Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea

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A software model estimating zones of impact on marine mammals around man-made noise [C. Erbe and D. M. Farmer, J. Acoust. Soc. Am. **108**, 1327–1331 (2000)] is applied to the case of icebreakers affecting beluga whales in the Beaufort Sea. Two types of noise emitted by the Canadian Coast Guard icebreaker *Henry Larsen* are analyzed: bubbler system noise and propeller cavitation noise. Effects on beluga whales are modeled both in a deep-water environment and a near-shore environment. The model estimates that the *Henry Larsen* is audible to beluga whales over ranges of 35–78 km, depending on location. The zone of behavioral disturbance is only slightly smaller. Masking of beluga communication signals is predicted within 14–71-km range. Temporary hearing damage can occur if a beluga stays within 1–4 km of the *Henry Larsen* for at least 20 min. Bubbler noise impacts over the short ranges quoted; propeller cavitation noise accounts for all the long-range effects. Serious problems can arise in heavily industrialized areas where animals are exposed to ongoing noise and where anthropogenic noise from a variety of sources adds up. © *2000 Acoustical Society of America.* [S0001-4966(00)04409-X]

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I. INTRODUCTION

Over the past few decades, public concern for the well-being of marine mammals has rapidly increased. Due to human impact, many species are listed on endangered species lists around the world. Some populations no longer exist, i.e., are extirpated. While hunting used to be the major factor reducing marine mammal population numbers many years ago, habitat degradation is now the major issue. This includes chemical water contamination (sewage), waste disposal (plastics, glass, metal, nets), over-harvesting of prey (fisheries), and anthropogenic noise. Man-made underwater noise has many sources: offshore hydrocarbon exploration (drill ships, oil rigs, tankers, trenchers, pipeline lay barges), seismic exploration, mineral mining, ocean dredging, fishing vessels, ocean acoustic research, military activities, and ship traffic ranging from large cargo vessels, ocean liners, passenger vessels, and ferries to small private boats, pleasure boats, and whale watching boats.

There are many different ways in which anthropogenic noise affects marine mammals, some of which likely play an important role in a population's survival. Noise can disturb animal behavior. In cases where noise causes avoidance reactions and animals temporarily leave the area of loud noise exposure, this is unlikely to be biologically significant. However, if important behavior such as mating, nursing, or feeding is disrupted, or if animals are scared away from critical habitat over long periods of time, the impact can affect the long-term survival of the population. Noise further has the potential to interfere with the animal's communication signals, echolocation signals in the case of odontocetes, environmental sounds (e.g., surf) animals might listen to for orientation, the sound of prey, and the sound of predators. In extreme cases, loud continuous noise or sudden blasts of noise can cause physiological damage to the ear or other organs and tissues.

In many countries, efforts are being made to reduce the risk of noise damage to marine mammals. There is a need for efficient, i.e., fast and rational, tools to estimate over which ranges noise affects animals in which way. Various mitigation methods can then be applied, see Ref. 1 for a detailed review. As examples, quieter vessels could substitute for noisier ones, loud equipment be altered or replaced, shipping routes changed and construction sites moved away from critical marine mammal habitat. Some operations such as seismic exploration or ocean acoustic research could be timed to take place in seasons of less marine mammal abundance. Operational procedures can be modified if marine mammals are sighted in the vicinity, e.g., ramping-up a sound source, reducing source levels, changing spectral characteristics, selecting duty cycles, or temporarily shutting down if animals are within an ''unsafe radius.''

For all of these mitigation procedures knowledge of the range over which noise affects marine mammals and in which way is crucial. Erbe and Farmer[2] developed a software package that combines a sound propagation model and impact threshold models. Given the source spectrum of a noise, the package estimates zones of audibility, behavioral disturbance, masking, and potential hearing damage for a marine mammal target species and any particular ocean environment. In the current article, this software package is applied to the case of icebreaker noise affecting beluga whales in the Beaufort Sea.

II. INPUT PARAMETERS OF THE SOFTWARE PACKAGE

A. Noise emitted by an icebreaker

Noise emitted by the Canadian Coast Guard icebreaker CCGS *Henry Larsen* was recorded while on route through

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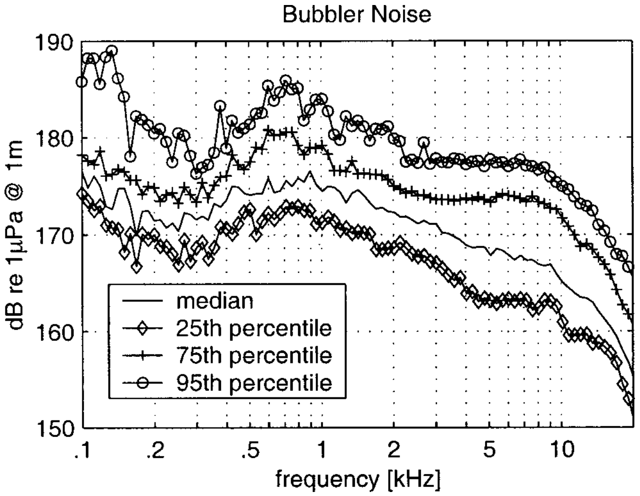

FIG. 1. Bubbler noise statistics. Plotted are 12th octave band levels of source spectra at 1-m range. Source levels are 189 (25th percentile), 192 (median), 195 (75th percentile) and 201 dB *re* 1 μPa at 1 m (95th percentile).

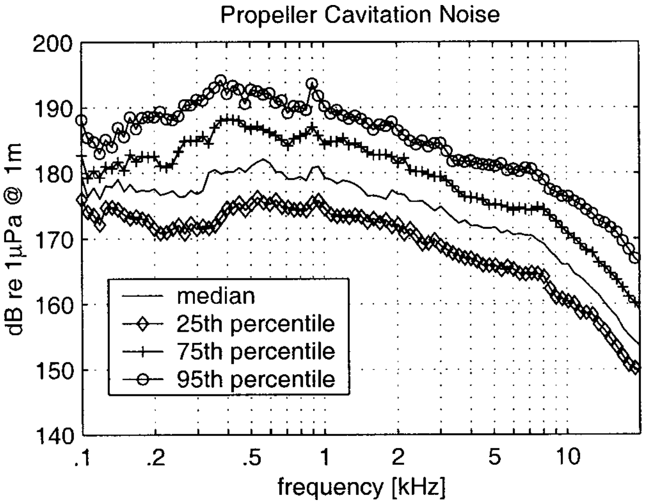

FIG. 2. Propeller cavitation noise statistics. Plotted are 12th octave band levels of source spectra at 1-m range. Source levels are 192 (25th percentile), 197 (median), 201 (75th percentile) and 205 dB *re* 1 μPa at 1 m (95th percentile).

the Beaufort Sea during August 1991. Two main types of noise were identified: bubbler system noise and propeller cavitation noise.[3] Some icebreakers are equipped with a so-called bubbler system blowing high-pressure air into the water in order to push floating ice away from the ship. The air bubbles introduced into the sea surface during the process make the ocean noisy. We call this type of noise ''bubbler noise.'' It was temporarily continuous and had a fairly white sound spectrum with most of its energy below 5 kHz. Spectrograms of single noise clips were shown earlier.[3] Figure 1 shows the statistical source spectrum levels in 12th octave bands between 100 Hz and 20 kHz, based on 36 sound files of 10-s length each. We calculated a median source level of 192 dB *re* 1 μPa at 1 m in this frequency range.

Propeller cavitation noise is caused by every propeller-driven ship. When the *Henry Larsen* tried to break an ice-ridge after building up momentum, but failed and was stopped by the ice with the propeller still turning at full speed, the noise was strongest. In this case, we refer to the noise as ''ramming noise.'' The frequency spectrum of propeller cavitation noise was broadband with energy up to 20 kHz (the maximum sampled frequency in our recording). The noise was not continuous with time, but consisted of sharp pulses occurring about 11 times per second (which was equal to the rotation frequency of the propeller times the number of blades). Figure 2 shows 12th octave band levels of propeller cavitation noise. Eighty-six sound files of 10-s length were used for the statistics. We calculated a median source level of 197 dB *re* 1 μPa at 1 m between 100 Hz and 22 kHz. For the subsequent analysis of ramming noise, we chose the loudest cavitation noise, i.e., the 95th percentile, with a corresponding source level of 205 dB *re* 1 μPa at 1 m.

B. Sound propagation modeling

The Beaufort Sea lies north of Alaska, the Yukon, and the western part of the Northwest Territories. A map of the study location is shown in Fig. 3. The chart shows the coastline and bathymetry lines for the continental shelf, continental slope, and abyssal plain of the Beaufort Sea. Pingo-like features exist on the continental shelf, locally reducing the water depth by 30%. A narrow shipping corridor through the pingo area is marked on nautical charts identifying individual pingos. The effects of ship noise on beluga whales were studied along two transects. Transect 1 assumed a ship in the shipping corridor and beluga whales anywhere between the shipping corridor and Beluga Bay. Transect 2 modeled offshore shipping and beluga whales. The sound propagation model was based on ray theory.[2] We accounted for frequency-dependent absorption by ocean water, surface scattering off the sea ice, and energy loss into the bottom sediment. We assumed a mixture of sand, silt, and clay as the sediment,[4] using its geoacoustic properties from Hamilton.[5] Mean temperature and salinity data with depth for the season of early autumn were obtained from the Levitus database of the International Research Institute for Climate Prediction and used to calculate sound speed profiles. During the fall, the chance of encountering a 50% ice-covered sea surface near the coast is 50%[6] with increasing probabilities further north over the continental slope and abyssal plain of the Beaufort Sea. We modeled first year surface ice with a rms roughness of 1 cm.[7] The sound propagation model took the noise source spectra as plotted in Figs. 1 and 2, and computed received noise spectra on a two-dimensional (depth versus range) grid of receiver locations.

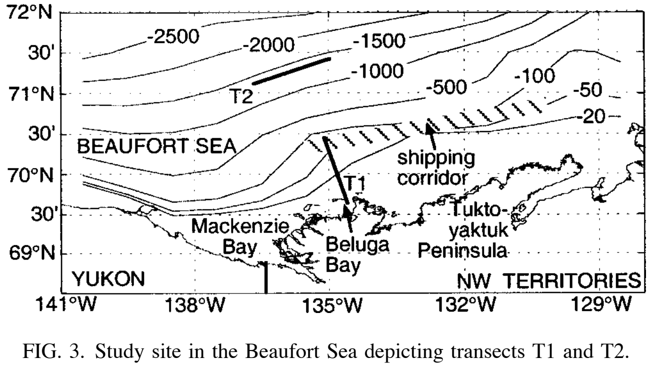

FIG. 3. Study site in the Beaufort Sea depicting transects T1 and T2.

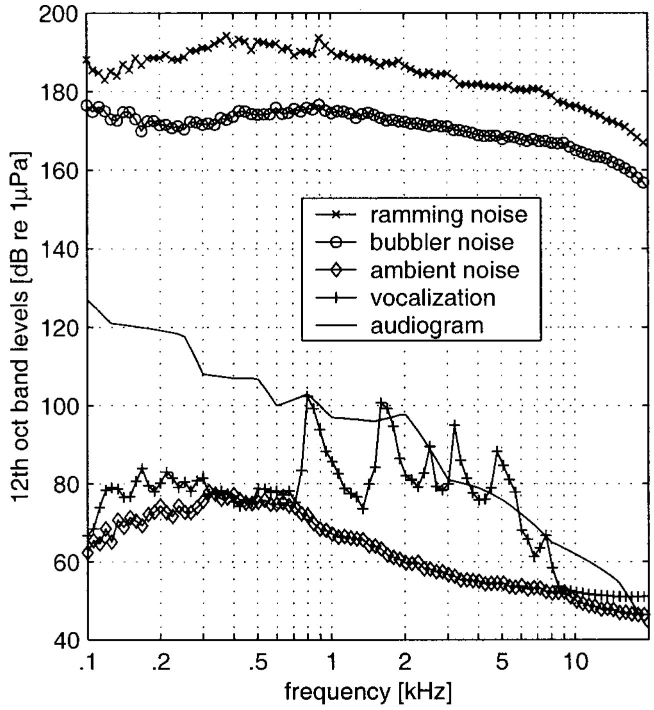

FIG. 4. The 12th octave band levels for ramming noise and median bubbler noise at the source (at 1 m), median ambient noise, a beluga vocalization at minimum recognizable level, and the beluga audiogram.

C. Calculation of the zone of audibility

This subroutine required knowledge of the widths of the critical bands of the animal's auditory filter. Erbe *et al.*[8] estimated critical bandwidths for beluga whales from critical ratio data.[9] It was shown that critical bands were about $\frac{1}{12}$ of an octave wide in the frequency range of interest. This subroutine also needed an audiogram (pure tone detection thresholds) of the target species. For beluga whales, seven audiograms have been published.[3,10–12] We calculated the means and interpolated at the center frequencies of the 12th octave bands, listed in Table I.[2] The resulting audiogram is shown in Fig. 4. Ambient arctic noise in the presence of first-year ice was recorded during an earlier study.[13,14] Figure 4 shows median 12th octave band levels based on ten recordings of 2-s length each, obtained over 5 days. In our case, ambient noise was mainly due to naturally occurring thermal and pressure icecracking, and wind and currents shuffling ice floes. The audibility model considered a noise source audible as long as the energy in at least one 12th octave band exceeded the audiogram and ambient noise.

D. Calculation of the zone of masking

This subroutine required spectra of the signals to be masked. Figure 4 shows the 12th octave band levels of a typical beluga vocalization at its minimum recognizable sound pressure level as determined by hearing experiments with a trained beluga whale.[3] In other words, in the absence of noise, this was the quietest level at which the animal recognized the vocalization. In the presence of noise, the same animal successfully recognized the call, if the energy in the 12th octave bands of the two lower frequency peaks was above the corresponding band levels of the noise.[15] This corroborated Fletcher's principle[16] stating that a signal will be masked by noise with equal or higher energy in the same critical band. In this subroutine, as long as both 12th octave band levels of the two lower-frequency peaks of the call were above the noise, the signal was assumed recognizable, otherwise it was masked.

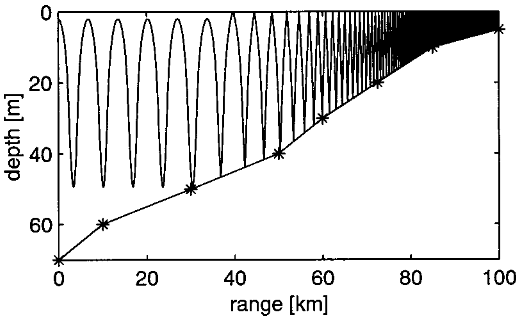

FIG. 5. Ray path up the continental slope along T1.

E. Calculation of the zone of disturbance

To estimate over what range disturbance can occur, data from field experiments are needed. LGL and Greeneridge observed groups of migrating beluga whales in the Beaufort Sea during playbacks of icebreaker noise. Six out of 17 groups altered their path when received levels were around 81 dB *re* 1 μPa (3rd octave band level at 5 kHz) during the strongest phases of propeller cavitation noise. We modified the subroutine to calculate this 3rd octave band level for the noises as a function of range and depth and we used 81 dB as the disturbance threshold.

F. Calculation of the zone of potential hearing damage

Two data sets were used to estimate over what ranges a temporary threshold shift (TTS) in hearing might occur. Au *et al.*[17] measured a TTS of 12–18 dB at 7.5 kHz after exposing a bottlenose dolphin for 30–50 min to an octave band of noise 96 dB above the audiogram. We calculated (overlapping) octave band levels at all frequencies listed in Table I,[2] and applied the 96-dB criterion to all frequencies. Kastak *et al.*[18] measured a TTS of on average 4.8 dB with three pinniped species after 20 min in octave band noise 60–75 dB above the audiogram.

III. RESULTS

A. Sound propagation

For transect T1, Fig. 5 shows a ray leaving a sound source in the shipping corridor at range 0, at 2-m depth, at a near-zero angle of −0.005 degrees. The ray starts out as a surface-and-bottom refracted ray in the mixed layer sound channel. As soon as it hits the upward sloping bottom, the ray follows a bottom-and-surface reflected path. Rays leaving the source at greater angles will turn into a reflected ray sooner. With each surface and bottom reflection, energy is lost. Therefore, only very little sound energy climbs up the

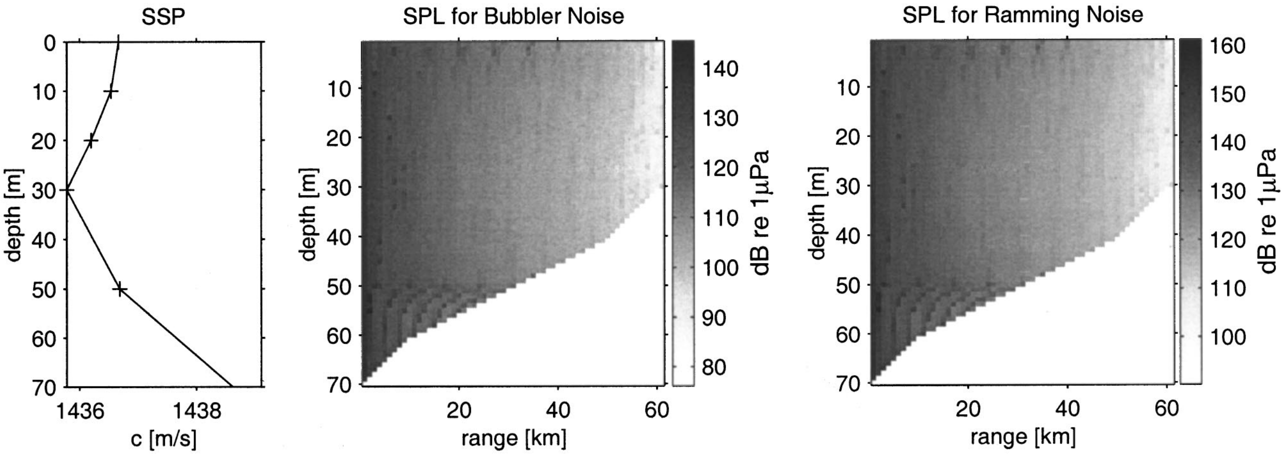

FIG. 6. Received sound pressure levels of median bubbler noise and ramming noise (95th percentile cavitation noise) along T1.

continental slope and is audible in the shallow coastal water of Beluga Bay. Acoustic energy traveling through the sea floor was neglected.

Figure 6 shows the sound speed profile (SSP) used for T1 and the received sound pressure levels (SPL) as a function of range and depth. The gray scale is in dB *re* 1 μPa. The source (the icebreaker) is located in the upper left corner. Received levels are fairly independent of depth in this shallow water and decrease with range. Beyond 60-km range, the water becomes shallower than 30 m and the SSP becomes downward refracting. Energy is lost very fast; basically no sound reaches water shallower than 30 m. We used a mean levitus SSP (early autumn season) from the deep end of T1 for the entire transect. Depending on the freshwater outflow from the Mackenzie River west of Beluga Bay, the SSP near shore might be highly variable and thus change received sound levels. Our sound propagation model allows for range-dependent SSPs, however, we did not have access to enough SSP data to do this.

Along transect T2 over the abyssal plain of the Beaufort Sea, ray propagation is typically arctic (upward refracting, Fig. 7). A shallow sound channel exists in the mixed surface layer. Figure 8 plots received sound pressure levels as a function of range and depth with the icebreaker again located in the upper left corner. Received levels decrease with range and depth. However, multiple convergence zones appear, where rays converge leading to high received sound levels.

B. Zones of audibility

Table I summarizes the impact ranges for the medians and percentiles of bubbler noise and propeller cavitation noise. A plot of the zone of audibility for median bubbler noise along T1 is shown in Fig. 9(a). The noise was audible to beluga ears at all depths out to ranges of 32 km (35 km on average over all depths). Figure 10 shows received bubbler spectra (in 12th octave bands) at a constant depth of 20 m at various ranges. At short ranges, the entire spectrum was audible. With increasing range, the low-frequency end of the bubbler spectrum became inaudible first, due to the insensitivity of the beluga ear to these low frequencies. At ranges greater than 10 km, the high-frequency end of the bubbler spectrum became inaudible, due to the increased absorption of sound energy by seawater at high frequencies. At long ranges, it was only the mid-frequencies between 3 and 10 kHz that were audible.

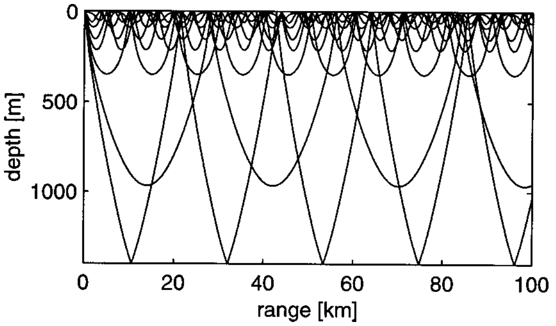

FIG. 7. Ray paths along T2 over the abyssal plain of the Beaufort Sea.

Along T1, ramming noise was audible at all depths to ranges of 50–54 km [Fig. 11(a)]. At short ranges, all frequencies were audible. Beyond 2-km range, frequencies below 500 Hz became inaudible. Beyond 40-km range, the high-frequency end of the spectrum became inaudible. At the longest ranges, it was only the mid-frequencies between 3 and 5 kHz that were audible.

Along T2, bubbler noise was audible to all depths down to 1400 m for ranges of 19 km [Fig. 12(a)]. In less deep water, particularly along the convergence zones, bubbler noise was audible to a maximum range of 53 km. At short ranges, all frequencies were audible. Beyond 15 km, only the band between 3 and 10 kHz was audible. In the case of ramming noise, audibility extended to 33 km at depth and 78 km in the upper 200 m [Fig. 13(a)]. Similar to bubbler noise, at short ranges, the entire spectrum was audible. Beyond 20 km, only spectral energy between 500 Hz and 10 kHz was audible to belugas.

In general, the range of audibility is limited by the ship noise levels dropping either below the animal's audiogram or below the ambient noise. In our case, ambient noise was only audible to beluga whales above 16 kHz. Therefore, only at higher frequencies was the ship audibility limited by the ambient noise. LGL and Greenridge[19] measured 3rd octave levels of ambient noise up to 6.3 kHz in the Beaufort Sea at the same time of the year that our ambient noise was measured. Integrating our measurements into 3rd octave bands, noise levels agreed between 150 Hz and 1 kHz. For higher frequencies, our ambient noise dropped off faster, creating a

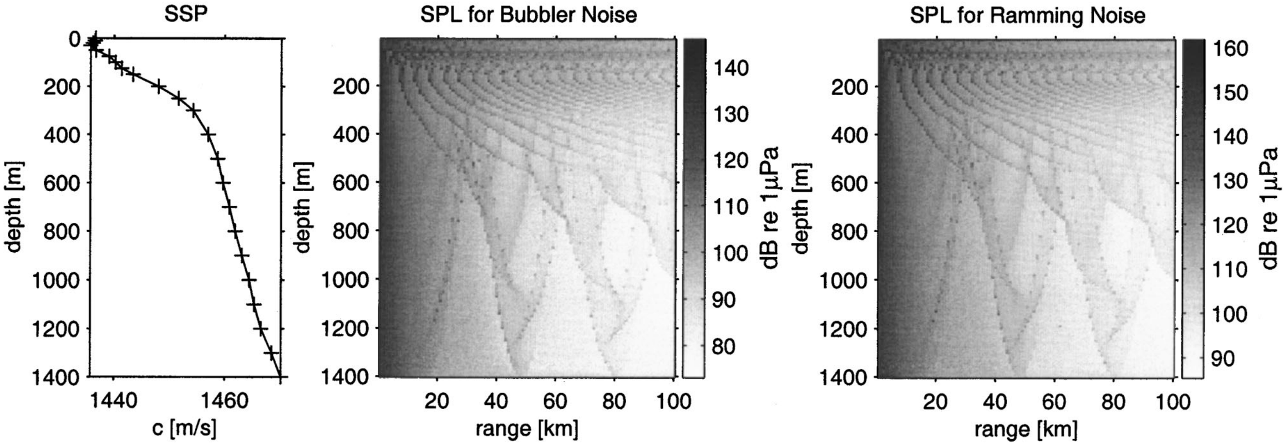

FIG. 8. Received sound pressure levels of median bubbler noise and ramming noise (95th percentile cavitation noise) along T2.

difference of 13 dB at 6 kHz. Greene[20] measured ambient noise up to 1.6 kHz in the same area, obtaining similar band levels to ours. Cosens and Dueck[21] measured spectrum levels between 20 and 5000 Hz. Integrating into 12th octave bands, their levels agreed with ours up to 1.5 kHz. Above, our levels dropped faster, creating a difference of 15 dB at 5 kHz. Ambient arctic noise is highly variable, depending on wind and sea state, on how broken up the ice is, and whether or not measurements were taken in a wind-shaded are behind ice ridges, or floes. Raised high-frequency ambient noise levels measured by LGL and Greeneridge[19] and Cosens and Dueck[21] would be audible to beluga whales above 5 kHz. Only in the case that there is enough ship noise energy above 5 kHz that propagates to long ranges can such ambient noise levels decrease the range of audibility of the ship noise.

C. Zones of masking

The following ranges are maximum ranges of masking, because the model was based on masking a very faint call that was barely recognizable in the absence of the icebreaker. Figure 9(b) indicates that masking of the beluga vocalization by bubbler noise along T1 over the continental slope occurred at all depths out to a range of about 14 km. Ramming noise masked over about 40 km range [Fig. 11(b)]. Over the abyssal plain, Figs. 12(b) and 13(b), the extent of the zone of masking was 6 km at depth and 29 km near the surface in the case of median bubbler noise, compared to 18 km at depth and 71 km near the surface in the case of ramming noise. In our case, ambient arctic noise did not add to the masking of icebreaker noise because it was considerably below audibility at the frequencies of the call. This would also be the case for the higher ambient noise levels measured by LGL and Greeneridge[19] and Cosens and Dueck.[21]

D. Zones of disturbance

As shown in Fig. 9(c) for bubbler noise along T1, the zone of behavioral disturbance extended to ranges of about 32 km and was thus almost as large as the zone of audibility (35 km). For ramming noise, disturbance went out to 46 km [Fig. 11(c)]. Over the abyssal plain [Fig. 12(c)] the range of disturbance was 19 km at depth and 44 km in shallow water

TABLE I. Impact ranges around bubbler and propeller cavitation noise (medians, 25th, 75th, and 95th percentiles). In cases where impact ranges do not vary much with depth, a mean range is given. If only one distance is listed (e.g., bubbler noise, T1, 95th percentile, audibility: 43 km), the distance refers to range and the impact occurred at all depths down to the seafloor. If the zone of impact does not extend to all depths (e.g., bubbler noise, T1, 75th percentile, TTS 12–18 dB), the maximum range ''R'' (in this case 80 m) and the maximum depth ''D'' (in this case 55 m) are given. In cases where impact ranges vary a lot with depth (e.g., bubbler noise, T2, 95th percentile, audibility), the range of impact is given both in deep ''d'' water (here 29 km) and in shallow ''s'' water (here 61 km).

	T1				T2			
	95%	75%	50%	25%	95%	75%	50%	25%
				Bubbler noise				
Audibility	43 km	39 km	35 km	29 km	29 km d, 61 km s	23 km d, 56 km s	19 km d, 53 km s	16 km d, 44 km s
Masking	30 km	19 km	14 km	10 km	12 km d, 47 km s	9 km d, 42 km s	6 km d, 29 km s	3 km d, 20 km s
Disturbance	40 km	37 km	32 km	24 km	26 km d, 53 km s	23 km d, 50 km s	19 km d, 44 km s	14 km d, 36 km s
TTS 12–18 dB	120 m	80 mR, 55 mD	40 mR, 25 mD	20 mR, 13 mD	160 mR, 100 mD	100 mR, 60 mD	40 mR, 30 mD	20 mR, 10 mD
TTS 4.8 dB	3–4 km	2–3 km	1–2 km	1 km	2 km	1–2 km	1kmR, 750 mD	1 kmR, 600 mD
				Propeller cavitation noise				
Audibility	52 km	47 km	41 km	33 km	33 km d, 78 km s	28 km d, 68 km	23 km d, 54 km s	17 km d, 48 km s
Masking	40 km	31 km	21 km	14 km	18 km d, 71 km s	14 km d, 52 km s	8 km d, 37 km s	4 km d, 26 km s
Disturbance	46 km	39 km	35 km	29 km	30 km d, 62 km s	25 km d, 55 km s	21 km d, 48 km s	16 km d, 42 km s
TTS 12–18 dB	120 m	60 mR, 45 mD	20 mR, 15 mD	none	120 mR, 100 mD	80 mR, 50 mD	40 mR, 20 mD	20 mR, 10 mD
TTS 4.8 dB	3–4 km	2 km	1–2 km	1 km	2 km	1 km	1 km R, 500 mD	900 mR, 300 mD

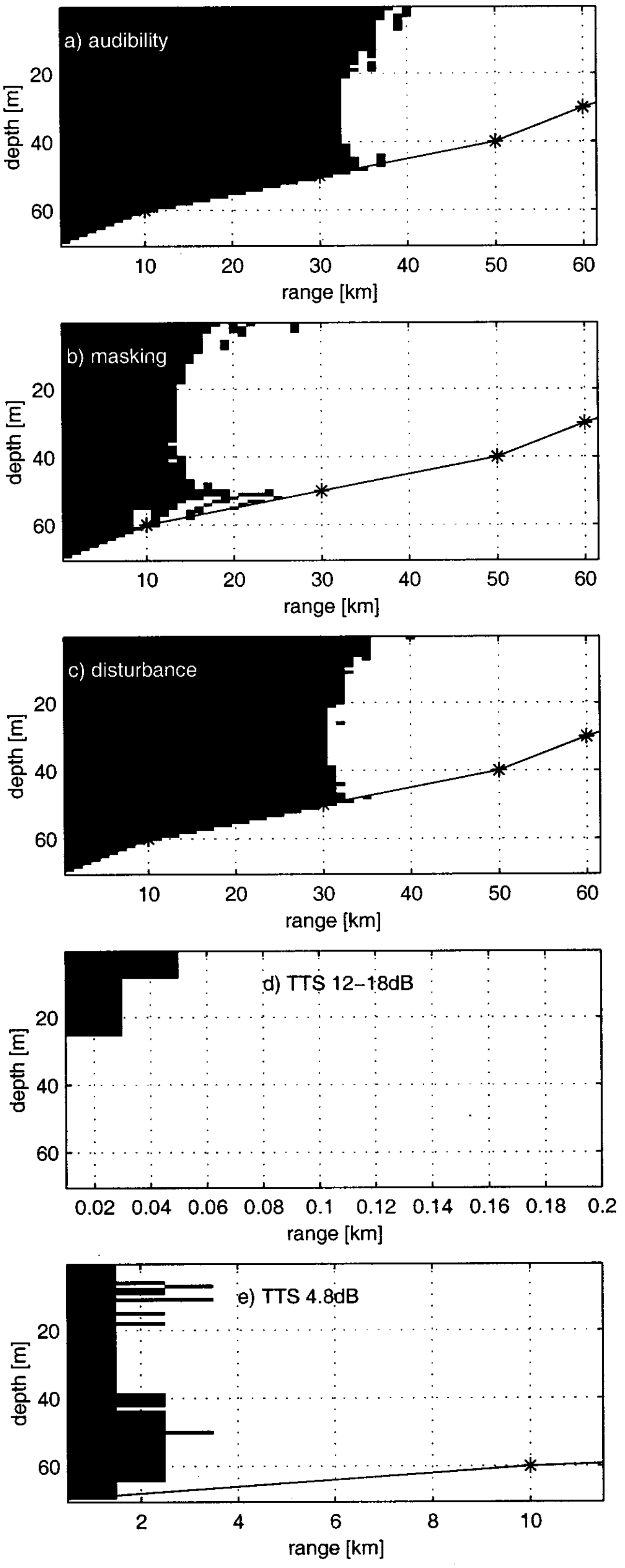

FIG. 9. Zones of impact around median bubbler noise for T1. Note the different range scale in (d) and (e).

for bubbler noise. For ramming noise [Fig. 13(c)] disturbance occurred to 30 km at depth and 62 km near the surface. The predicted zone of disturbance was only slightly smaller than the predicted zone of audibility in all four cases.

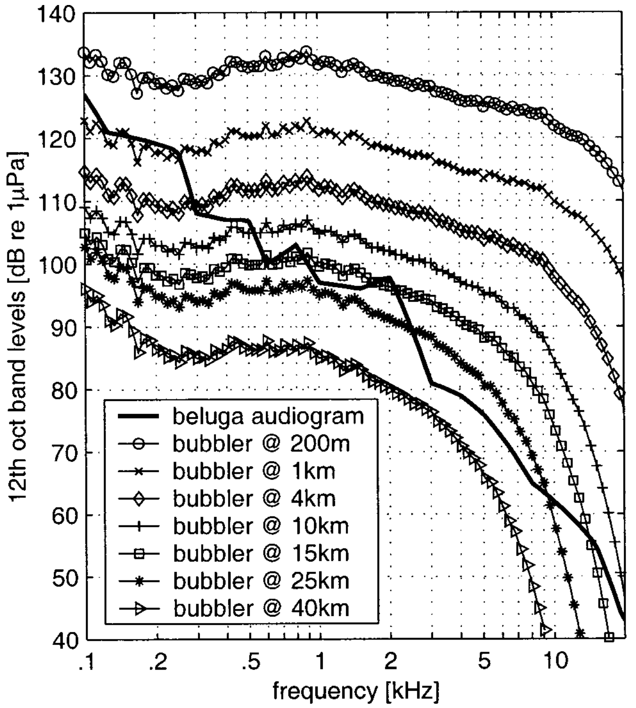

FIG. 10. Received 12th octave band levels of median bubbler noise at various ranges, taken at a depth of 20 m.

E. Zones of potential hearing damage

For median bubbler noise along T1 [Fig. 9(d)] we modeled a TTS of 12–18 dB if the animal stayed within 40-m range and 25-m depth of the icebreaker for over 30 min. It is unlikely that an animal would stay that close for that long. A smaller TTS of 4.8 dB is more likely, if the animal stays within 1–2 km for 20 min [Fig. 9(e)]. Ramming noise [Figs. 11(d) and (e)] had a larger range of impact. We predicted a TTS of 12–18 dB at all depths out to 120-m range, and a TTS of 4.8 dB over 3–4 km range. Over the abyssal plain, in the case of bubbler noise [Figs. 12(d) and (e)], a large TTS was possible to depths of 30 m and ranges of 40 m. A small TTS was possible over 750-m depth and 1-km range. In the case of ramming noise [Figs. 13(d) and (e)], a TTS of 12–18 dB could occur if an animal spent over 30 min within 120-m range and 100-m depth of the icebreaker. A TTS of 4.8 dB could occur if an animal spent over 20 min within 2-km range at all depths down to 1400 m.

From an examination of received spectra, we concluded that in all cases, hearing damage would occur only at the highest frequencies looked at, i.e., mostly between 10 and 20 kHz. The smaller TTS of 4.8 dB occurred more broadband, i.e., to lower frequencies, than the higher TTS of 12–18 dB. Also, the higher the percentile of the statistical noise spectrum (i.e., the louder the source), and the closer the animal was to the ship, the more did the hearing damage extend to lower frequencies. For example, the 25th percentile of bubbler noise along T1 was predicted to cause a TTS of 4.8 dB between 1 and 20 kHz. The 95th percentile, however, was predicted to cause a TTS of 4.8 dB between 300 Hz and 20 kHz. Ramming noise (95th percentile propeller cavitation noise) along T2 caused a TTS of 12–18 dB between 5 and 20 kHz and a TTS of 4.8 dB between 170 Hz and 20 kHz.

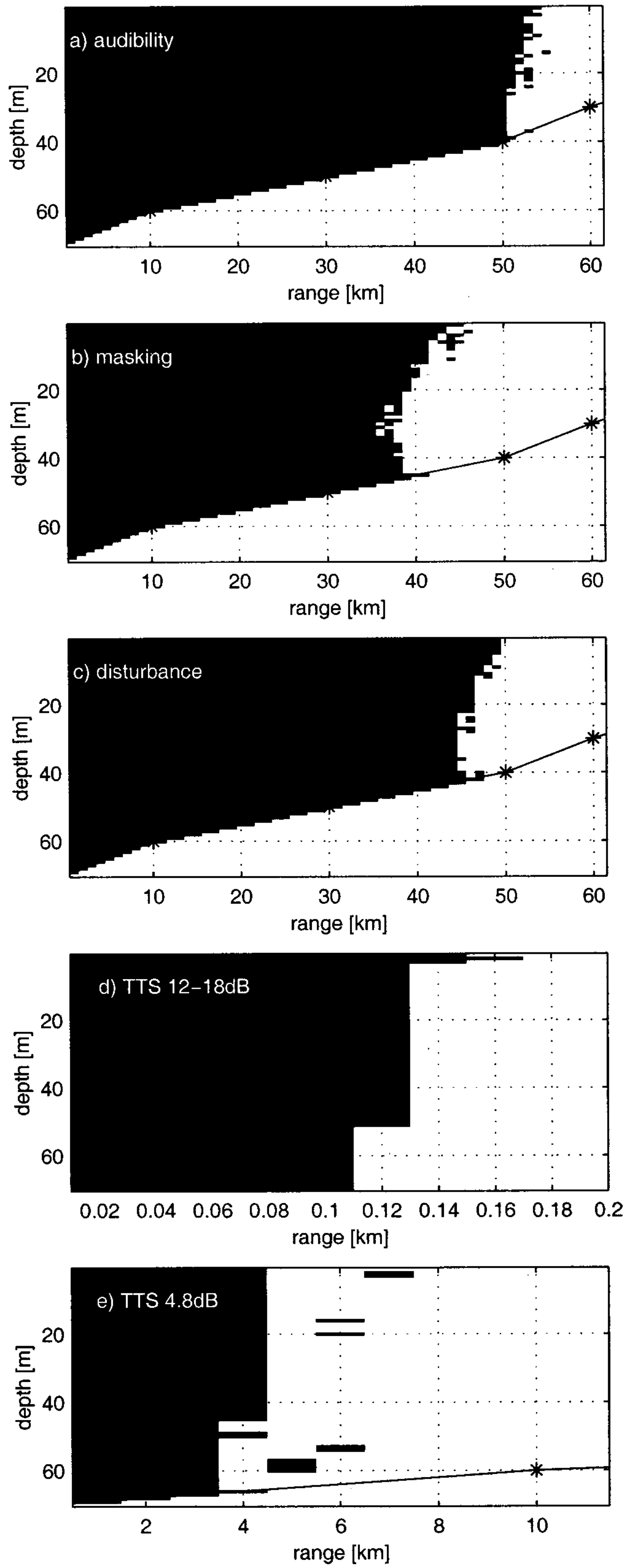

FIG. 11. Zones of impact around ramming noise for T1. Note the different range scale in (d) and (e).

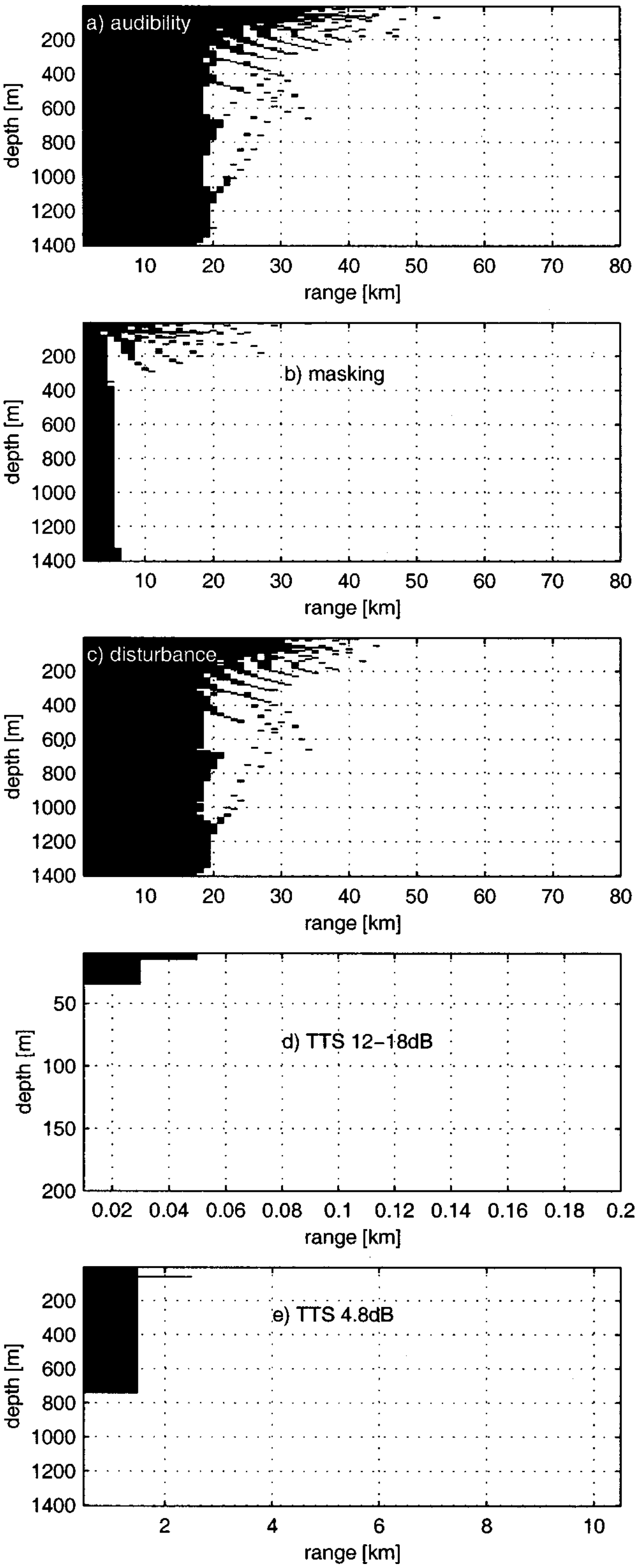

FIG. 12. Zones of impact around median bubbler noise for T2. Note the different range scale in (d) and (e), and the different depth scale in (d).

IV. DISCUSSION

A software package has been developed which combines a sound propagation model for broadband sound and impact threshold models for noise effects on marine mammals.[2] In this article, the tool was applied to estimate the ranges over which icebreakers may affect beluga whales in the Beaufort Sea. Bubbler system noise and propeller cavitation noise recorded from the Canadian Coast Guard icebreaker *Henry Larsen*[3] were analyzed for two ship locations: over the abyssal plain in the Beaufort Sea (T2) and in the shipping corridor over the continental shelf near Beluga Bay (T1). For both

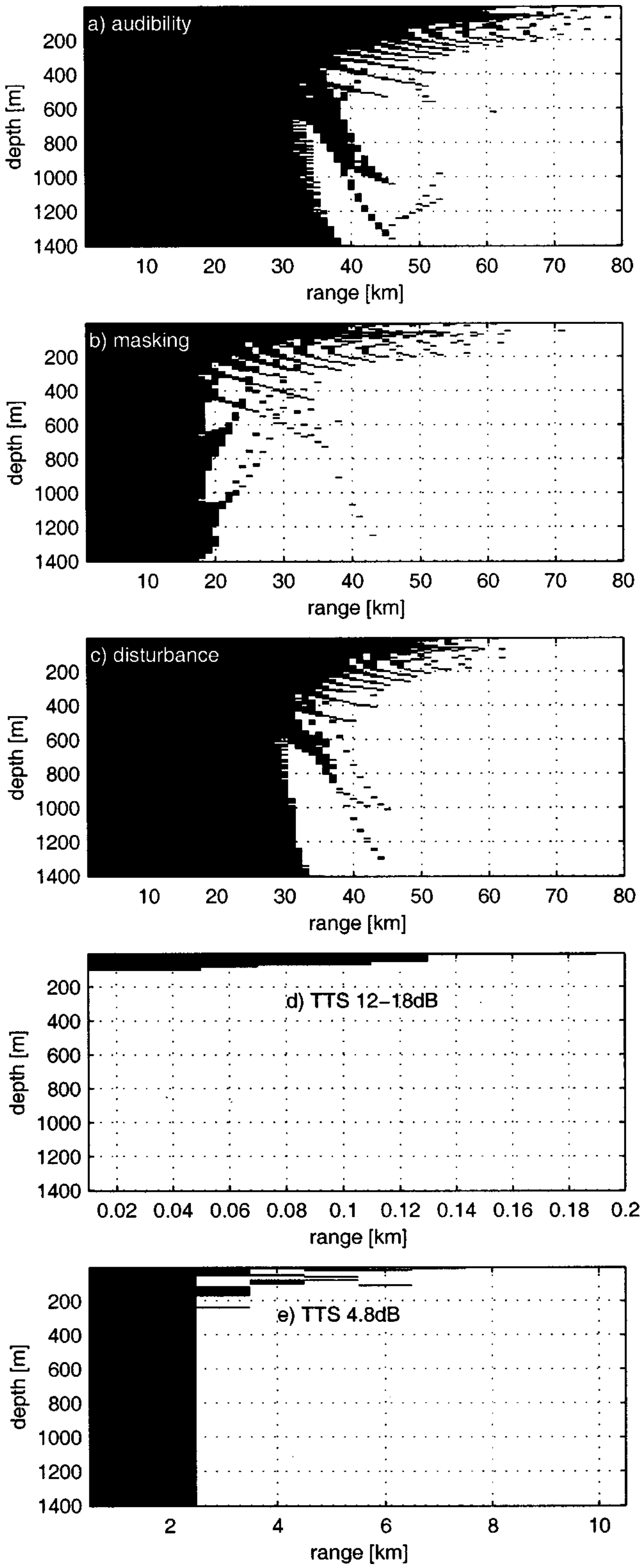

FIG. 13. Zones of impact around ramming noise for T2. Note the different range scale in (d) and (e).

noises, median spectra as well as 25th, 75th, and 95th percentiles were given. The 95th percentiles of propeller cavitation noise were taken to model ramming noise, the loudest part of cavitation noise occurring when the icebreaker rams an iceridge and is stopped by the ice.

Results showed that the *Henry Larsen* was audible to beluga whales in the Beaufort Sea over very long ranges of 35 (T1) to 53 km (T2) due to median bubbler noise and 52 (T1) to 78 km (T2) when ramming noise occurred. The range over which her noise interfered with beluga communication, however, was up to 24 km shorter. This was because of the different spectral characteristics of call and noise. The call was relatively low in frequency, with its 800-Hz and 1.6-kHz components most important in masking.[15] But it was the mid-frequencies of the noise (3–10 kHz) that remained audible over long ranges.

The ranges of masking were maximum, in the sense that the call was taken at its quietest recognizable level in the absence of noise. In other words, two communicating animals were modeled as being furthest apart. For animals closer together, received call levels would likely be louder, making the range over which ship noise could mask shorter. The relationship between animal–animal distance, ship–animal distance, and range of masking was illustrated elsewhere.[22]

Masking is a very complex and still poorly understood process and affects a variety of acoustic signals important to marine animals. We only examined the masking of intraspecies communication signals. The masking of echolocation signals, environmental cues, and predator and prey sounds was not analyzed. In none of the cases do we know the biological significance of masking. What are the long-term effects on an individual and a population? It is further unclear if and what type of means marine mammals might have to avoid masking. With respect to masking of their own sounds, this could be done by changing the volume and spectral characteristics of emitted signals. Humans adapt the loudness of their speech according to the loudness of ambient noise, the loudness with which they receive incoming speech, and the loudness with which they perceive their own signals.[23] Dolphins have been shown to echolocate louder and change the frequency spectrum of emitted clicks in the presence of noise.[24] Lesage *et al.*[25] measured the vocal behavior of beluga whales in the St. Lawrence in the absence and presence of a ferry and a small motorboat. The animals emitted calls repetitively, changed the types of calls used, and shifted the mean call frequency up during noise exposure. Whether animals manage to communicate the same information during noise exposure, or whether calls heard are simply ''alarm calls,'' is unknown.

Zones of disturbance were large and only slightly smaller than the predicted zones of audibility. This is in accordance with observed reaction distances. Cosens and Dueck[26] as well as Finley *et al.*[27] observed changes in beluga swimming behavior at distances of 40–60 km from an icebreaker in Lancaster Sound in the Canadian High Arctic. Cosens and Dueck[21] concluded that these animals avoid an icebreaker as soon as they detect it. Habituation or sensitization, however, affects the extent of the zone of disturbance. Beluga whales in the St. Lawrence Estuary approach large ships to much shorter distances.[28,29] One possible explanation is that these animals are more used to heavy traffic and habituated. On the other hand, this beluga population might be hearing impaired because of ongoing noise exposure or, in fact, (PCB) water contamination or parasites affecting their hearing.

Data on what sound levels over what periods of time cause either temporary (TTS) or permanent threshold shift (PTS) in beluga whales do not exist. For an estimation of the range of hearing damage, we used TTS data from a bottlenose dolphin[17] and three pinniped species.[18] A TTS of 12–18 dB was modeled if beluga whales stayed within 40 m of median bubbler noise and within 120 m of ramming noise for over 30 min. Given the high mobility of beluga whales, this is unlikely. However, for a TTS of 4.8 dB to occur, an animal would ''only'' have to be within 1–2 km of median bubbler noise and 2–4 km of ramming noise for 20 min. This is conceivable. Hearing can be expected to return to normal within 24 h.[18] Unfortunately, it is not known if repeated exposure to TTS, particularly what noise dose, causes permanent hearing damage.

In summary, the *Henry Larsen* icebreaker studied in this project was audible to beluga whales over very long ranges of 35–78 km. Arctic beluga whales generally avoid icebreakers almost as soon as they detect them. The animals do not get close enough for potentially harmful effects to occur such as masking of their communication signals or damage to their auditory system. However, if the animals are engaged in important behavior such as mating, nursing, or feeding, they might not flee but put up with louder, possibly too loud, noise. Problems can arise particularly in heavily industrialized areas where a variety of noisy activities take place such as geophysical (seismic) exploration; oil drilling; mineral mining; offshore construction; helicopter, icebreaker, tanker, cargo, freighter, fishing (factory), and passenger vessel traffic; and ocean acoustics research. Summed noise levels could be very high and ongoing for long durations and cover large areas such that animals might either be permanently scared away from critical habitat or be adversely affected because they have nowhere to flee to. While this article assessed the impact of the Canadian Coast Guard vessel *Henry Larsen* in particular, projects focusing on critical locations and addressing a large variety of man-made noise are needed. The tools developed here can be used for a variety of ocean environments and differing animal species.

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