



Assessing vessel slowdown for reducing auditory masking for marine mammals and fish of the western Canadian Arctic

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ABSTRACT

Vessel slowdown 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 in marine mammals and fish from a 10 knot speed reduction of container and cruise ships. The mitigation effect from slower vessels was not equal between ambient sound conditions, species or vessel-type. Under quiet ambient conditions, a speed reduction from 25 to 15 knots resulted in smaller listening space reductions by 16–23%, 10–18%, 1–2%, 5–8% and 8% respectively for belugas, bowheads, bearded seals, ringed seals, and fish, depending on vessel-type. However, under noisy conditions, those savings were between 9 and 19% more, depending on the species. This was due to the differences in species' hearing sensitivities and the low ambient sound levels measured in the study region. Vessel slowdown could be an effective mitigation strategy for reducing masking.

1. 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 et al., 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 et al., 2013; Insley et al., 2017; Roth et al., 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 and Ruiz, 2014; Ware et al., 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 (92%) 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 and 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 auditory masking from these exposures will lead to adverse ecological effects (Erbe et al., 2016; Slabbekoorn et al., 2010).

Marine mammals and fish use sound for critical life processes, such as communication, foraging, avoiding predators, reproduction, navigating and/or maintaining group cohesion. They are therefore more vulnerable to impacts caused by anthropogenic noise, such as injury, including hearing damage, stress, habitat avoidance, shifts in migration routes and behavioural changes (see reviews from Nowacek et al. (2007); Southall et al. (2007); and Weilgart (2007)). 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

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Canadian mainland coastline, forming summer core habitat areas in the western Canadian Arctic (Harwood et al., 2017). Beluga whales (*Delphinapterus leucas*) form several summer core habitat areas, including the Tuktoyaktuk Peninsula, Amundsen Gulf near Ulukhaktok and Viscount-Melville Sound (for males) (Hauser et al., 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 et al., 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 et al., 2017; Stanley et al., 2017), thereby making them impacted by masking. Vocalisations from bowhead whales vary in complexity and frequency range (Cummings and Holliday, 1987; Stafford et al., 2017; Tervo et al., 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 et al., 2016). Ringed seals produce yelps, barks and growls between 50 and 4 kHz (Mizuguchi et al., 2016), and arctic cod calls have been described as short (approximately 289 ms) grunts consisting of 6–12 pulses under 250 Hz (Riera et al., 2018). Vessel noise is very broadband (McKenna et al., 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 (Simard et al., 2016) 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 (> 170 dB re 1 μ Pa @ 1 m (Veirs et al., 2016)), 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 (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, signal gains 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 (Clark et al., 2009). Unfortunately, these inputs are often unknown or are highly variable for many species, particularly for mysticete cetaceans (baleen whales). 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 et al., 2010; Matthews et al., 2016). This volume is referred to as the listening space, and differs from communication space in that it is not focussed on the vocalising animal but rather an animal that is listening for any biologically-important signal. 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 and Hastings, 2008; Bradbury and Vehrencamp, 2000; Clark, 1990). For example, mysticetes, including bowhead whales, sing to attract mates (Payne and 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 (Arctic Council, 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 (Arctic Council, 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 et al., 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 (from their normal operating speed of 25 knots) 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.

2. Methods and materials

2.1. 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 (15 knots was selected as being more realistic than 10 knots, and is not being considered for legislation). 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 (Fig. 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).

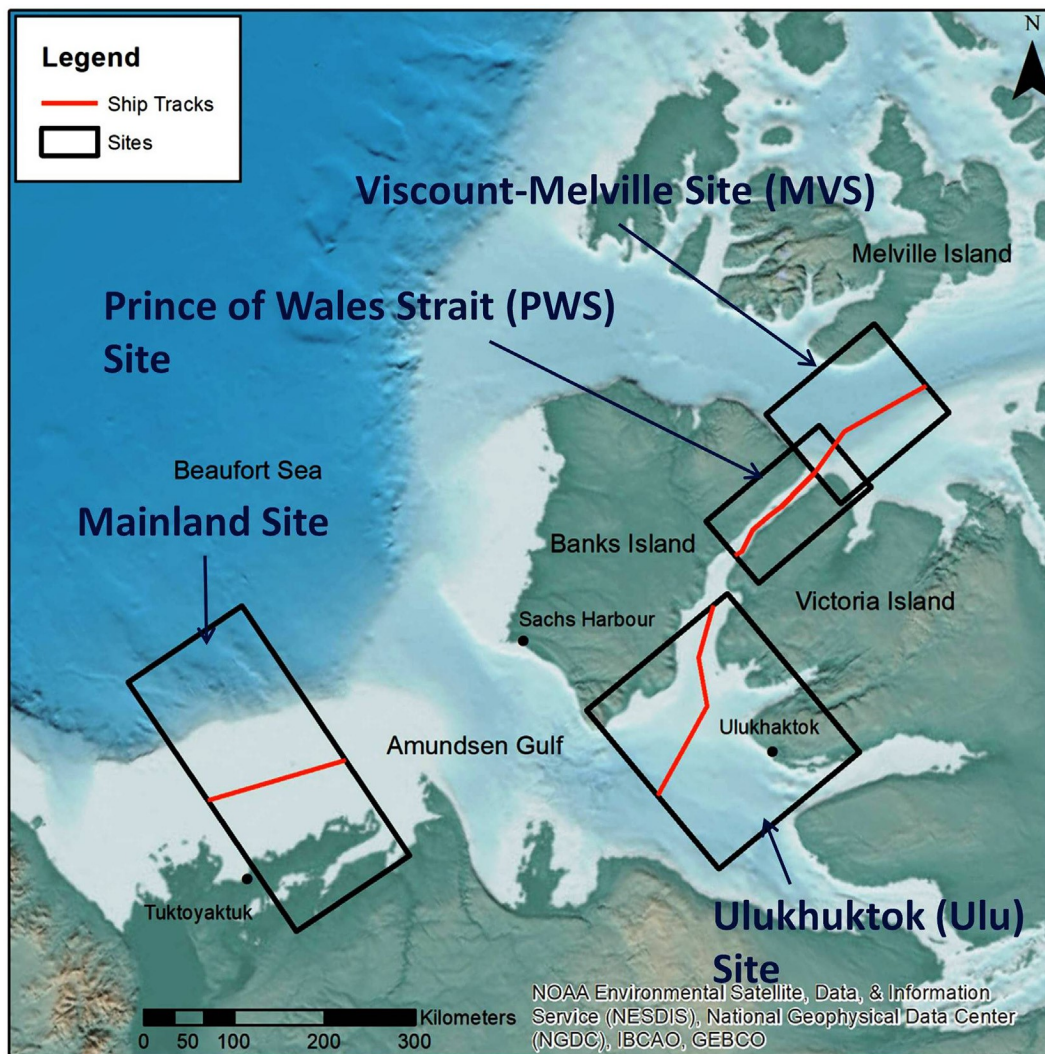


Fig. 1. Map of the study region with black rectangles outlining each sub-area. The red lines represent the simulated vessel sail tracks through each sub-area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. 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 (Fig. 2). ECHO uses a combination of automatic identification system (AIS) tracking and acoustic tracking of the vessel's acoustic centre (using a tetrahedral hydrophone array). The hydrophone array tracks the accurate position of the vessel along the track, while the track line is identified by multiple AIS transmissions. The station is operated by JASCO Applied Sciences and Ocean Networks Canada. Aside from vessel source levels in each 1/3 octave band 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. Since the differences in masking due to slowing vessels was being considered herein, the results are relatively insensitive to the choice between mean or median source levels.

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, C_v , were

obtained from the ECHO program measurements (POV, 2017) for container and cruise ships.

$$SL_{x_{knots}} = vSL + C_v \cdot 10 \log \left(\frac{v_1}{v_0} \right) \quad (1)$$

where $SL_{x_{knots}}$ is the third octave source level for the given vessel type underway at x knots (15 and 25 knots were used herein), 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 (i.e. 15 or 25 knots), and v_0 is the reference speed through water of the vessels from which source level measurements were made (18.12 and 16.36 knots, for the container and cruise ships, respectively) (Ross, 1987).

2.3. 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), as a percentage, for each species due to reduced masking noise from slowing the vessels (Hannay et al., 2016; Matthews et al., 2016). The LSRs were calculated using the equations presented by Hannay et al. (2016) and 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

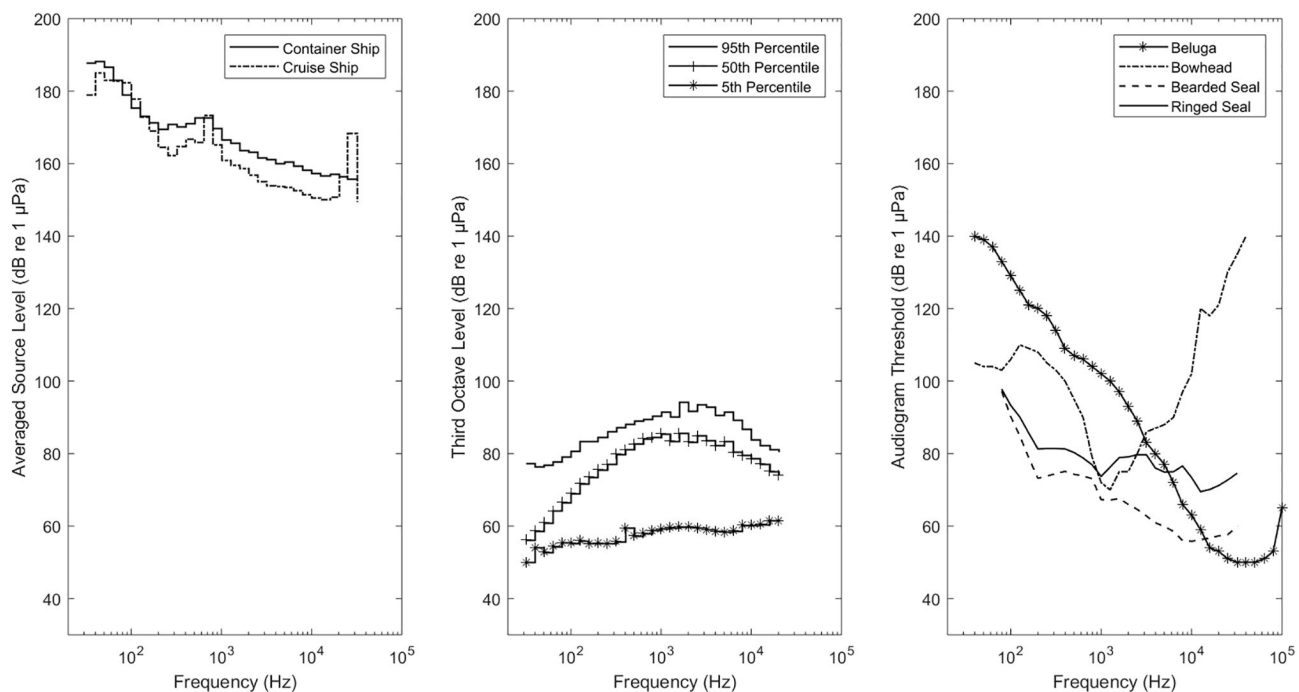


Fig. 2. Third octave band source levels (dB re 1 μ Pa @ 1 m) of the container and cruise ships, measured ambient sound levels (dB re 1 μ Pa) and audiogram values (dB re 1 μ Pa) for marine mammals investigated in this study.

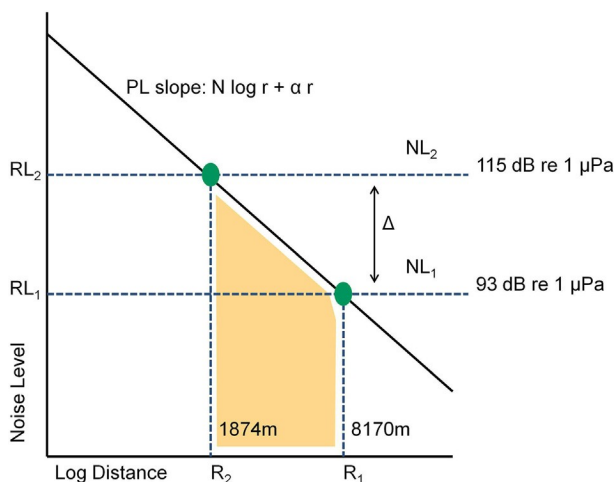


Fig. 3. Schematic plot showing the relationship between rising noise levels (NL_1 and NL_2) from a passing vessel and the decreasing distance (R_x) over which a hypothetical call (received levels, RL) can be detected, as a function of the call's propagation loss (the PL slope). Underwater natural ambient sound conditions (NL_1), there will be a maximum listening range, R_1 , representing the distance from a source (for example, the prey) to a listener (for example, a seal) within which the source's call can be detected. As a vessel passes at some distance from the listener, noise from the vessel (i.e. masking noise) will increase that ambient sound level (to NL_2), thus increasing masking and reducing R_1 to a new (smaller) listening range, R_2 . The difference between R_1 and R_2 (i.e. the distance factor) will depend on the level of the increased masking noise level (NL_2), and the area shaded yellow represents the listening space reduction (LSR). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 (see Fig. 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.:

$$PL = N \log_{10}(R) \quad (2)$$

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 v2.2 L platform (see 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 500 m 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 (Clark et al., 2009), but excluding signal gain:

$$SE = SL - PL - NL_1 - DT \quad (3)$$

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 (Clark et al., 2009; Kastelein et al., 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 (Fig. 3). The masking noise level in each F_c caused by the vessel, NL_2 , for a particular vessel location can be calculated from the vessel's

source level (for each F_c) at its transiting speed and the propagation loss from the ship position to the listener position:

$$NL_2 = SL_{xknots} - PL_v \quad (4)$$

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 (Fig. 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:

$$NL_2 - NL_1 = -N \log\left(\frac{R_2}{R_1}\right) \quad (5)$$

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:

$$100\left(1 - \left(\frac{R_2}{R_1}\right)^2\right). \quad (6)$$

It can be expressed as:

$$LSR = 100\left(1 - \left(\frac{R_2}{R_1}\right)^2\right) = 100\left(1 - 10^{2\frac{NL_2 - NL_1}{N}}\right);$$

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

where Δ is the difference between NL_2 and NL_1 . The result of Eq. (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 (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 et al., 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 et al., 2004) and modelled audiograms for the bearded seal (Li et al., 2011) and fin whale (Cranford and 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)) (Fig. 2). This time period is representative of most ship traffic in the region (based on AIS data from 2012 to 2017 (Halliday, unpublished data)) and Sachs Harbour is the only location in the study region where ambient sound measurements have been undertaken. 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 23.5 m (Insley et al., 2017). The vessel source spectrum, ambient sound levels and audiogram values used are provided in Fig. 2.

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 80 km long), were made (at the Ulu site, being representative of the study region) and the corresponding LSR values were calculated for each vessel speed.

3. Results

3.1. 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 (Figs. 4, 5). The greatest impact occurred for phocid listeners (earless seals, i.e. the ringed and bearded seals herein), with maximum averaged $LSRs$ near the sail track exceeding 90% for both bearded and ringed seals, compared to approximately 76 and 83% for bowhead and beluga whales, respectively (Fig. 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 (Fig. 4) and Mainland sub-area. A 90% LSR was predicted for both bearded and ringed seals approximately 2 km from the sail track (Fig. 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 (Fig. 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 7–10 km. The $LSRs$ near the shorelines of the Strait, at Banks and Victoria Islands, were between approximately 25 and 30% (Fig. 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 Fig. 2).

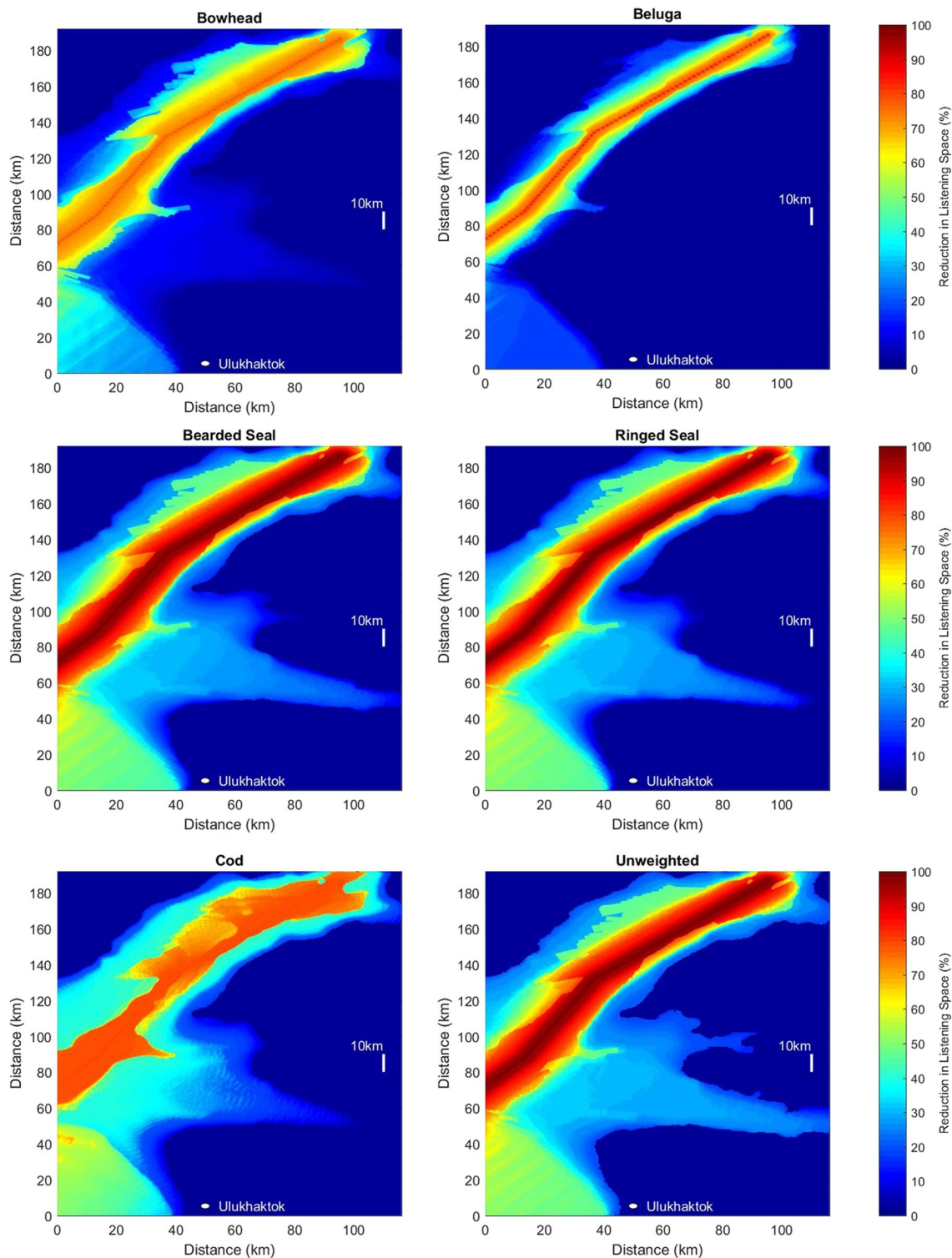


Fig. 4. Plots showing the spatial extent of LSRs from a container vessel underway at 25 knots under median noise conditions (50th percentile levels) through the Ulu sub-area for each listener species, and for when no audiogram filter was applied (unweighted). Differences between these plots are due to the different hearing sensitivities of each species.

3.2. 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 (Fig. 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 (Fig. 6). Under quiet noise conditions, a speed reduction from 25 to 15 knots resulted in smaller *LSRs* 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 (Fig. 6). Under noisy conditions, *LSRs* for listeners on the sail track were

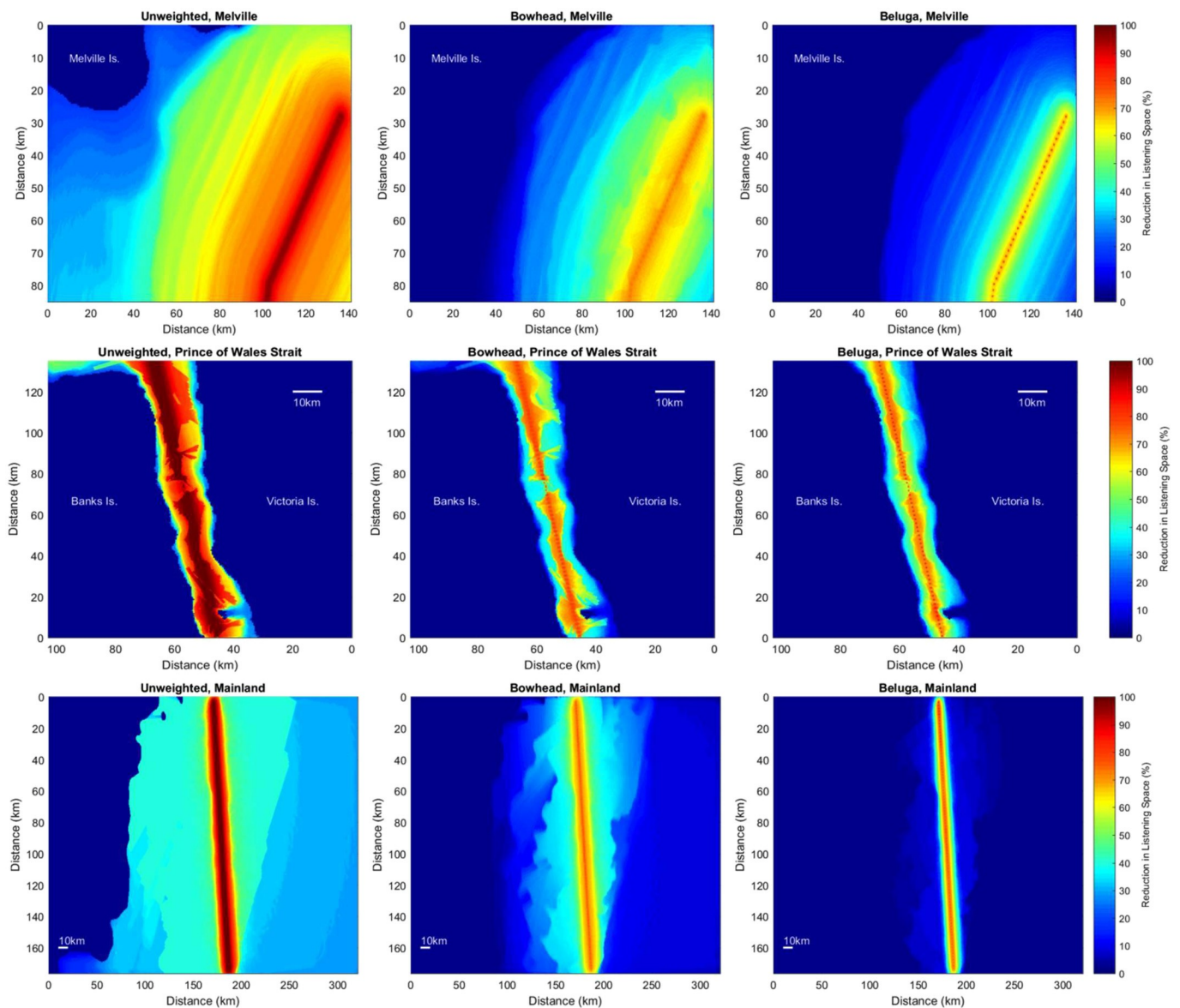


Fig. 5. Plots showing the spatial extent of LSRs from a container vessel underway at 25 knots through the VMS, PWS and Mainland sub-areas, under median noise conditions (50th percentile levels). The left column represents the modelled unweighted LSRs (i.e. no auditory filter applied), while the middle and right columns represent the modelled LSRs for a bowhead and beluga whale listener, respectively.

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 LSRs 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.

3.3. 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 LSRs of the other species, with differences noted between the two vessel types (Fig. 6). 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) (Fig. 7). 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 (Fig. 6).

While the extent of masking as quantified by LSRs 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 Fig. 2).

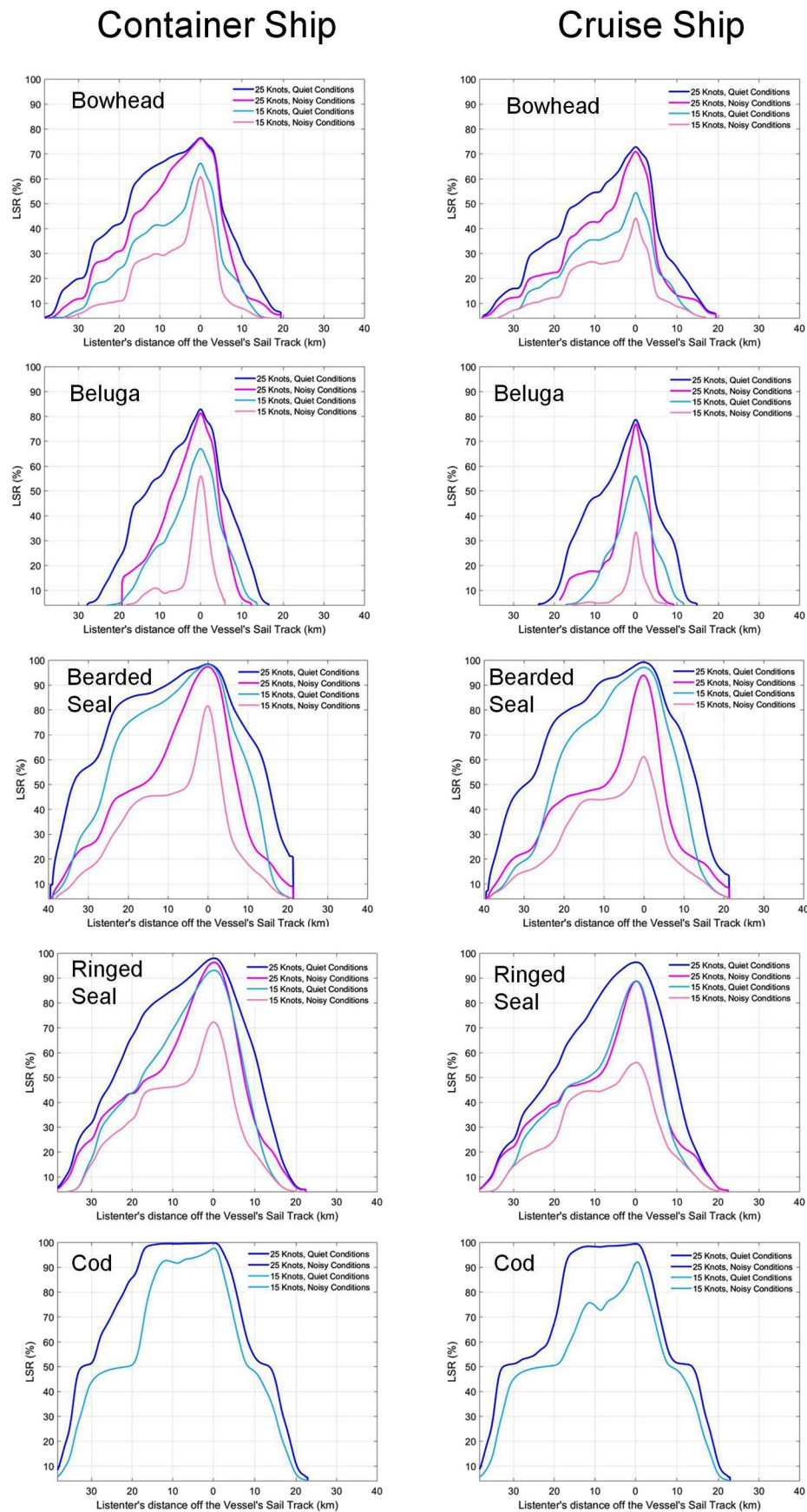


Fig. 6. Plots showing the modelled LSR (%) from a representative container and cruise ship underway at 15 and 25 knots under quiet and noisy noise conditions (represented by the 5th and 95th percentile noise levels) as a function of distance from the vessel's sail track (km).

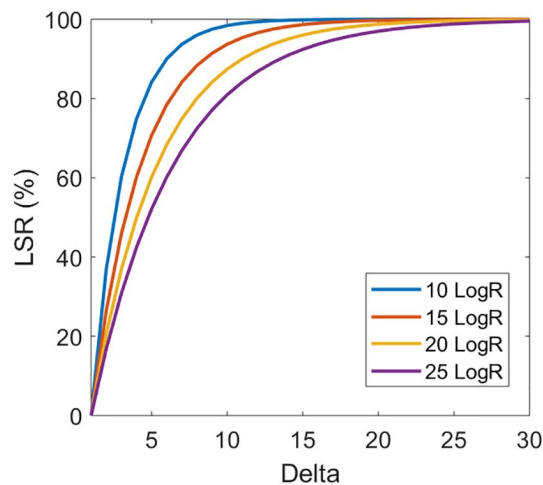


Fig. 7. Plot showing the relationship between the size of Δ and corresponding LSR value under different N values ($N \text{ LogR}$). The change in Δ due to ambient noise conditions produces smaller changes in LSR when Δ is large (i.e. near a vessel) than when Δ is small (i.e. away from a vessel). This 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.

4. Discussion

Increased shipping in the Arctic due to lower seasonal ice presence could lead to adverse auditory 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 auditory 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 higher 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 (Fig. 2). Since vessel noise is largely low-mid frequency, seal listeners experience the higher averaged LSRs at the vessel's sail track (and over several kilometres) 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 LSRs in the high frequency bands (see Fig. 8). 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., 2018) which occur below 1 kHz. Therefore, the degree of masking impact that vessel noise will have on listeners can be dependent on the vocal context of the animal.

Our modelling 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

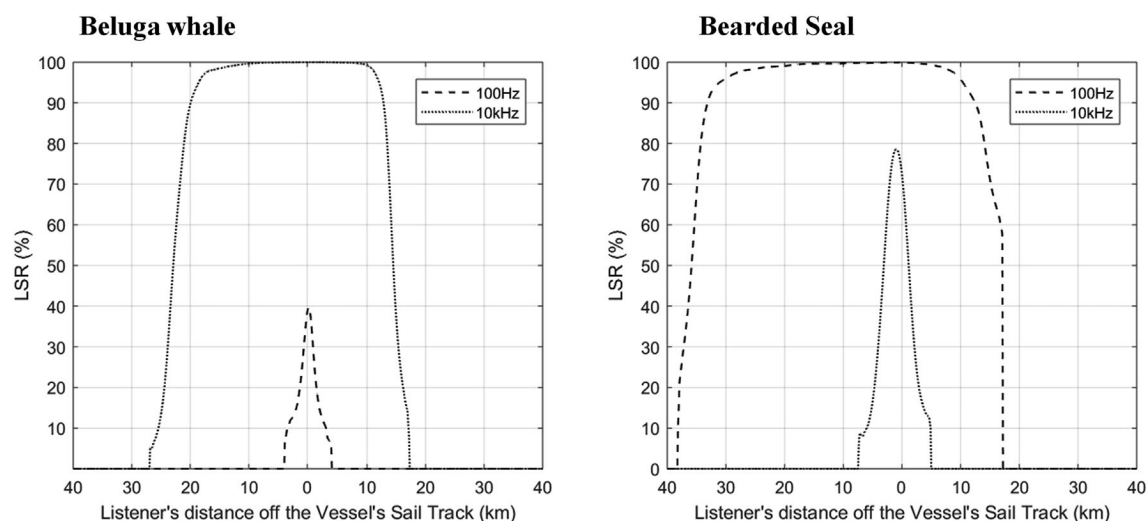
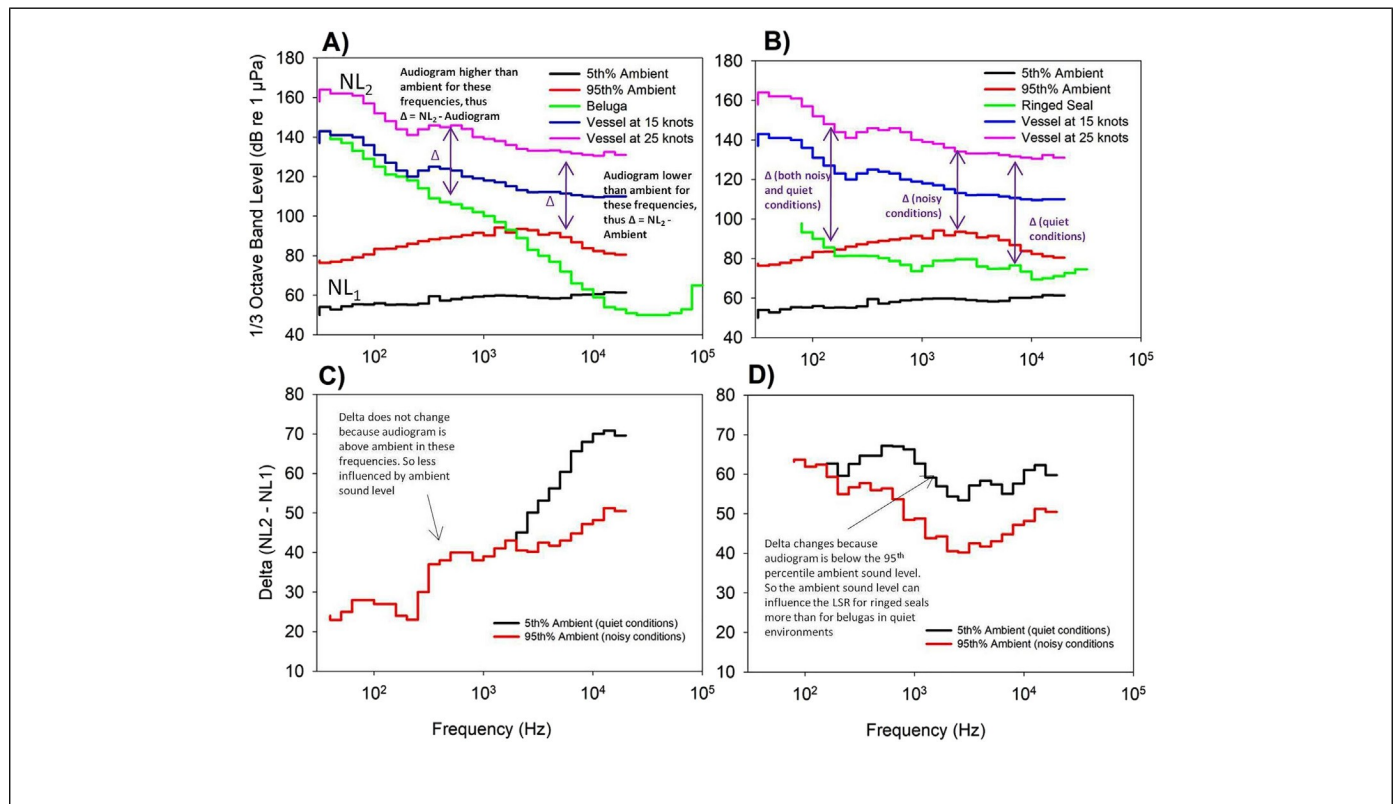


Fig. 8. Calculated LSRs for 100 Hz and 10 kHz due to a container vessel underway at 25 knots for beluga whales and bearded seals. Beluga whales have lower hearing thresholds (i.e. better hearing) at 10 kHz compared to bearded seals and therefore greater LSRs at 10 kHz are seen, compared to the bearded 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 $[LSR = 100(1 - 10^{-2(\Delta/N)}]$, 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 cannot 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.



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 $LSRs$ 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 Fig. 6) 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 noisiest 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, $LSRs > 10\%$ 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, 2015; Spiga et al., 2017).

Furthermore, vessel noise can mask signals and reduce the communication space of several fish species (Codarin et al., 2009; de Jong et al., 2017; Putland et al., 2017; Slabbekoorn et al., 2010; Vasconcelos et al., 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 and 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 spatially variable (Arctic-wide) (Insley et al., 2017; Ozanich et al., 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 5th percentile ambient sound level below 6 kHz within that area (Halliday et al., 2017b). Consequently, ambient levels could vary enough spatially to influence the Δ values in the *LSR* calculation in areas outside the study-region, 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 (23.5 m) 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_2 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 30 m 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 in the past 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 et al., 2013). Thus, given so few vessels presently pass through the study region (Halliday et al., 2017a, 2017b) 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 and Bettridge, 2012). Therefore, the application of speed restrictions through sensitive marine mammal habitat should be carefully considered along with other vessel management strategies (McWhinnie et al., 2018).

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