a mitigated speed of 15 knots. The ships were simulated passing through four sub-areas of the western Canadian Arctic (together referred to as the study region) via the Northwest Passage (**Figure 1**). The sub-areas (referred to as the Mainland, Ulukhuktok (Ulu), Prince of Wales Strait (PWS), and Viscount-Melville Sound (VMS)) were selected based on current knowledge of core-use areas for bowhead whales and beluga whales and known aggregation areas for bearded and ringed seals(Citta et al., 2015; Harwood et al., 2017; Hauser et al., 2014). Fish species were assumed to occur at all sites, although no information on their distributions was found. The use of multiple sub-sites, with differing bathymetries, sound speed profiles and seafloor compositions, helped demonstrate differences in masking effects due to these parameters. Currently, container and cruise ships make up very few vessel transits through the Amundsen Gulf(NWT, 2015), with no vessels travelling through the PWS or VMS sites (those two sites were selected to investigate a future marine traffic route, and to provide region-wide estimates of masking impact in marine mammals and fish).

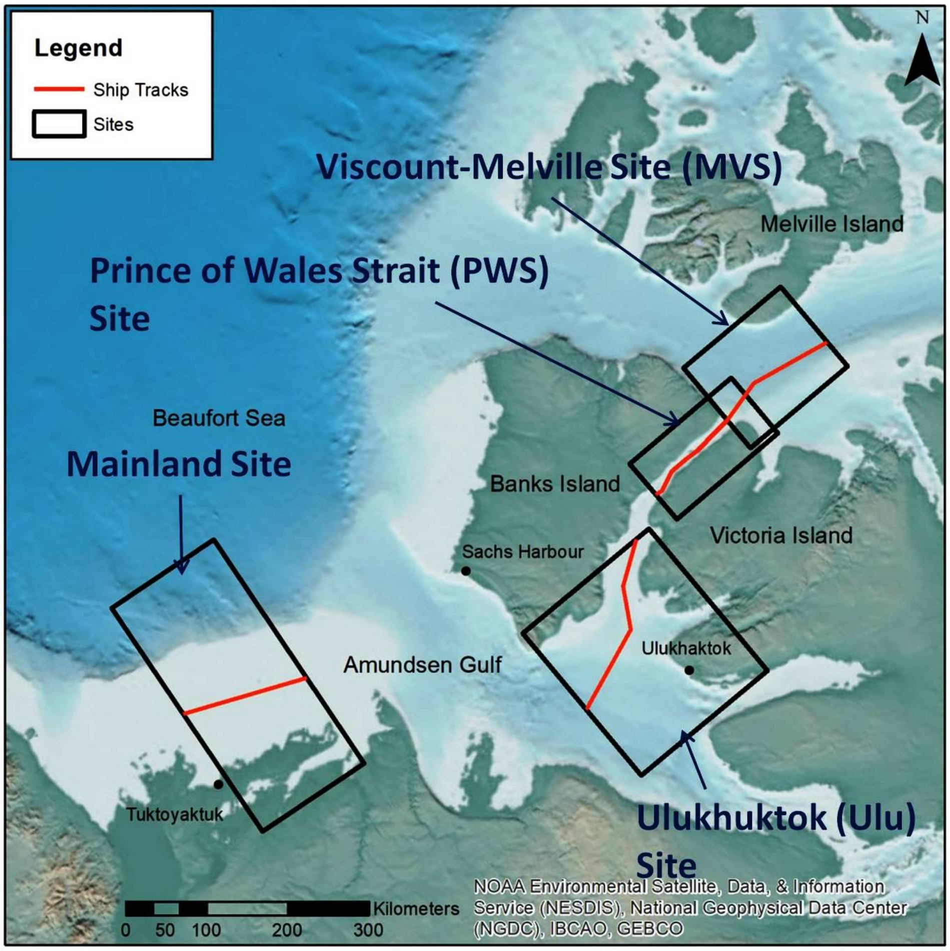

Figure 1: Map of the study region with black rectangles outlining each sub-area. The red lines represent the simulated vessel sail tracks through each sub-area.

Vessel Source Levels

The vessel source levels, in 1/3-octave bands from 10 Hz to 32 kHz, used herein were the averages of measurements of 384 container ships between 184 m and 339 m (average length 265 m, average speed 18.12 knots) and 25 cruise ships between 105 m and 294 m (average length 247 m, average speed 16.36 knots) obtained through the Ports of Vancouver's ECHO (Enhancing Cetacean Habitat through Observation) program's underwater listening station (**Figure 2**). The station is operated by JASCO Applied Science and Ocean Networks Canada. Aside from vessel source levels being measured as monopole source levels (as opposed to radiated noise levels), measurements were undertaken in approximate conformance with ASA S12.69 (2009) Grade-C.

Speed dependence of source levels was assumed to vary as the logarithm of the ratio of vessel speed to a reference speed, as shown in Eq. 1 (Ross, 1987). The logarithmic slope coefficients, Cv, were obtained from the ECHO program measurements (POV, 2017) for container and cruise ships.

$$SL_{x_{knots}} = vSL + C_v \, 10 \, Log\left(\frac{v_1}{v_0}\right) \qquad \text{eq.1}$$

where $SL_{x_{knots}}$ is the third octave source level for the given vessel type underway at *x* knots, C_v is the measured speed slope coefficient for that vessel type (set at 3.16 or 4.94 for container or cruise ships, respectively), v_1 is the speed of the vessel for which $SL_{x_{knots}}$ will represent, and v_0 is the reference speed through water of the vessels from which source level measurements were made(Ross, 1987).

Calculating Reductions in the Available Listening Space

The potential relief in masking from a 10 knot speed reduction in container and cruise ships was assessed by calculating the listening space reduction (*LSR*) for each species due to reduced masking noise from slowing the vessels(Hannay, Matthews, & Schlesinger, 2016; Matthews et al., 2016). The percentage reductions in the available listening space were calculated using the equations presented by Hannay et al. (2016)(Hannay et al., 2016) and Matthews et al. (2016)(Matthews et al., 2016). Under natural ambient sound conditions, there will be a maximum listening range (R_1), representing the distance from a source to a listener, within which the source's sound can be detected. As a vessel passes at some distance from the listener, noise from the vessel will increase that background noise, thus increasing masking and reducing R_1. A new (smaller) maximum listening range (R_2) will depend on the level of the increased masking noise level (**Figure 3**). The ratio of listening distances is referred to as the distance factor, i.e. [R_2/R_1](Barber et al., 2010).

The distance factor depends on the slope of propagation loss (PL) with logarithm of distance, R, of the source from the listener within some frequency band, i.e.:

$$PL = N \, Log_{10}(R); \qquad \text{eq. 2}$$

The *PL* slope coefficient, *N*, was calculated by curve-fitting the modelled *PL* of each third octave centre frequency (F_c) between 60 Hz and 32 kHz (using either the fully range-dependent parabolic equation (RAMGeo (for frequencies below 1.2 kHz)) or ray/Gaussian beam tracing (Bellhop (for frequencies above 1.2 kHz)), in Curtin University's AcTUP v2.2L platform (see Wang et al. (2014)(Wang et al., 2014) for a review of these models) from the receiver's location. Bathymetry for the study region was sourced from the International Bathymetric Chart of the Arctic Ocean (3rd Edition) with 500m resolution(Jakobsson et al., 2012). Sediment properties were obtained from Natural Resources Canada (http://ed.gdr.nrcan.gc.ca/index_e.php). The sound speed profiles were calculated from conductivity, temperature and depth (CTD) data collected during Arctic Net Cruise 1103 (available from the Polar Data Catalogue: www.polardata.ca).

The fit coefficient for *N* was made at a distance from the receiver based on an estimate of R_1, because this slope can have some range dependence. The range dependence, however, is generally quite small, so the error is relatively insensitive to our estimate of R_1. For each F_c, R_1 was estimated for each study site using a simplified sonar equation following Clark et al. 2009(Christopher W. Clark et al., 2009)**,** but excluding signal gain:

$$SE = SL - PL - NL_1 - DT \qquad \text{eq. 4}$$

where signal excess (*SE*) is set to zero to indicate detection onset, NL_1 is the ambient noise level based on the 5th percentile level of measurements made nearby ((Insley et al., 2017)) and *DT* is a detection threshold (conservatively set at 10 dB for marine mammals(Christopher W. Clark et al., 2009; Kastelein, van Heerden, Gransier, & Hoek, 2013; Putland et al., 2017) and 15 dB for cod(Stanley et al., 2017)).

As the vessel approaches the listener, masking noise levels will increase. The masking noise level caused by the vessel, NL_2, for a particular vessel location can be calculated from the vessel's source level at its transiting speed and the propagation loss from the ship position to the listener position:

$$NL_2 = SL_{xknots} - PL_v \qquad \text{eq. 5}$$

where PL_v is the modelled propagation loss of vessel noise in a 1/3 octave band (using the same RAMGeo/Bellhop implementation as for N, for 72 radials). The increase in masking noise reduces R_2 (**Figure** 3). Since the fitted PL slope for the call is constant, the difference between NL_1 and NL_2 is related to the distance factor [R_2/R_1] according to:

$$NL_2 - NL_1 = -N\, Log\left(\frac{R_2}{R_1}\right) \quad \text{eq. 6}$$

As water depths over the study area are expected to be substantially less than the initial detection distances, the listening space is nearly disk-shaped (the top and bottom being the sea surface and sea floor) and its volume therefore approximately proportional to the detection distance squared. The fraction of listening space available after an increase in masking noise in this case is therefore proportional to the square of the distance factor. The Listening Space Reduction (*LSR*) is the fractional decrease in the listening space, in shallow waters given by:

$$100(1 - \left(\frac{R_2}{R_1}\right)^2).$$

It can be expressed as:

$$LSR = 100(1 - \left(\frac{R_2}{R_1}\right)^2) = 100(1 - 10^{2\frac{NL\,2 - NL\,1}{N}});$$

$$\therefore LSR = 100(1 - 10^{-2\frac{\Delta}{N}}) \quad \text{eq. 7}$$

where Δ is the difference between NL_2 and NL_1. The result of equation 7 is quite stable since it does not require knowledge of the prey/caller's source level or the receiver's detection threshold (two parameters that have high variability and uncertainty between species). Since NL_1 is the perceived base ambient noise level, it is the maximum of the receiver's hearing threshold (audiogram value) and the ambient level inside a critical bandwidth(Erbe et al., 2016). For this study, the critical bandwidths were approximated by 1/3 octave bands for marine mammals(Erbe et al., 2016) and a 1/1 octave band for cod(Putland et al., 2017; Stanley et al., 2017). While critical bandwidths have been studied in bottlenose dolphins, northern elephant seals, California sea lions and harbour seals(Erbe et al., 2016), no information exists for species considered in this study. The results are likely insensitive to the estimate of critical bandwidth, because the bandwidths of calls and masking noise are generally wider than the critical bandwidth; thus using a wider band increases the level of both the call and masking noise, keeping signal to noise ratio constant. Audiograms for beluga whales(Castellote et al., 2014; Erbe et al., 2016) and ringed seals(Sills, Southall, & Reichmuth, 2015) were used to estimate hearing thresholds in each critical band. There are no audiograms available for the Arctic or polar cod, bearded seals or bowhead whale. Consequently, an Atlantic cod (*Gadus morhua*) audiogram(Nedwell, Edwards, Turnpenny, & Gordon, 2004) and modelled audiograms for the bearded seal(Li, MacGillivray, & Wladichuk, 2011) and fin whale(Cranford & Krysl, 2015) were used herein. The analysis considered ambient levels at the 5th, 50th and 95th percentile (referred to as quiet, median and noisy conditions, respectively) obtained from measurements made August – September 2015 near Sachs Harbour (see Insley et al. (2017) (Insley et al., 2017)). This time period is representative of most ship traffic in the region. The ambient sound levels between 50 Hz and 24 kHz were recorded from a bottom-mounted SM3M autonomous acoustic recorder at an approximate depth of 23.5m(Insley et al., 2017).

Since vessels and listeners are continually moving with respect to each other, Δ will be highly variable. If we assume the receiver is stationary, Δ will gradually increase as the vessel approaches to its closest point of approach (CPA), or the listener approaches the vessel's sail track, after which Δ will decrease back to 0. Area-wide vessel noise footprints were modelled for vessel positions 2 km along sail tracks defined in the centre of prospective sail corridors. These results were translated in smaller steps between modelled locations to obtain vessel noise estimates on a finer resolution. The vessel movement step size was 200 m. The *LSR* values at all possible fixed listener positions on a 119 m grid were calculated for each 1/3 or 1/1 octave band for each vessel position along its sail track. The modelled depth resolution was 10 m (referred to as depth-step), and *LSR* was calculated at each depth-step from surface to seafloor. A maximum *LSR* for each location, in each frequency band, was obtained from the maximum value over depth from the surface to 10 m above the seafloor. These results were used to generate 2D spatial maps. Finally, a broadband *LSR* map was obtained by averaging the single band maximum *LSR* values from F_c 63 Hz to 30 kHz. For each sub-area that could be used to represent each receiver, the 2D spatial maps for each 1/3 or 1/1 octave band were overlaid, forming a 3D matrix, and averaged through the third dimension to provide an overall average for each sub-area. To show the effects of vessel-slow down on mitigating the *LSR*, horizontal transects through the vessel's sail track, that started and ended 40 km either side of the sail track (thus 80km long), were made (at the Ulu site, being representative of the study region) and the corresponding *LSR* values were calculated for each vessel speed.

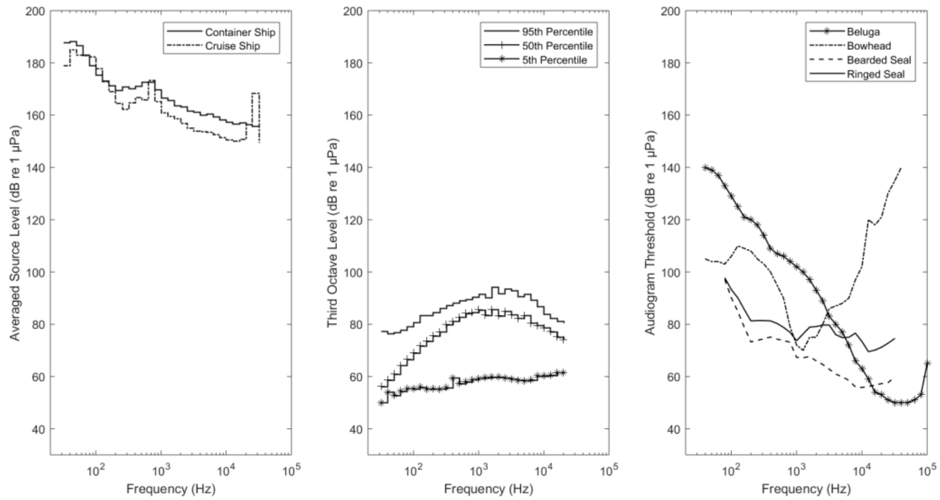

Figure 2: Third octave band source levels (dB re 1 μPa @ 1 m) of the container and cruise ships, measured ambient sound levels (dB re 1 μPa) and audiogram values (dB re 1 μPa) for marine mammals investigated in this study.

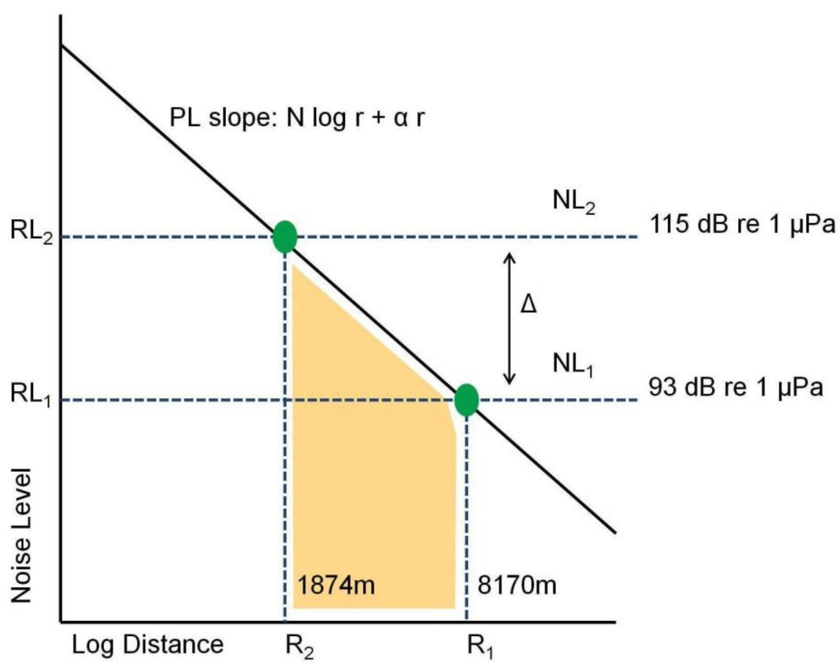

Figure 3: Schematic plot showing the relationship between rising noise levels (NL_1 and NL_2) from a passing vessel and the decreasing distance (R_x) over which a hypothetical call (received levels, RL) can be detected.

RESULTS:

Effects of Vessel Noise on LSRs

The effects of shipping noise on the available listening space varied between locations, the listener species, vessel type and speed, and ambient noise conditions. The *LSR* values for all species showed considerable spatial variation, within each of the study sub-areas due to differing sound propagation conditions (**Figures 4, 5**). The greatest impact occurred for phocid listeners, with maximum averaged *LSR*s near the sail track exceeding 90 % for both bearded and ringed seals, compared to approximately 76 and 83% for bowhead and beluga whales, respectively (**Figure 4**). It is important to note that these percentages are the averaged *LSR* over all frequencies, and therefore poorer hearing sensitivities in some frequencies can pull-down the overall average. The distances from the vessel sail track at which 10 % *LSR* occurred differed between species. For example, the greatest range at which listening space was reduced by at least 10 % was 102 km for bearded seals and 95 km for ringed seals under quiet noise conditions. These maximum distances both occurred at the Ulu sub-area (**Figure 4**) and Mainland sub-area. A 90 % *LSR* was predicted for both bearded and ringed seals approximately 2 km from the sail track (**Figure 4**). The *LSRs* of beluga and bowhead whales were greatest at the VMS sub-area, the PWS sub-area (between Victoria and Banks Islands), and off the mainland coast (Mainland sub-area), where relatively consistent depth trend variations favoured better vessel noise propagation (**Figure 5**). The narrow Prince of Wales Strait (the PWS sub-area) restricts the maximum distance animals can be away from the sail track line to approximately 7-10km. The *LSR*s near the shorelines of the Strait, at Banks and Victoria Islands, were between approximately 25 and 30% (**Figure 5**). In general, the distance off the sail track at which *LSR* decreased to 0 was shortest for beluga whales, followed by bowhead whales, cod, ringed seals, and then bearded seals. These differences were due to different hearing sensitivities of these species to vessel noise (see **Figure 2**).

Effects of 10 knot speed reduction on LSRs

This investigation showed that vessel noise produced masking effects that extend several kilometres off the vessel sail track, as indicated by *LSR*, and that reducing vessel speed from 25 knots to 15 knots could substantially reduce the *LSR* for all species assessed herein (**Figure 6**). For example, under quiet conditions, *LSR* for beluga whales is halved (*LSR* =

50%) at 7-14 km off the vessel track when ships were sailing at 25 knots, but only 2-4 km off the sail track when these vessels were slowed to 15 knots (**Figure 6**). Under quiet noise conditions, a speed reduction from 25 to 15 knots resulted in smaller *LSR*s by 16-23 %, 10-18%, 1-2%, 5-8% and 8% respectively for belugas, bowheads, bearded seals, ringed seals, and cod, depending on vessel-type (**Figure 6**). Under noisy conditions, *LSR*s for listeners on the sail track were 25-43%, 15-27%, 16-33%, 24-33%, and 2-8% smaller for belugas, bowheads, bearded seals, ringed seals, and cod, respectively, following a 10 knot speed reduction, depending on vessel-type. Therefore, the mitigation effectiveness of a 10 knot speed reduction on the *LSR*s at short distances from the vessel's sail track was greater under noisy conditions than under quiet conditions. The mitigation effect of a 10 knot speed reduction on *LSR* was also similar for both container and cruise ships.

Influence of Ambient Sound Levels on LSRs

Ambient sound conditions had less influence on *LSR* for bowheads than for the other mammal species considered in this study, and zero influence on the *LSR* for cod. This result is due to Arctic noise levels being below or close to the audible thresholds of bowheads and cod in many, or all, frequency bands. Ambient sound levels had noticeable influence on *LSR*s of the other species, with differences noted between the two vessel types (**Figure 7**). Generally, ambient sound levels had less effect on the *LSR* close to the vessel sail track than further away. This is due to higher Δ values occurring near the sail tracks – the change in Δ (due to differences in ambient sound levels) produces a smaller change in *LSR* when Δ is large (near the sail track) than when Δ is small (away from the sail track) (**Figure 8**). For example, the differences between *LSR* values for noisy and quiet conditions at the container vessel's sail track were below 10 % for beluga and bowhead whales and bearded seals, but as much as 40 % at 20 km from the sail track for bearded seals. No corresponding difference was predicted for cod, due to their hearing thresholds being above the highest ambient sound levels below 1 kHz. Distances from the sail track of both vessel types, at which available listening spaces were reduced by 50%, were considerably shorter under noisy conditions than quiet conditions (**Figure 7**).

While the extent of masking as quantified by *LSR*s was similar for the two vessel types, distances at which listening spaces were reduced by 50% were typically smaller for cruise ships than container ships. That difference was due to container ships having higher source levels than cruise ships in most frequency bands (see **Figure 2**).

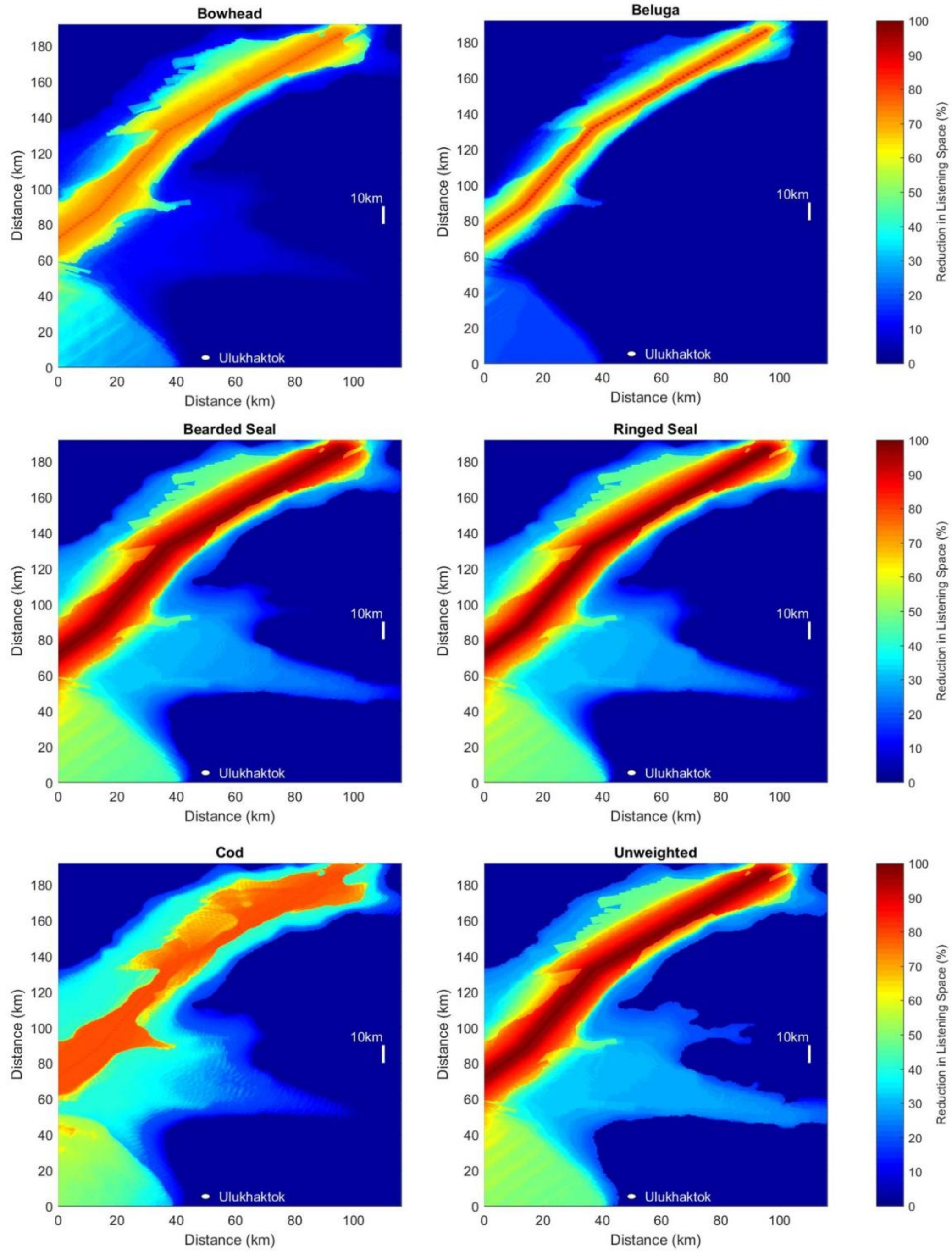

Figure 4: Plots showing the spatial extent of LSRs from a container vessel underway at 25 knots under median noise conditions through the Ulu sub-area for each listener species, and for when no audiogram filter was applied (unweighted). Differences between these plots are due to the different hearing sensitivities of each species.

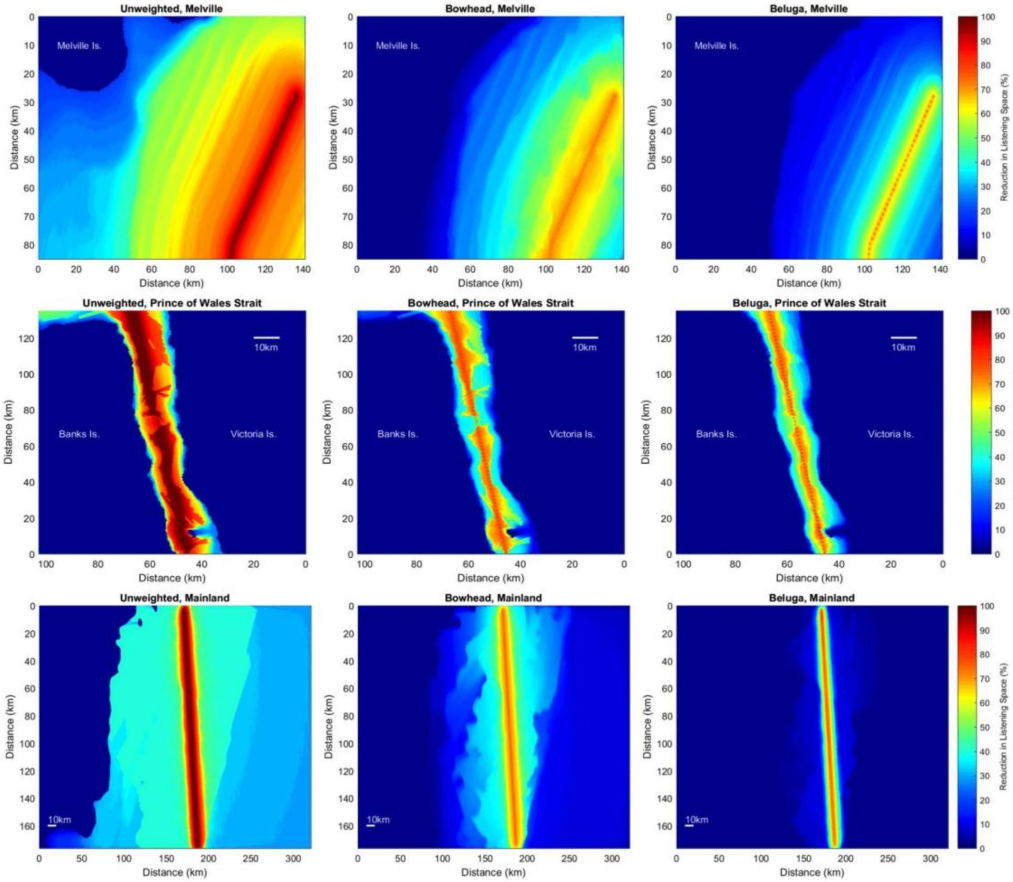

Figure 5: Plots showing the spatial extent of LSRs from a container vessel underway at 25 knots through the VMS, PWS and Mainland sub-areas. The left column represents the modelled unweighted LSRs (i.e. no auditory filter applied), while the middle and right columns represent the modelled LSRs for a bowhead and beluga whale listener, respectively.

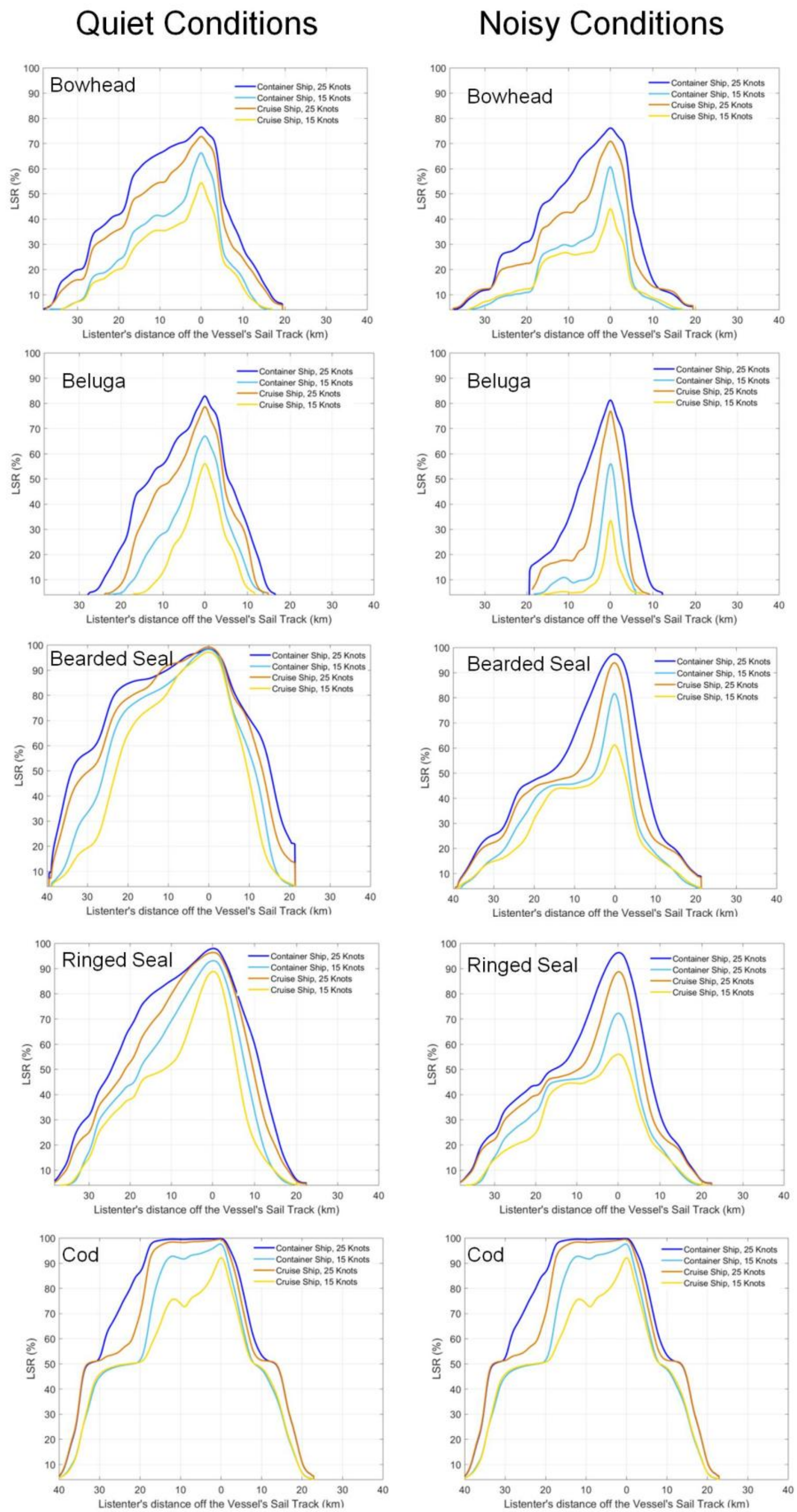

Figure 6: Plots showing the modelled LSR (%) from a representative container and cruise ship underway at 15 and 25 knots under quiet and noisy noise conditions (represented by the 5th and 95th percentile noise levels) as a function of distance from the vessel's sail track (km).

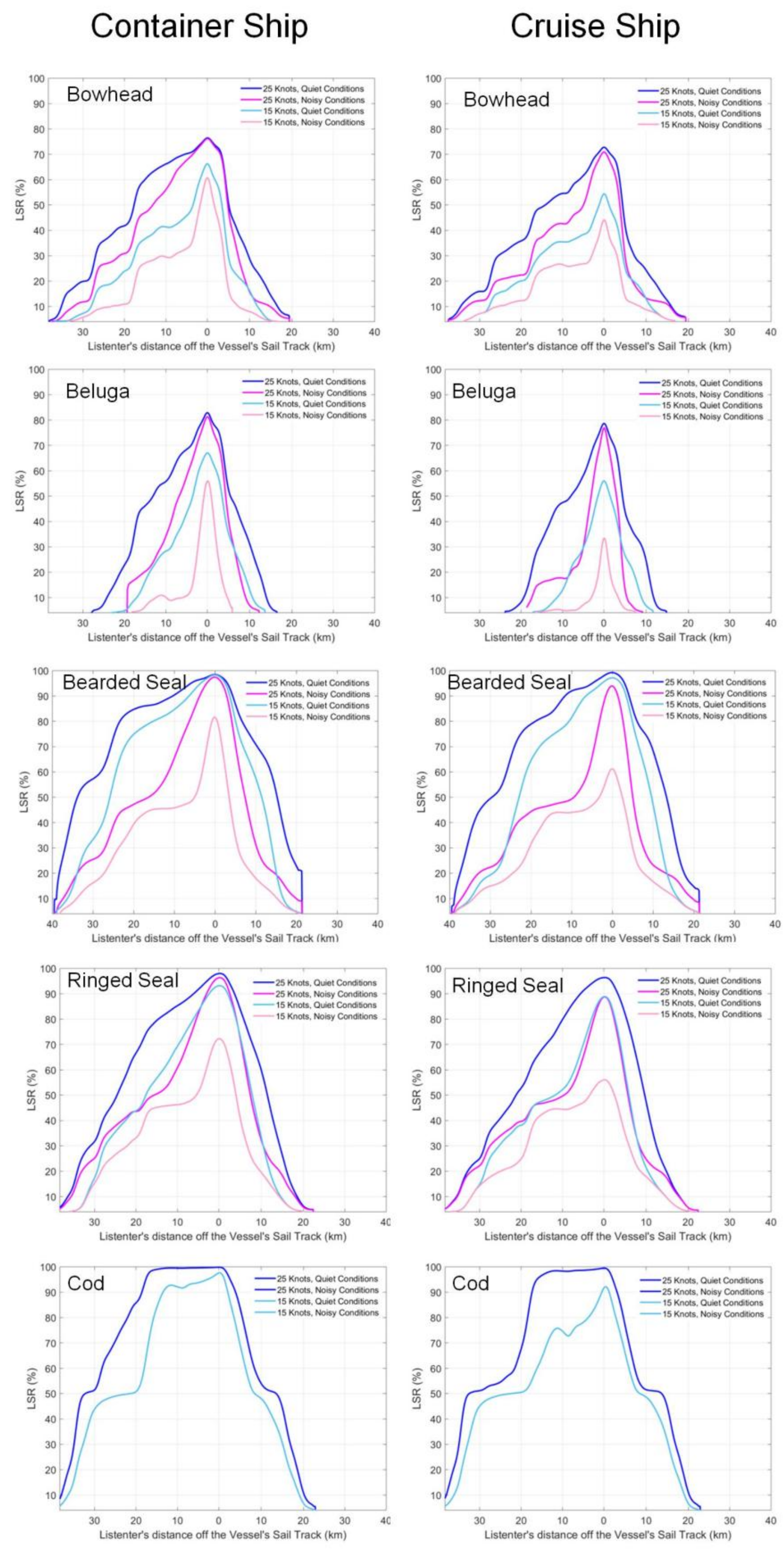

Figure 7: Plots showing the modelled LSR (%) from a representative container and cruise ship underway at 15 and 25 knots under quiet and noisy noise conditions (represented by the 5th and 95th percentile noise levels) as a function of distance from the vessel's sail track (km).

DISCUSSION:

Increased shipping in the Arctic due to lower seasonal ice presence could lead to adverse acoustic masking effects on marine fauna near shipping lanes, in an environment that has historically been very quiet. Mitigation strategies such as slowing down vessels should be considered to reduce the masking effects of this future increased shipping.

This study applied a relatively new approach to quantify the potential relief in masking from slowing container and cruise ships. The *LSR* method applied here does not calculate exact detection distances for biologically-important sounds but rather the fractional (percentage) change in the available listening space of animals. Its interpretation in terms of absolute biological relevance is not as direct as the active communication space analysis method, but it is applicable to all types of biologically-important sounds, it is less variable, and it can be computed with higher confidence. Its greater stability arises because it does not rely on parameters such as acoustic detection threshold and the source level of the important sound. The listening space assessment is also relevant to particle motion masking effects, assuming particle motion decays similarly to acoustic pressure with distance from the sound source. The results indicate that vessel noise reduces the available listening space of animals located up to tens of kilometres away from the vessels' sail tracks. From a management perspective, a crucial first step to assessing masking effects is to quantify the geographic area over which the effects could occur. The next step is to evaluate the effectiveness of approaches that reduce masking and the areas over which these benefits occur. The extent of acoustic masking caused by vessels is dependent on their noise emissions, the source levels of biologically important sound sources such as prey or calling conspecifics, the rate of propagation loss in the ocean, and the absolute hearing sensitivity of the listener as a function of sound frequency. Frequency-dependent hearing thresholds have been measured in some phocids, odontocetes and fish species(Erbe et al., 2016; Nedwell et al., 2004), but no measurements are available for mysticetes, such as bowhead whales (since none are kept in captivity, therefore preventing hearing tests from being performed). Bearded and ringed seal hearing studies indicate they have better hearing sensitivity than mysticetes below 500 Hz. They have similar sensitivity from about 1-3 kHz, above which the mysticetes appear to again be less sensitive. Beluga hearing sensitivity is much lower than the seals and mysticetes below about 3 kHz, but their sensitivity increases rapidly with frequency, reaching maximum sensitivity between 30 and 50 kHz (**Figure 2**). Since vessel noise is largely low-mid frequency, seal listeners experience the higher averaged *LSR*s at the vessel's sail track (and over several kilometers) compared to bowhead and beluga whales that are respectively most sensitive to vessels' mid- and high-frequency noise. When we examine masking across frequency bands, beluga whales experience greater *LSR*s in the high frequency bands (**Figure 9**). The effect of masking on belugas therefore depends on the frequency content of the biologically important signal. For example, conspecific communication (such as whistles) in belugas occurs at higher frequencies where more masking is expected than when eavesdropping on calls of their prey (such as low frequency calls from cod(Riera et al., n.d.)) which occur below 1 kHz. Therefore, the degree of masking impact that vessel noise will have on listeners can be dependent on the behavioural context of the animal.

Our modeling study shows that reduction in the listening space caused by vessel noise masking is substantial and varies between species. The model also shows that the degree of possible masking relief from a 10 knot reduction in speed varies between vessel type and species. Phocid and fish receivers were predicted to experience the largest *LSR* due to vessel noise, but a 10 knot speed reduction from 25 knots to 15 knots under quiet conditions produced little relief in masking (a difference of only 1-8 % in *LSR* between the two speeds for bearded seal listeners near the sail track). However, under noisy conditions, the differences in *LSR*s between speeds for both vessel types were much greater (a difference of 16-33 % *LSR* near the vessel sail track). Higher masking relief under noisy conditions was also found for the cetacean listeners but the difference in masking relief between noisy and quiet conditions was not as pronounced as for the seals. This is a good example of how the *LSR* model's assumptions on ambient noise conditions and species audiograms can affect masking assessment results. In this case, the *LSR* differences between noise conditions occur because the phocid audiograms lie between the 5th percentile (quiet conditions) and the 95th percentile (noisy conditions) sound levels above 160 Hz. Therefore, Δ (being the key variable in determining *LSR*) is more influenced by change in ambient sound conditions compared to the cetacean listeners. To better explain this, **Box 1** illustrates how the Δ values are closely linked to the species' hearing thresholds (i.e. the audiogram) and ambient sound levels.

Like marine mammals, fish also rely on underwater sound for critical life processes, particularly for predator avoidance and reproduction(Slabbekoorn et al., 2010). For this study, the influence of vessel noise on the *LSR* in cod used the Atlantic cod audiogram because no hearing threshold data are available for the Arctic or polar cod. The *LSR* calculation for cod was based on 1/1 octave band levels and examined only for frequencies below 1 kHz. As such, the shape of the *LSR* curves for cod (in **Figures 6 and 7**) are different than those for marine mammals. The *LSR* for cod peaked at 100 % at the vessel's sail track, the highest of all the species considered in this study, regardless of vessel type and ambient sound conditions. There was no difference in the *LSR* curves between the two ambient sound conditions because the assumed cod hearing thresholds were above the nosiest ambient sound levels. While the speed reduction in container vessels levied some relief in terms of masking (a difference of only 2 % between the two speeds at the vessel's sail track), it showed more relief for cruise ship noise (a difference of 8 % between the two speeds at the vessel's sail track). However, substantial differences occurred only within 20 km from the vessel's sail track, beyond which the degree of masking relief from of speed reduction for both vessel types was effectively nil. Despite the speed reduction in cruise ships, *LSR*s greater than 10 % were still seen within 37 km from the vessel's sail track and *LSR* was over 90 % within 2 km – meaning that substantial reduction in cod's ability to detect predators could occur over large areas. Vessel noise has been shown to inhibit predator-avoidance behaviours in fish, leading to increased predation rates(Ferrari et al., 2018; Simpson et al., 2016; Simpson, Purser, & Radford, 2015; Spiga, Aldred, & Caldwell, 2017). Furthermore, vessel noise can mask signals and reduce the communication space of several fish species(Codarin, Wysocki, Ladich, & Picciulin, 2009; de Jong, Amorim, Fonseca, Fox, & Heubel, 2017; Putland et al., 2017; Slabbekoorn et al., 2010; Vasconcelos, Amorim, & Ladich, 2007), including the Atlantic cod(Stanley et al., 2017). Reduced communication space may lead to disrupted spawning and reproductive success(Stanley et al., 2017). Spawning behaviours and mating calls in Arctic cod are unknown; however, given their phylogeny and comparable call types to Atlantic cod, they may produce sound as an attraction call during spawning. Atlantic cod females do not remain in close contact with the males during spawning, but rather move between locations(Nordeide & Folstad, 2000). Therefore, being able to detect a male's call is critical. Even a small reduction in the cod's listening space will increase the chances of a female not detecting a male's advertisement call, especially since their source levels are low(Stanley et al., 2017). However, before conclusions on the ecological significance associated with any *LSR* for Arctic or polar cod can be made, understanding the mating behaviours of either cod species is needed, as well as their sound production and their seasonal variation.

Ambient sound levels used in this study were obtained from measurements near Sachs Harbour(Insley et al., 2017) and these were assumed to be representative of ambient sound levels throughout the study region. Ambient soundscapes during the Arctic summer can be highly variable, both spatially and temporally(Insley et al., 2017; Ozanich, Gerstoft, Worcester, Dzieciuch, & Thode, 2017). The Arctic's biophony (the biological component of an underwater soundscape) within core use habitats for marine mammals can dominate the soundscape over several weeks, particularly in frequencies that overlap vessel noise(Stafford et al., 2017). For example, the soundscape off Sachs Harbour can sometimes include continuous calls from bearded seals that control the 5^{th} percentile ambient sound level below 6kHz within that area(William D Halliday, Insley, Jong, & Mouy, 2017). Consequently, ambient levels could vary enough spatially to influence the Δ values in the *LSR* calculation, as shown in **Box 1**. As ambient sound data from a range of sites within the Canadian Arctic are obtained, ambient sound levels from each site should be integrated into the *LSR* model. Given the importance of understanding the ambient soundscape in assessing auditory masking, especially with regard to listening space, such research on the spatio-temporal variation in ambient soundscapes is critical.

Ambient sound levels can also differ with depth. The ambient sound levels used within this study were obtained from a recorder at a relatively shallow (23.5m) depth(Insley et al., 2017). While marine mammals and fish do spend time near the surface, their important habitat can extend much deeper. Propagation loss can vary with receiver depth, causing the propagation loss coefficient (*N* in the *LSR* equation, eq.7) to also vary. This change in depth also means that the increased ambient sound level from shipping (the NL_o variable in the *LSR* equation, eq. 7) will also be different at the receiver's position. In this study, the *LSR* plots are based on the receiver being within 30m of the sea surface – an important assumption. While there are a range of assumptions with the calculated *LSR* maps, they are largely environmental assumptions which are obtainable and quantifiable in future investigations.

When re-routing shipping corridors is not possible, reducing vessel speeds through core marine mammal habitats may be the only alternative. The Ports of Vancouver(POV, 2017)and the Ports of Auckland(Constantine et al., 2015; POAL, 2015; Putland et al., 2017), have implemented voluntary slowdown trials to reduce the risk of vessel strike and/or auditory masking. Recently, the benefits of speed restrictions for communication ranges in fish and marine mammals have been investigated(Putland et al., 2017). However, no studies focusing on the percentage differences after the same vessel type has slowed down (i.e. relief in masking) were found. This study is the first to plot those differences between vessel speeds for the two types of vessels that are expected to increase in numbers the most in the Northwest Passage. The two vessel types in this study are generic representatives based on the measurements of 384 container ships and 25 cruise ships. As such, there will be some variation in the spectrum between an individual ship and the averaged spectrum used herein, depending on ship age, construction and load(McKenna, Wiggins, & Hildebrand, 2013). Thus, given so few vessels presently pass through the study region(W.D. Halliday, Insley, Hilliard, de Jong, & Pine, 2017) care should be taken before applying vessel slowdown as a blanket solution, especially given the spectral variations between vessels travelling at sub-optimal speeds. Furthermore, vessel slowdowns will lead to increased transit times, potentially pushing up the lower percentile received levels due to vessel noise being present for longer (as seen from the Ports of Vancouver slowdown trial(POV, 2017)) as well as increased fuel consumption due to travelling at sub-optimal speeds(Constantine et al., 2015; Silber & Bettridge, 2012). Therefore, the application of speed restrictions through sensitive marine mammal habitat should be carefully considered along with other vessel management strategies(McWhinnie, Halliday, Insley, Hilliard, & Canessa, 2018).

AUTHOR CONTRIBUTIONS

MKP conceived and designed the study, wrote the MATLAB code, undertook the modelling and drafted the manuscript. DEH conceived and designed the study, oversaw the modelling results and subsequent calculations and drafted the manuscript. SJI, WDH and FJ helped design the study and draft the manuscript. All authors gave final approval for publication.

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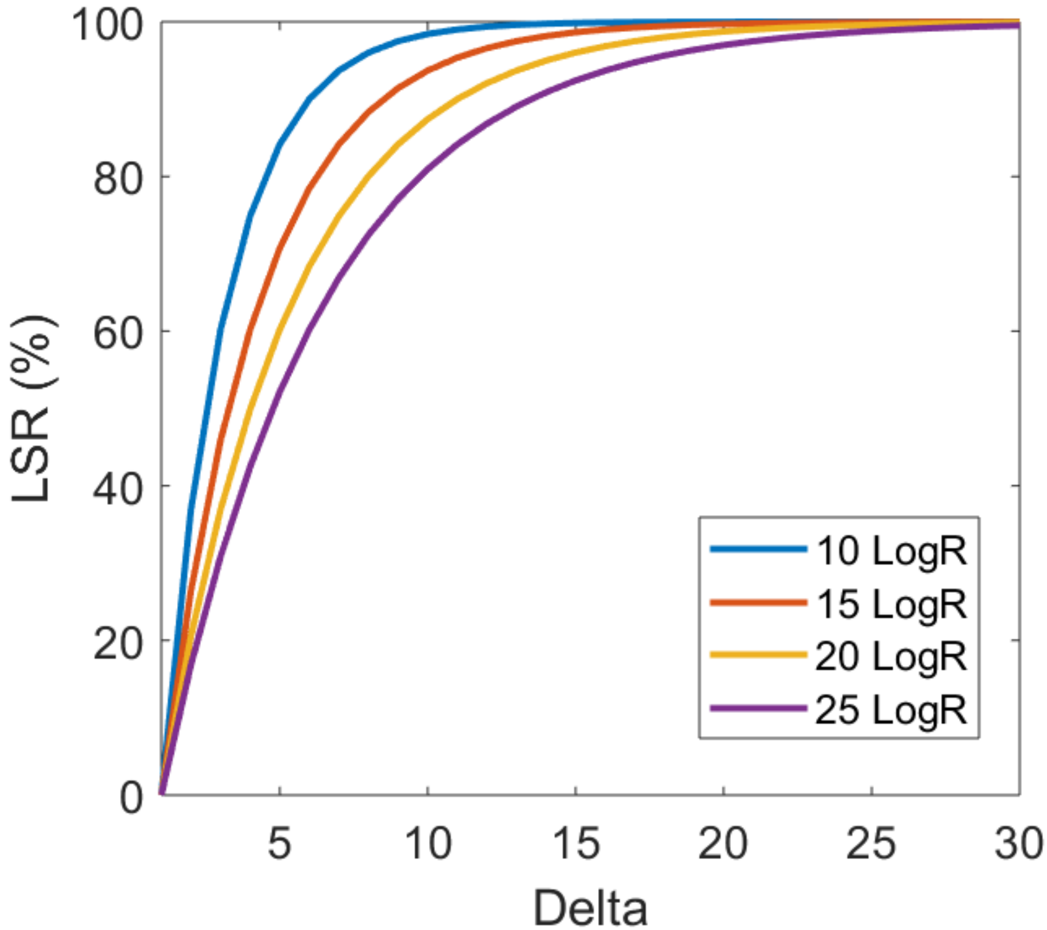


Figure 8: Plot showing the relationship between the size of Δ and corresponding LSR value under different N values (N LogR). The change in Δ due to ambient noise conditions produces smaller changes in LSR when Δ is large (i.e. near a vessel) than when Δ is small (i.e. away from a vessel). This is why increases in the ambient noise conditions do not affect LSRs near the vessel's sail track in this study, but do affect LSRs away from the sail track.

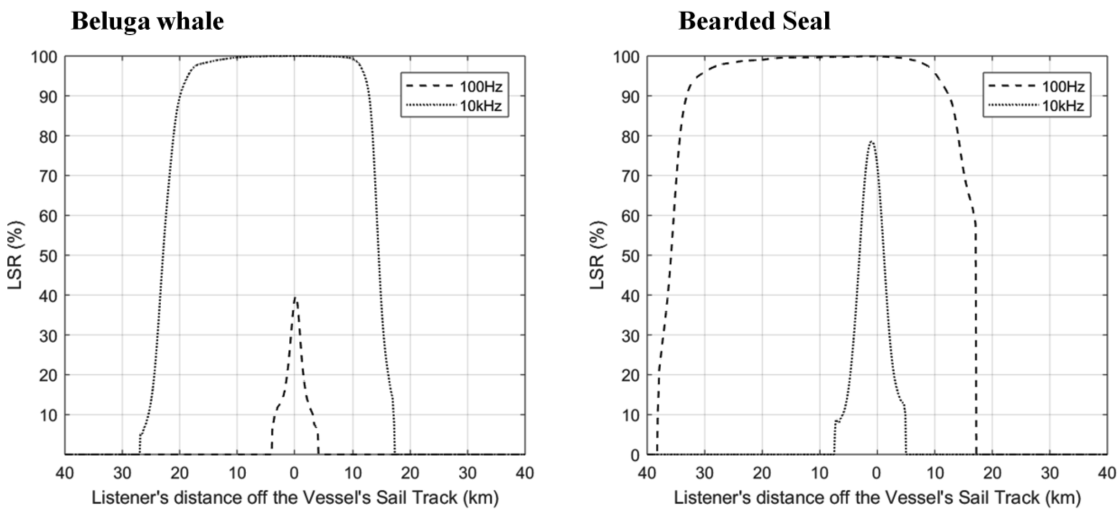
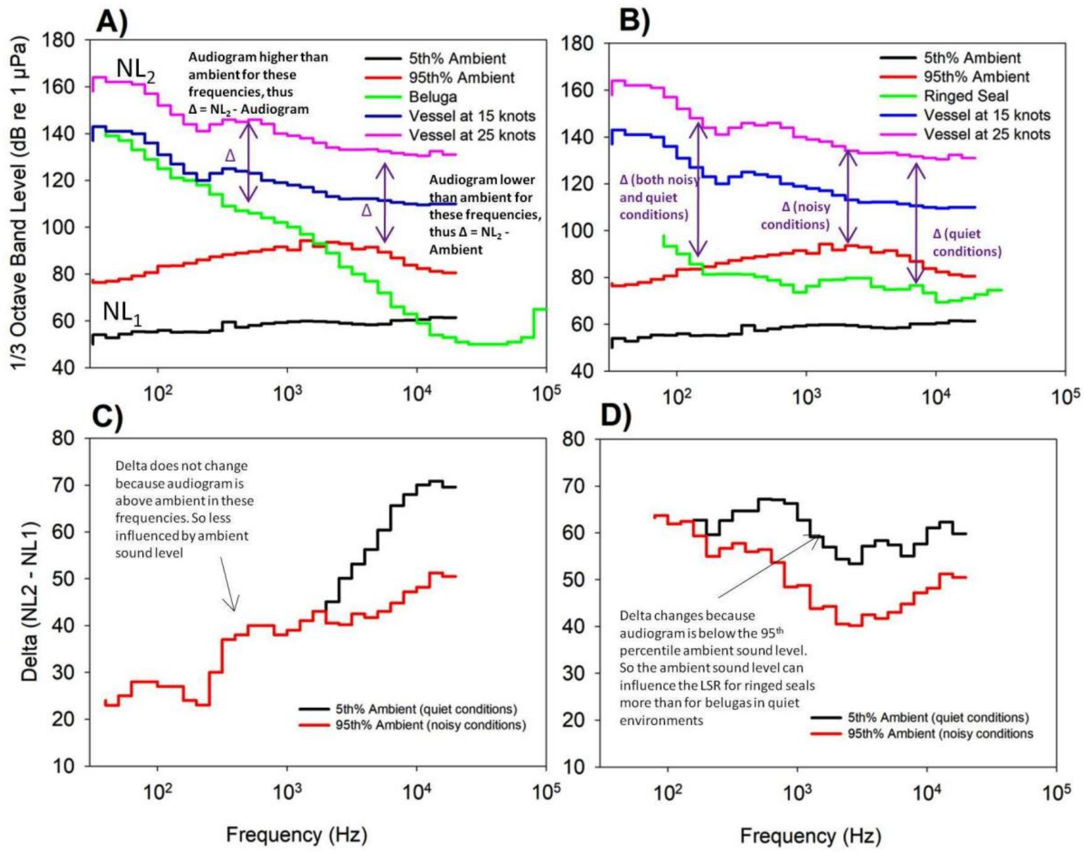


Figure 9: Calculated LSRs for 100 Hz and 10 kHz due to a container vessel underway at 25 knots for beluga whales and bearded seals. Beluga whales have lower hearing thresholds (i.e. better hearing) at 10 kHz compared to bearded seals and therefore greater LSRs at 10 kHz are seen, compared to the bearded seal. The opposite is seen for 100 Hz as the seal has substantially better hearing at that frequency compared to the whale.



Box 1: Schematic plot showing how audiogram and ambient sound conditions affect the delta (Δ) value in the LSR calculation: (A) is for a beluga; (B) is for a ringed seal; (C) is the calculated Δ values for the two ambient sound conditions for a beluga; and (D) is the calculated Δ values for the two ambient sound conditions for a ringed seal. Given the PL coefficient (N) is similar between species in each environment and frequency, the key variable affecting the LSR between species is the change in the ambient noise over time (i.e. Δ in [$LSR = 100(1\text{-}10^{-2(\Delta/N)})$], the difference between the new ambient sound level associated with the passing vessel (NL_2) and the perceived ambient sound level (NL_1)). If the ambient sound level is below the receiver's audiogram, the perceived ambient sound level will be the audiogram level, since it can not detect sound below its hearing threshold. If the ambient sound level is above the audiogram, then the perceived ambient sound level will be the ambient sound level. In environments where the ambient sound level is very low, such as in the western Canadian Arctic, the entire ambient sound level can either above (under noisy conditions, the 95th percentile level) or below (quiet conditions, the 5th percentile level) the audiogram for some species (such as the ringed seal in B above). In that case, the differences in Δ between noisy and quiet conditions will be more varied across all octave bands (in D

above) compared to the beluga whale (in C above). Thus, given there is a single Δ value for each octave band and the overall LSR calculated is the averaged LSR across all frequency bands, the audiogram and ambient levels across the whole spectrum is very important.

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