Assessment of Bioacoustic Impact of Ships on Humpback Whales in Glacier Bay, Alaska

Report

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Objective

The objective of this study was to assess whether ships travelling in Glacier Bay, Alaska, had any acoustic impact on humpback whales. The type of bioacoustic impact and impact ranges were determined. This study made use of a software package that had originally been developed by the author for the Department of Fisheries and Oceans Canada, for the purpose of assessing anthropogenic (human-caused), bioacoustic impact on the marine environment. However, due to limitations in knowledge about the hearing thresholds of humpback whales, the model is based on a transfer of data from odontocetes, pinnipeds and terrestrial mammals to humpback whales. The feasibility and accuracy of such an interspecies transfer is highly debatable. Therefore, the results of this modeling exercise should not be used for environmental decision-making.

1. Introduction

Given that water conducts sound very well and light very poorly, marine mammals evolved to primarily use acoustics for communication, foraging and navigation. Underwater noise –both natural and anthropogenic- has the potential for interfering with acoustic signals that are biologically important to marine mammals. Anthropogenic (man-made) noise in the ocean has steadily increased over the past few decades, due to ship traffic, industrial construction in coastal areas, military activities, oil and mineral exploration, and to a lesser extent ocean acoustic research (e.g. Curtis *et al*. 1999).

Effects of underwater noise include the masking of marine mammal communication signals. Marine mammal vocalizations function in social cohesion, group activities, mating, mother-calf contact, warning or individual identification. Noise can further disrupt odontocete (toothed whale) echolocation signals, impeding the animal's ability to navigate or find food. Noise potentially interferes with environmental sounds or prey and predator sounds that animals listen to. For example, animals likely recognize the sound of surf, which guides them away from shallow water.

Underwater noise has the potential of disrupting “normal” animal behavior. This could include a cessation of feeding, resting, socializing and an onset of alertness or avoidance.

Any type of noise at some level has the ability to induce physiological damage to tissues and organs, for example the ear. Hearing impairment can be either temporary (i.e. fully recoverable over time) or permanent depending on factors such as the spectral characteristics of the noise (frequency and amplitude), the amount of energy per time for impulsive noise, the hearing sensitivity (audiogram) of the species, the duration of noise exposure and the duty cycle or recovery time in between exposures.

This report examines whether ship noise has the potential for causing masking, behavioral reactions or hearing damage in humpback whales in Glacier Bay.

2. Sound Sources

2.1 Capelin

Capelin (Fig. 1) is a landing craft, belonging to the National Park Service and being used by Glacier Bay National Park and Preserve employees as part of their official duties in park waters. Capelin is a 26 foot aluminum landing craft with a 350 horsepower inboard engine, capable of a maximum speed of approximately 30 knots. Underwater sound emission by Capelin was recorded in October 2002 as part of a study of underwater sound production of small National Park Service vessels (Kipple and

Gabriele 2003). Sound spectra were measured with a hydrophone at 100 foot depth and a range of 500 yards, with the vessel travelling at 20 knots.

One-third octave band levels related to the source at 1m distance were presented in a report to Glacier Bay National Park and Preserve (Kipple and Gabriele 2003). A one-third octave source spectrum related to Capelin travelling at 20kt speed is shown in Fig. 3.

Figure 1: Photo of Capelin.

2.2 Cruise Ship

Cruise ship sound emissions were measured with a calibrated hydrophone array at the U.S. Navy's SEAFAC Facility in Ketchikan, Alaska in September 1999 – June 2001. Details of the measurement protocols and results are found in Kipple (2002a). From the six ships tested, a 230m ship with a direct diesel engine, travelling at 19 knots, was chosen as input for the model. A one-third octave source spectrum related to the cruise ship travelling at 19 knot speed is shown in Fig. 3.

Figure 2: Image of the cruise ship.

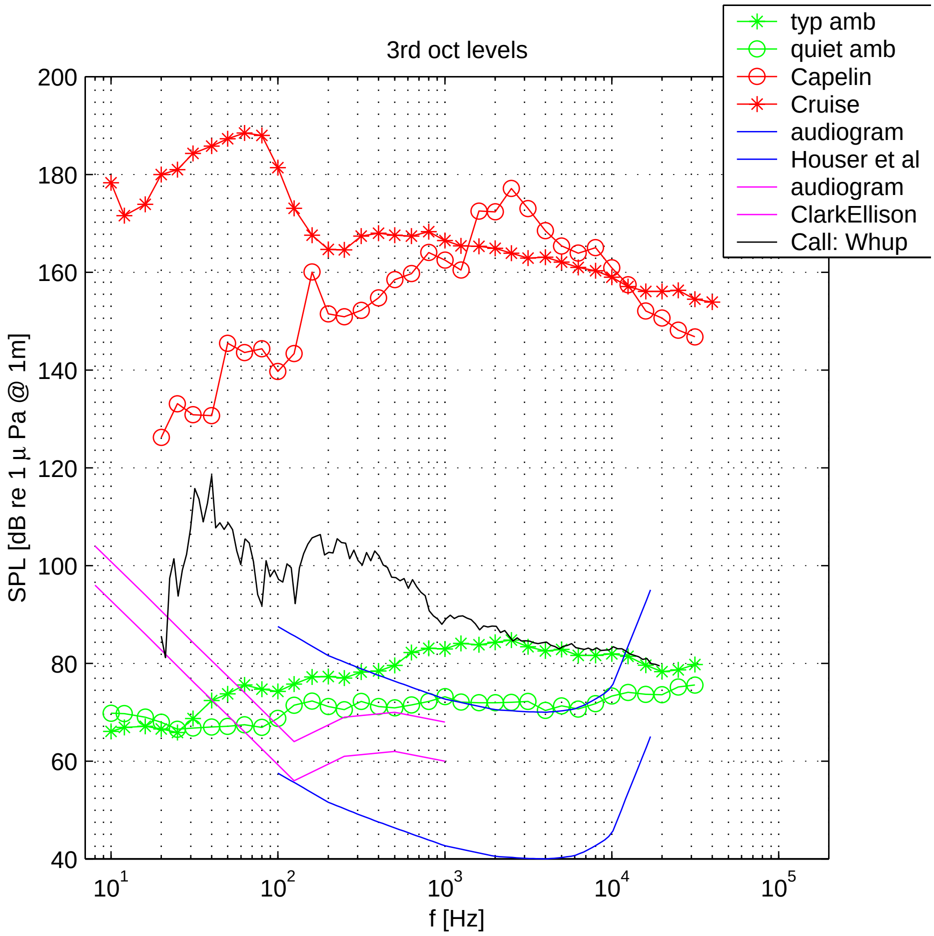

Figure 3: 1/3 octave band levels of Capelin and the cruise ship (source levels in dB re 1µPa @ 1m); typical ambient noise including rain, and quiet ambient noise that is prevalent less than 10% of the time (dB re 1µPa). 1/1/12th octave band levels of a humpback whale call – whup- at an unspecified distance (dB re 1µPa). Audiogram estimates for humpback whales. The two purple lines are the upper and lower audiogram envelope derived by Clark & Ellison; the blue lines were based on the study by Houser et al. *2001.*

3. Study Site

3.1 Geography and Geology

The bioacoustic impact assessment was done in the lower part of Glacier Bay (Fig. 4). The seafloor of lower Glacier Bay is nearly flat at approximately 55m, with steep slopes at the shore, characteristic of glacial fjords (Fig 5).

Figure 4: Map of Glacier Bay, Alaska.

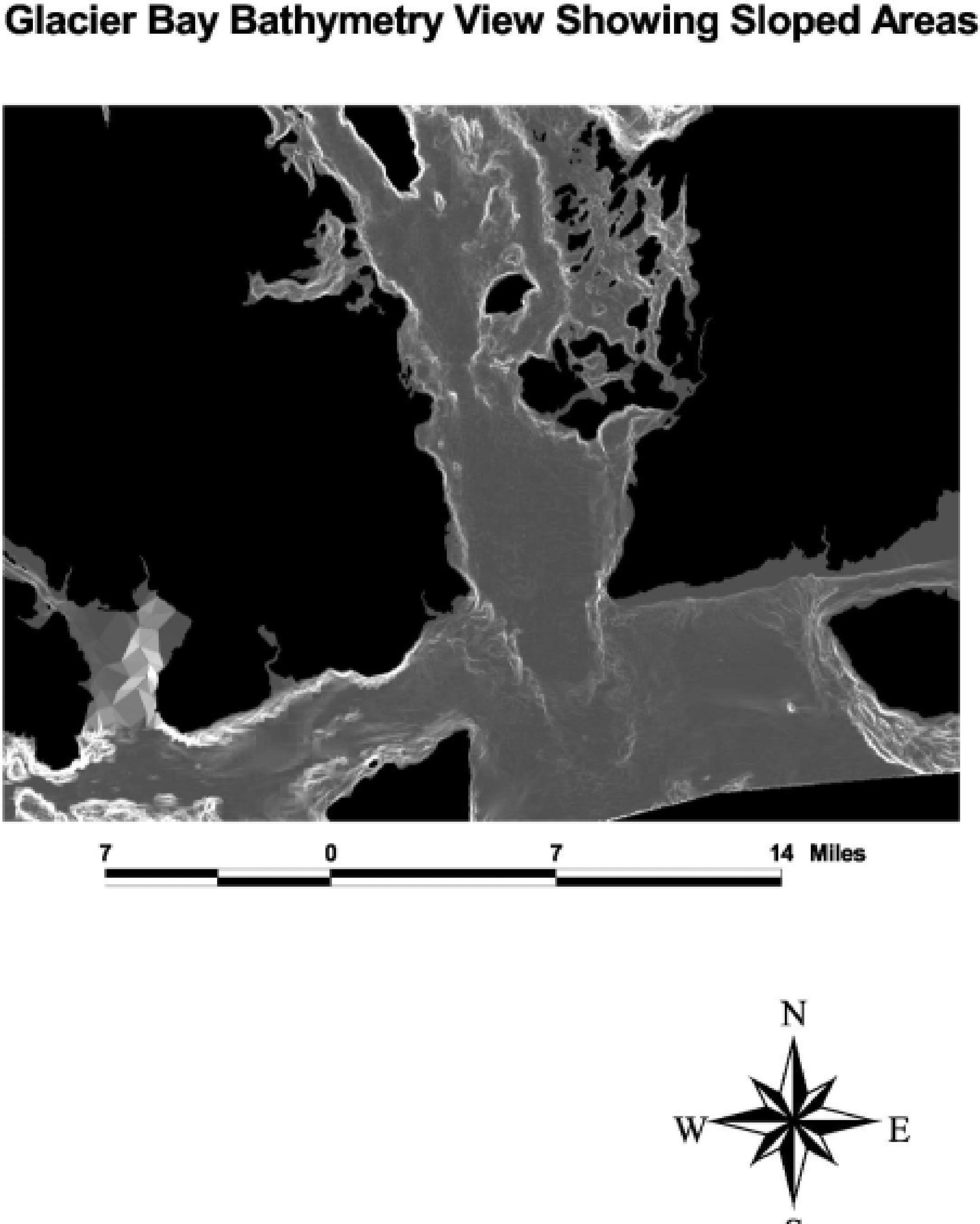

Figure 5: Slopes in bathymetry in Glacier Bay.

For the model, boats were assumed about half-way between Pt Gustavus and Pt Carolus. Bathymetry was modeled along a north-western line towards Rush Point (Fig. 6). Only the area of Glacier Bay shown in the chart is of interest here; however, audibility was modeled over longer ranges over which the bottom was assumed flat. Malme *et al*. (1982) measured the bottom to be hard rock, acoustically reflective. This was used in the model.

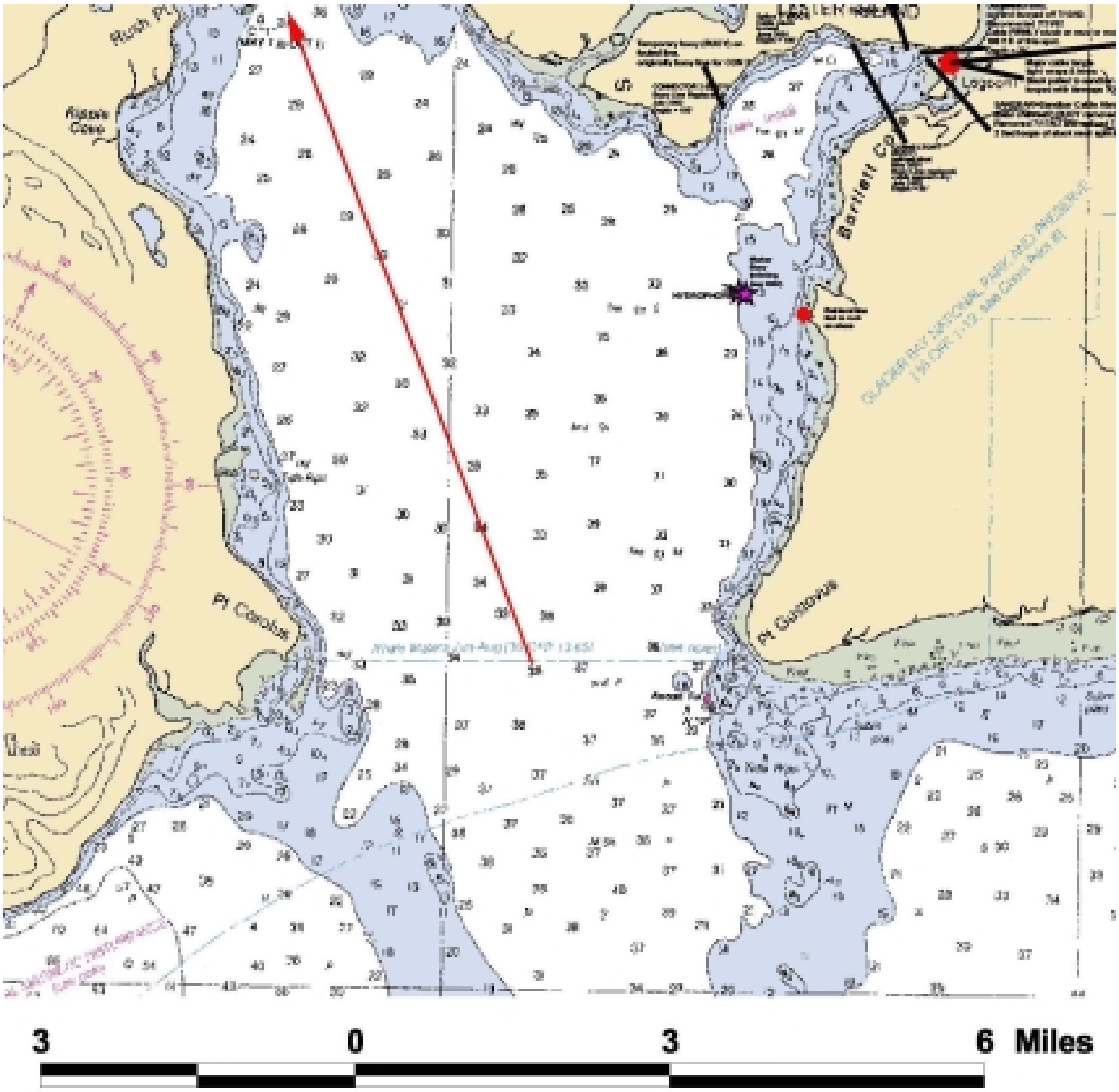

Figure 6: Bathymetry was modelled along the red arrow. The chart lists depths in fathoms; 1 fathom = 1.829m.

3.2 Sound Speed Profiles

Sound speed profiles are routinely recorded using a CTD during oceanographic monitoring (Hooge and Hooge 2002). . A profile measured at Oceanography Station 1 (58.412910 N, 135.993279 W) in the mouth of Glacier Bay during the summer on August 9, 2002, at the beginning of flood was chosen for the current model (Fig. 7).

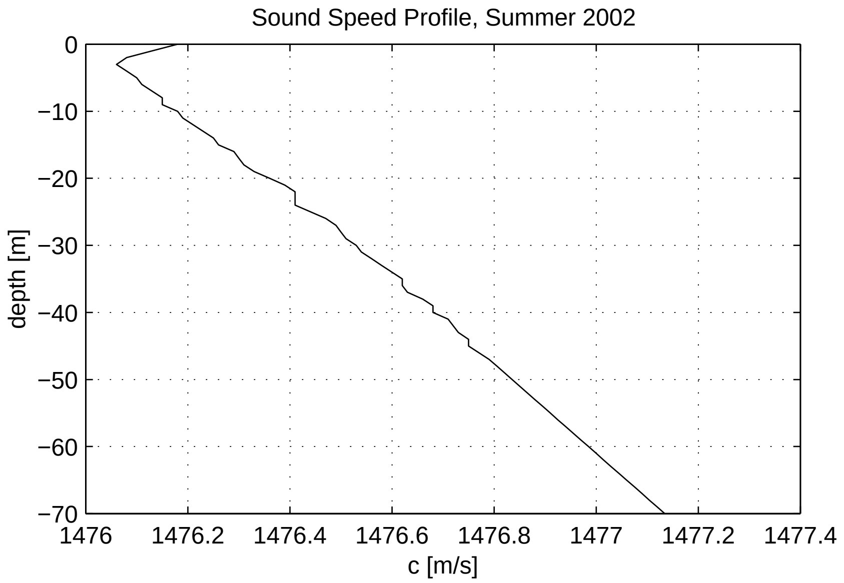

Figure 7: Sound speed profiles for the summer and winter.

3.3 Ambient Noise

Ambient noise includes all underwater noise at the study site apart from the anthropogenic (man-made) sources of study. This is commonly noise from wind and waves, biological noise, distant shipping etc. Ambient noise was recorded in Glacier Bay as part of the Park's underwater acoustic monitoring program (Kipple 2002). Two samples were chosen. The first recording was fairly noisy, containing the sound of moderate wind and rain. It was considered the more 'typical' ambient noise recording based on 2000-2002 ambient noise statistics. The second recording was quieter and considered rather uncommon, prevalent only about 10% of the time. Fig. 3 shows one-third octave band levels of the two noise recordings.

4. Humpback Whales

Biological impact is computed for the humpback whale, a baleen whale (Order *Cetacea*, Suborder *Mysticeti*).

Figure 8: A humpback whale, Megaptera novaeangliae.

Humpback whales are present in Glacier Bay from spring to fall. They concentrate along the shores, but are found throughout the lower Bay area evaluated here (Fig. 9).

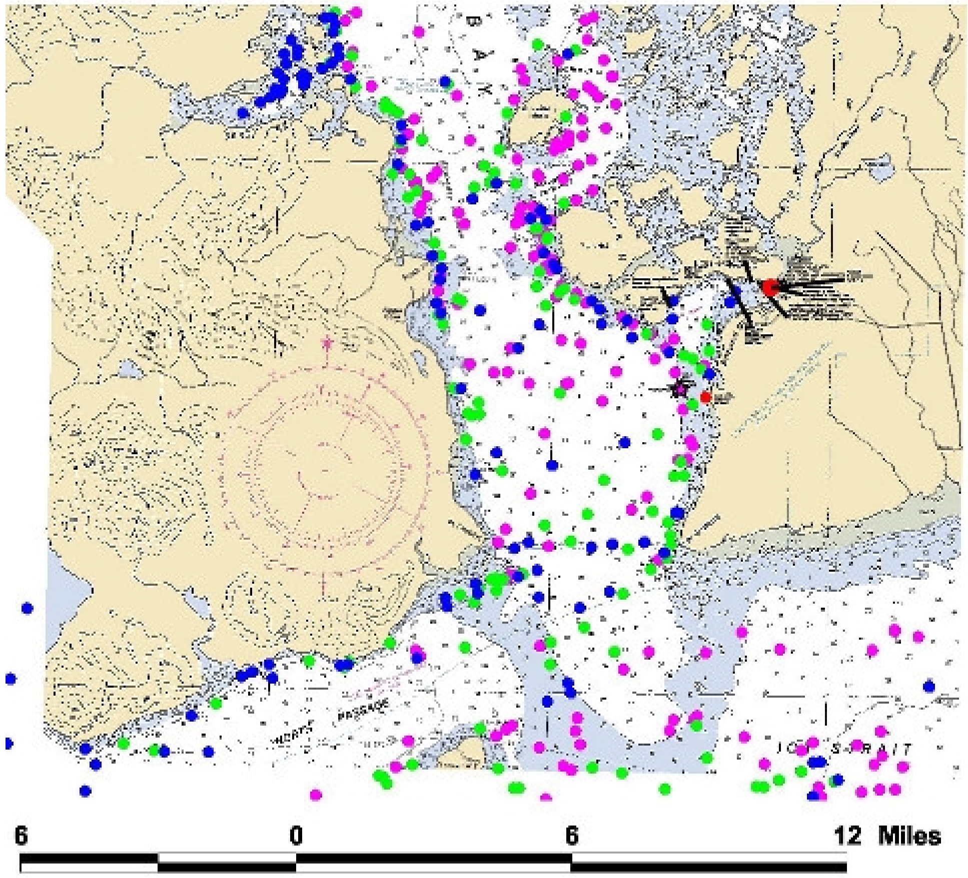

Figure 9: Marine chart of the lower Glacier Bay study area with humpback whale locations, 2000-2002. Humpback whale location dots from 2000 are pink, 2001 are green, and 2002 are blue.

4.1 Audiogram

Mysticetes do not exist in captivity in aquaria and they have therefore been inaccessible for bioacoustic measurements such as hearing thresholds at various frequencies (audiograms) and critical bands. Scientists in the US have been working on the development of a portable electrophysiological system that should ultimately be able to measure audiograms electrophysiologically on live, stranded or entangled animals within a few minutes. However, so far, due to technical problems, no audiogram has been recorded successfully. A gray whale calf spent a couple of months at SeaWorld San Diego. Audiogram measurements were attempted but were unsuccessful due to logistic and technical difficulties [Ridgway and Carder 2001].

All mammalian (terrestrial and marine) audiograms measured so far are U-shaped, identifying a frequency band of best hearing sensitivity, with decreasing sensitivity at lower and higher frequencies. At the frequencies of best sensitivity, absolute detection thresholds range between 40-70 dB re 1 μPa in odontocetes and pinnipeds. It is therefore often assumed that mysticetes have similar absolute thresholds at their frequencies of best hearing.

Baleen whale inner ear anatomy has been studied with dissected ears of dead, stranded animals. Ketten [1991, 1992, 1994, 1997] concluded that baleen whales are most sensitive at low sonic to infrasonic (<20Hz) frequencies. The basilar membrane of the cochlea (inner ear) is much broader, thinner and less rigidly supported than in odontocetes, who are high-frequency hearing specialists.

Houser *et al*. [2001] used such data from anatomical studies of humpback whale basilar membranes in combination with psychoacoustic data and anatomical hearing indices of well-studied land-mammals (the cat and the human) to predict a humpback whale audiogram of relative hearing sensitivity. It is plotted twice in Fig. 3, it was positioned on the y-axis such that the minimum threshold at the frequency of best hearing was 40 dB re 1μPa for the first curve and 70 dB re 1 μPa for the second curve. If one assumed that the humpback had absolute thresholds in the range of other non-baleen marine mammal species, the true humpback audiogram should lie somewhere between the two curves.

All animals can hear their own vocalizations and usually the frequency bandwidth of vocalizations overlaps with the frequency range of best hearing sensitivity. The audiogram shows maximum sensitivity between 2-6 kHz, and a region of best sensitivity (defined as relative sensitivity < 0.2) between 700 Hz and 10 kHz. The range of best sensitivity corresponds to the range of humpback calls as listed below. However, maximum sensitivity occurs at slightly higher frequencies than what one would have expected from humpback calls and ear anatomy. Houser *et al*. [2001] suggested that this could be an inherent contribution of the cat and human audiograms used to predict the humpback audiogram.

Behavioral reactions of baleen whales to biological and industrial sounds have been measured in the field. Obviously, animals hear the sounds they react to. These studies give absolute suprathresholds of hearing. Animals might not react to a sound that is just audible, but only react to a sound that is a certain level louder. Reaction thresholds will depend on the current behavioral state of the animal; its previous experience with the particular (similar or other) sound (habituation versus sensitization); age, gender and health of the animal; group composition (groups with calves appear more responsive); habitat and geographic location (e.g. close to shore vs. offshore); season and time of day. The lowest reported behavioral thresholds for humpbacks were 80-90 dB re 1 μPa received level from pingers at 4 kHz (Todd *et al*. 1992). Assuming that the response threshold likely lies somewhat above the audibility threshold, absolute sensitivity at 4 kHz could well be near the upper range of best sensitivity of other marine mammals: 70dB.

Ambient noise in the ocean at the humpback's frequencies of best hearing sensitivity is quite high. Even in quiet conditions (sea state 1) without any industrial activities nearby, average ambient noise levels below 1 kHz are above 70 dB re 1 μPa (one-third octave band levels). Therefore, acoustic detection thresholds of biological and industrial sounds might be limited by ambient noise rather than the baleen audiogram at those frequencies.

Clark and Ellison [2003] argue that ambient noise in the ocean likely played an evolutionary role in shaping marine mammal audiograms. They also assume that baleen whales should be most sensitive at the frequencies of their own calls. Historical levels of ambient noise (without industrial sources like shipping) might have shaped the humpback audiogram at these frequencies. Clark and Ellison [2003] use a 10^{th} percentile spectrum of ambient noise and add the critical ratio measured with other mammals. Critical ratios relate the energy of a signal to the energy of a noise at detection threshold. Clark and Ellison argue that evolution should have located the audiogram such that the dynamic range of the auditory system be used most efficiently. Critical ratios in other mammals range between 16-24 dB re 1Hz. The resulting upper and lower envelope of their baleen whale audiogram is shown in Fig. 3.

In the following impact assessment, Clark and Ellison's audiograms were used for low frequencies and the audiograms derived from Houser *et al*. were used for frequencies above 1kHz. It appears that with both sets of audiograms, audibility at mid-frequencies would be limited by ambient noise in Glacier Bay.

4.2 Critical Bandwidths

Critical bandwidths are a measure of the widths of the auditory filter of the target species. The mammalian auditory system can be represented as a series of bandpass filters. The intensity of received sound is integrated over frequency within each 'critical band'. It is the output of each critical band that determines whether an acoustic signal is audible or is masked by noise. There is no data on humpback whale critical bands in the literature. There is only one reference for critical band (CB) measurements in odontocetes. In a bottlenose dolphin above 30 kHz, critical bands were about a 1/3 octave wide [Au and Moore 1990]. At lower frequencies, critical ratios (CR) were measured for bottlenose dolphins [Johnson 1968, Au and Moore 1990], a beluga [Johnson *et al*. 1989] and a false killer whale [Thomas *et al*. 1990]. For a more detailed discussion of CB and CR, see Erbe *et al*. 1999. Using Fletcher's [1940] equal-power-assumption, critical bandwidths were estimated as $CB=10^{CR/10}$. For odontocetes, these were on average a 1/1/12th of an octave wide [Erbe *et al*. 1999]. Erbe [2000] corroborated Fletcher's equal-power-assumption for odontocetes (beluga whales).

Houser *et al*. [2001] further applied 'evolutionary programming' to develop a bandpass filter model of the humpback ear, yielding a similar audiogram as plotted in Fig. 3. The modelled bandpass filters, however, should not be used directly as indicators of critical bandwidths [pers. comm. 2002]. In the absence of indicators for critical bandwidths in baleen whales, the 1/1/12th octave band approach is applied here.

4.3 Vocalizations

Humpback whales emit a variety of sounds, the most extensively studied being their long-duration song on the winter breeding grounds. The dominant frequencies of song lie between 120 – 4000 Hz, with a total bandwidth of 20-8000 Hz and weak high-frequency components up to and above 15 kHz [e.g. Thompson *et al*. 1979; Payne and Payne 1985; Au *et al*. 2001a, 2001b; Cerchio *et al*. 2001]. Source levels have been estimated to 144-189 dB re 1 μPa @1m. On the summer foraging grounds in Alaska, moans of 0.2-1s duration, 175-192 dB re 1 μPa @1m source level, 300-500 Hz dominant frequency, 20-2000 Hz bandwidth are heard [e.g. Thompson *et al*. 1986, Cerchio and Dahlheim 2001]. In Glacier Bay, a signal that is very often heard is referred to here as a 'whup'. It was recorded by Glacier Bay National Park and Preserve on April 3, 2003. The precise source level of this particular sample was unknown, although the whale was known to be quite near the hydrophone when the recording was made.

The corresponding spectrogram is shown in Fig. 10. It was recorded with 44.1 kHz sampling frequency, 16 bit resolution. The frequency resolution of the spectrogram is 21 Hz. The time series was Hamming windowed with 50% overlap. A 1/12th octave band level spectrum is shown in Fig. 3.

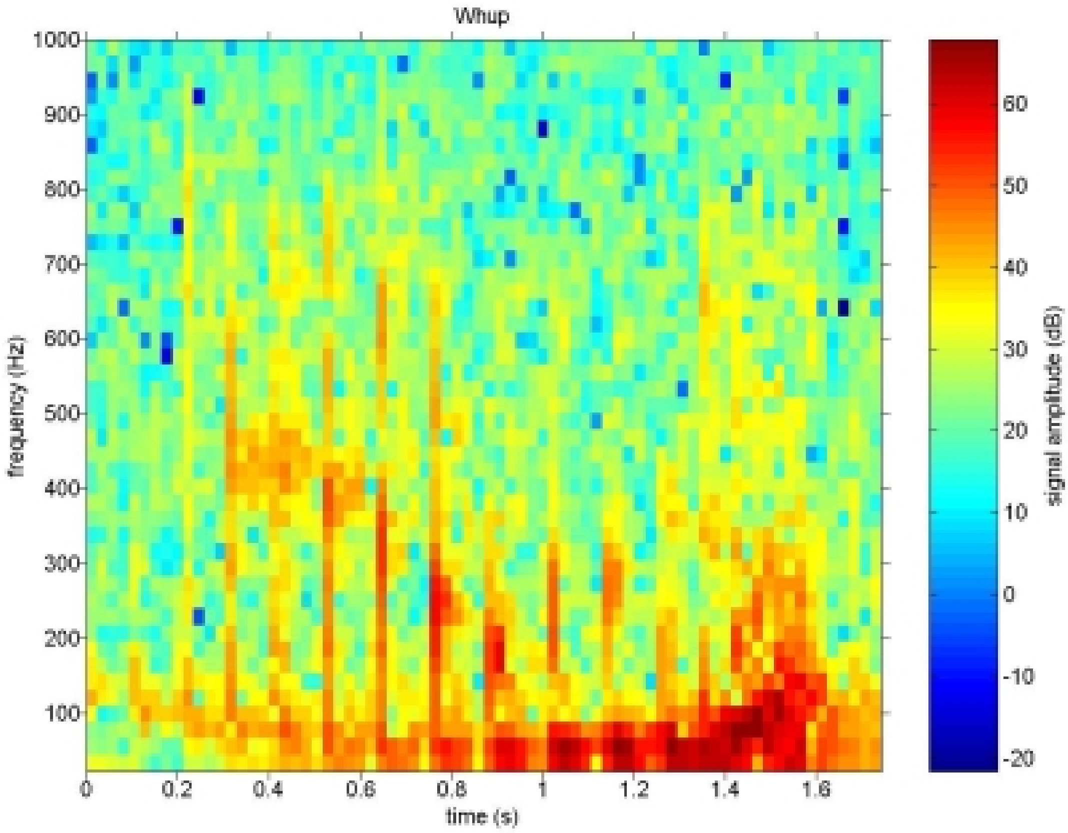

Figure 10: Spectrogram of the humpback call used for masking.

4.4 Behavioral Responses to Noise

Maybaum [1993] studied the response of humpback whales in Hawaii to a 3.3 kHz sonar. Todd *et al*. [1992] reported a reduced entanglement of humpbacks in nets fitted with pingers emitting 4 kHz tones at 80-90 dB re 1µPa @1m. Tyack [1998], Miller *et al*. [2000] and Biassoni *et al*. [2000] observed humpback whale reactions to SURTASS LFA sonar (100-500 Hz) at received levels of 120-150 dB re 1 µPa. In another study, humpback whales approached a synthetic frequency-modulated sweep between 10-1400 Hz at received levels of 106 dB re 1 µPa [Frankel *et al*. 1995]. Humpback whales prolonged their dives and changed their swim direction near the ATOC 75 Hz signal at received levels of 98-130 dB re 1 µPa in the 60-90 Hz band [Frankel and Clark 1998, 2000]. Humpback whales approached an underwater loudspeaker playing back humpback song between 400-550 Hz at received levels of 100-115 dB re 1 µPa [Frankel and Herman 1993, Frankel *et al*. 1995, Tyack and Whitehead 1983]. Baker and Herman [1989] observed behavioral responses of humpback whales to ships in Glacier Bay. Breaches, lunges and head-slaps began when the received noise level of a cruise ship suddenly increased (due to switching of engines/thruster etc.) and continued while received levels were 125-130 dB at the whales, broad-band. A 125dB threshold is used to model behavioral responses to both Capelin and the cruise ship.

4.5 Hearing Damage

Humpback whales are susceptible to hearing damage from underwater noise as has been shown with dissected ears of dead, stranded animals [Ketten *et al*. 1993, Ketten 1995]. However, exposure characteristics and levels were unknown. There is no data demonstrating the noise levels and durations that would cause hearing damage in humpback whales. Data from bottlenose dolphins [Au *et al*. 1999], three pinniped species [Kastak *et al*. 1999] and humans [Kryter 1985] are used instead after adjusting for the humpback audiogram.

5. The Sound Propagation Model

The sound propagation model was based on ray theory [Jensen *et al.* 1994]. Rays were traced in two dimensions through the ocean environment in Glacier Bay, described by its bathymetry, sound speed profile and bottom sediment. The core of the ray model was the program RAY developed by Bowlin *et al.* [1992]. Functions for frequency-dependent absorption, a search for eigenrays, and an integration of rays over a grid of receivers were added to Bowlin's code by Erbe [Erbe and Farmer 2000a]. Given a source spectrum of underwater noise, the outputs of the sound propagation model are matrices of received sound spectra as functions of range and depth.

For data reduction and computational speed, sound propagation was modeled for 120 center frequencies of adjacent 1/12th octave bands between 20 Hz and 20 kHz, listed in Table 1, rather than 1 Hz bands. The 1/12th octave band approach is further justified biologically, since it resembles the finest frequency resolution (critical bandwidth) of the auditory filter of any marine mammal tested so far. Twelfth octave band levels were computed from the one-third octave band levels plotted in Fig. 3 by splitting each one-third octave band into four 1/12th octave bands of equal intensity.

Table 1: Center frequencies [Hz] of adjacent 1/12th octave bands.

Octave Number									
1	2	3	4	5	6	7	8	9	10
20	40	80	160	320	640	1280	2560	5120	10240
21	42	85	170	339	678	1356	2712	5424	10849
22	45	90	180	359	718	1437	2874	5747	11494
24	48	95	190	381	761	1522	3044	6089	12177
25	50	101	202	403	806	1613	3225	6451	12902
27	53	107	214	427	854	1709	3417	6834	13669
28	57	113	226	453	905	1810	3620	7241	14482
30	60	120	240	479	959	1918	3836	7671	15343
32	63	127	254	508	1016	2032	4064	8127	16255
34	67	135	269	538	1076	2153	4305	8611	17222
36	71	143	285	570	1140	2281	4561	9123	18246
38	76	151	302	604	1208	2416	4833	9665	19331

Even though it is obvious from Fig. 3 that the boats are audible to humpback whales below 20Hz, the ray approach of the model does not allow to model any lower in frequency.

Received signal spectra from both vessels were calculated for a grid of receiver locations every 3m in depth and every 10m in range from 10m to 100m, then every 50m out to 1 km range, then every 1 km out to 15 km range, and every 5 km beyond that. Transmission loss is defined as the ratio of source intensity to received intensity. As the ray model was frequency-dependent, transmission loss (TL) was a function of range, depth and frequency. TL was therefore integrated over all 1/12th octave bands and thus represents a broadband transmission loss over 20 Hz – 20 kHz.

6. The Bioacoustic Impact Model

The biological impact model was developed by Erbe for the Department of Fisheries and Oceans Canada, for environmental assessments of anthropogenic underwater noise [Erbe and Farmer 2000a, 2000b]. The model estimates over what range and depth the noise is audible to marine mammals, interferes with marine mammal communication, leads to a behavioral reaction and causes physiological damage to the animals' auditory system. The model takes the received sound spectrum levels computed by the propagation algorithm as input. It further requires some basic bioacoustic information on the target species. This information includes an audiogram (a hearing curve), the width of the critical bands (auditory filters), vocalizations (or other signals to be masked by the anthropogenic source of interest), thresholds for behavioral responses (avoidance, disturbance, change of dive-pattern or breathing-pattern, or other), and thresholds for hearing damage.

6.1 Zone of Audibility

The zone of audibility of a vessel noise source predicts over what ranges and depths the noise is audible to the target marine mammal species. Audibility is limited by the audiogram of the target species and by ambient noise at the oceanographic location of interest. The audibility model first computes critical band levels of the anthropogenic noise. It then subtracts the transmission loss data from the sound propagation model at all ranges and depths to compute received noise intensity in the animal's critical bands. The model compares the anthropogenic noise band levels to the animal audiogram and to band levels of the ambient noise (also integrated into critical bands). If any of the received noise band levels are above the audiogram and ambient noise levels at the corresponding frequencies, then the anthropogenic noise is considered audible. This argument is based on Fletcher's equal-power-assumption [Fletcher 1940], which was originally derived for humans, but later corroborated for some marine [Erbe 2000] and terrestrial animals.

6.2 Zone of Masking

The zone of masking predicts over what ranges and depths the anthropogenic noise might obscure communication calls of marine mammals. Masking depends on the loudness of the call. The louder the call, the less likely it is to be masked. Two communicating whales close together will be less affected by masking noise than two animals further apart. The degree of masking as a function of distance between two communicating animals was examined in Erbe [1997], however, the developed model has not yet been incorporated into the current software package. Therefore, the current software only models the case where two communicating animals are furthest apart, so far that they can just hear each other in the presence of ambient noise and absence of ship noise. This is considered the 'conservative' case. The extent of the zone of masking is greatest, because the call is quietest, i.e., just recognizable in the absence of the masking noise. The predicted ranges of masking are hence *maximum possible ranges* of impact. In the real world, masking further depends on the directional hearing abilities of the listening animal. Masking will be strongest, when the noise and the signal come from the same direction. Directional hearing capabilities of humpback whales are unknown. At low frequencies, directional resolution is physically 'difficult' in any case. The current model ignores directional hearing and thus simulates the strongest case, yielding conservative impact ranges.

The software routine computing the zone of masking carries out the following steps. Critical band levels of the call to be masked and of the local ambient noise are computed. The call band levels are compared to the audiogram of the target species and to the ambient noise band levels in order to decide at what minimum level the call would just be recognizable in the local ambient noise. Erbe [2000] distinguished between signal detection and signal recognition. The signal was a beluga vocalization containing a base frequency and harmonic and non-harmonic higher components. In the absence of masking noise, the trained animal stopped recognizing the call as soon as the major frequencies (carrying most of the acoustic energy) dropped below audibility. Other spectral components of the call, however, would have been audible (detectable) to much lower sound pressure levels. The reverse was also true: The call remained recognizable to the whale as long as the major frequency components remained audible, even though some spectral peaks were already inaudible or masked. It was concluded that the whale cued on the (two) major frequency peaks (carrying most of the energy) of the call. In the current software routine, the signal level is therefore lowered until the two major frequencies in the spectrum just surpass the audiogram and the ambient noise. The resulting spectrum is the quietest call that the animal can recognize.

Critical band levels for the vessel noise are computed. Transmission loss (as calculated in the sound propagation model) is subtracted at each range and depth. The received noise band levels are then compared to the minimum recognizable signal levels. If the two major peaks of the signal are above the corresponding band levels of the noise, then the model predicts no masking. Masking is assumed to occur if the band levels of the noise are equal to or higher than the band levels of the signal following Fletcher's [1940] equal-power-assumption. This assumption was corroborated with behavioural auditory experiments involving a beluga whale (Erbe and Farmer 1998, Erbe 2000).

6.3 Zone of Behavioral Reaction

The zone of behavioral reaction predicts over what ranges animals are likely to respond behaviorally to the vessel noise. The reaction threshold may depend on a variety of factors, such as the received noise level, the bandwidth of the vessel noise, the vessel-to-ambient noise ratio, the behavioral state of the animals prior to noise exposure, age and sex of the animals, past experience, habituation or sensitization. The software routine requires knowledge of sound pressure levels that have reportedly led to observed behavioral changes in the target species, under certain circumstances. The broad-band levels reported by Baker and Herman [1989] are used in the current model.

The software routine takes the noise source spectrum and subtracts the transmission loss at each range and depth that was calculated with the sound propagation model. Broad-band received noise spectrum levels are computed. If the received sound levels are greater than or equal to the reported threshold levels, the documented behavioral response is predicted to occur, otherwise not.

6.4 Zone of Hearing Damage

The zone of hearing damage predicts over what ranges and depths a temporary or permanent hearing loss might occur. Hearing impairment depends on the spectral characteristics of the noise, the amount of energy per time for impulsive noise, the duration of noise exposure and the duty cycle or recovery time in between exposures. There is only a handful of studies in the peer-reviewed literature on auditory threshold shifts in marine mammals. This software routine therefore estimates hearing damage for humpback whales from very specific noise-exposure experiments with bottlenose dolphins, harbor seals, California sea lions, northern elephant seals and humans.

(1) Au *et al*. [1999] exposed a bottlenose dolphin to octave band noise between 5 and 10 kHz for 30-50 minutes. The level was 96 dB above the normal center-frequency threshold at 7.5 kHz. Immediately afterwards, they measured a temporary threshold shift (TTS) of 12-18 dB at the center frequency. Schlundt *et al*.'s [2000] study with bottlenose dolphins indicates that maximum hearing damage occurs half an octave to one octave above the center frequency of the damaging sound. This is also the case in humans and other terrestrial mammals [Yost 1994, Clark 1991]. Unfortunately, Au *et al*. [1999] did not measure TTS above the center frequency, but according to Schlundt's study, Au's animals might have received up to 10 dB higher TTS an octave above 7.5 kHz.

(2) Kastak *et al*. [1999] exposed a harbor seal, two California sea lions and one northern elephant seal to octave band noise 60-75dB above the normal center-frequency thresholds. After 20 minutes, threshold shifts of on average 4.8 dB were measured at frequencies between 100 Hz and 2000 Hz. Hearing recovered to normal within 24h.

(3) There is no data on permanent hearing loss in marine mammals. At the moment we can only extrapolate to marine mammals from data for terrestrial mammals. For human ears, Kryter [1985] estimated a permanent threshold shift (PTS) of 2-5 dB at the most sensitive frequency (4 kHz) after 50 years of 8h/d exposure to noise levels of 60 dBA. Equally long exposure to 75 dBA increased PTS to 8-10 dB at 4 kHz. Kryter quoted A-weighted sound levels in dBA. These are broadband sensation levels, weighted relative to the 40-phon equal-loudness contour in humans. The low-frequency and high-frequency ends of the noise spectrum are de-emphasized corresponding to the equal-loudness contour, before integrating the energy over all frequencies.

The software algorithm predicting TTS and PTS takes all three data sets into account. The noise source spectrum levels are reduced by the transmission loss calculated in the sound propagation model. Octave band levels of the received vessel noise are then calculated at a series of frequencies. If these are more than 96 dB above the target species' audiogram, a TTS of at least 12-18 dB is modeled to occur after 30-50 min according to Au *et al*.'s [1999] study. If these are more than 60 dB above the audiogram, a TTS of 4.8 dB is modeled after 20 min exposure according to Kastak *et al*.'s [1999] study.

For PTS, equal-loudness contours have not been measured in marine mammals yet. In other mammals, they roughly follow the audiogram. Therefore, the target species audiogram is subtracted from the critical band levels of the vessel noise at each range and depth. Then energy is integrated over all frequencies. This yields a broadband sensation level. If it is greater than 60 dB re 1µPa, a PTS of 2-5 dB is considered possible after decades of daily exposure.

7. Results

7.1 Transmission Loss

Fig. 11 shows the results of the ray propagation model for a boat located in the top left corner. There is a near-surface sound channel, in which rays propagate by undulation without surface or bottom interaction. These rays carry sound energy very far. The general profile is typically arctic; rays are upwards refracting. Convergence zones yielding high received sound levels and shadow zones yielding low received sound levels can be seen. In this model, shadow zones are only reached by rays reflecting off the bottom. Two such rays that reflect off the bottom at 9-10km range are drawn. Fig. 12 shows the transmission loss, integrated over all frequencies from 20 Hz to 20 kHz.

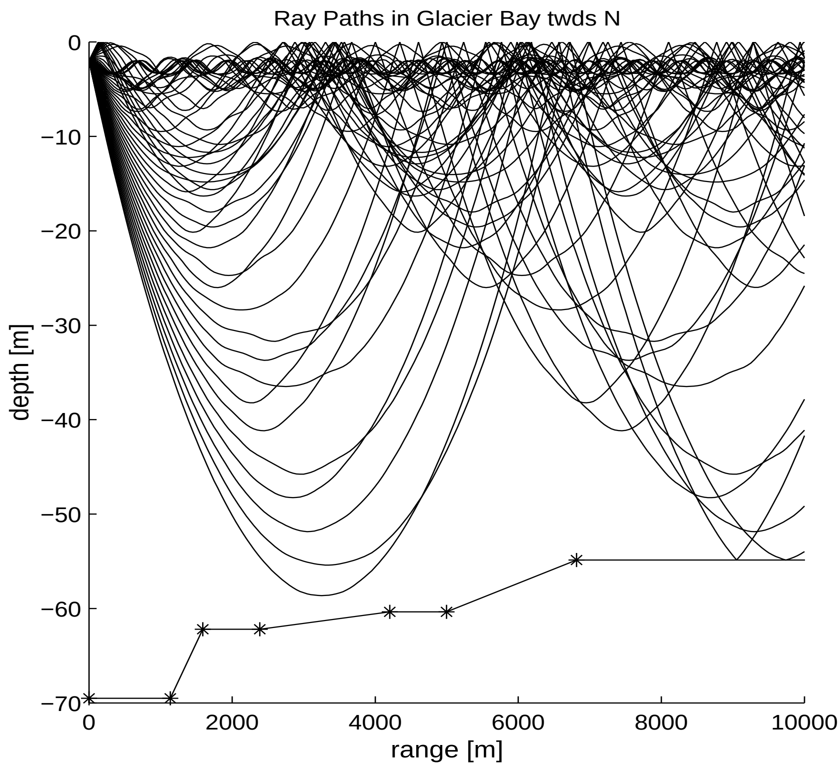

Figure 11: Ray paths in Glacier Bay.

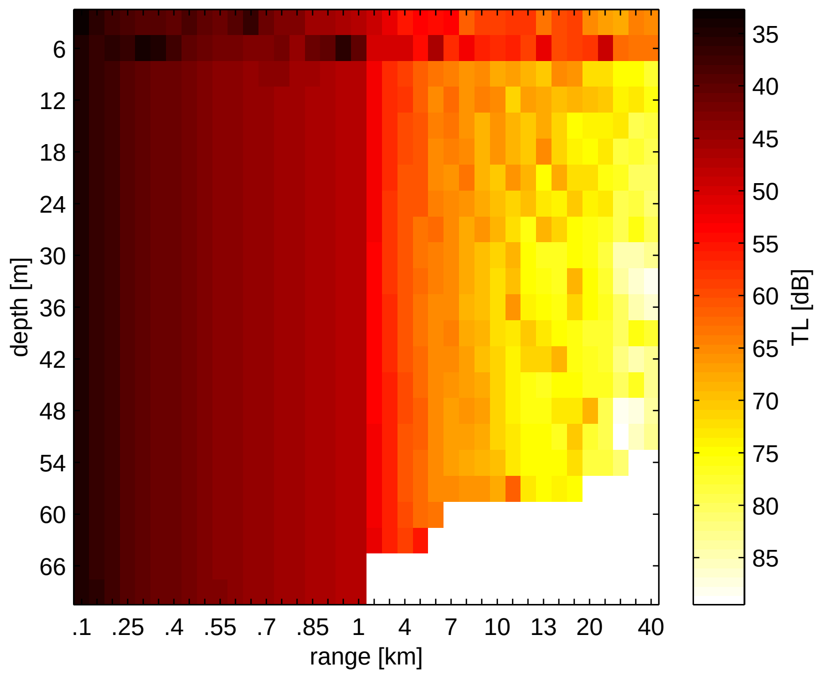

Figure 12: Transmission loss during the summer. Please note the changing x-axis scale. TL was computed every 50m between 100m and 1km range, then every 1km out to 15km range and every 5km beyond that.

7.2 Capelin in Typical Ambient Noise

Zones of impact plotted in Fig. 13 correspond to the upper estimate of the humpback audiogram; zones of impact plotted in Fig. 14 correspond to the lower estimate of the humpback audiogram. The true humpback audiogram is expected to lie somewhere in between.

Capelin was predicted audible to humpback whales over all depths and ranges modelled within Glacier Bay, for both the upper and the lower audiogram envelopes. In the near-surface sound-channel at around 3m depth, sound would be audible over much longer ranges. Near the boat, all frequencies were audible. At a few hundred meters range, the low and high frequencies became inaudible. At 40km range and depths below the sound channel, only the energy between 2-3kHz remained audible.

Given that Capelin's main energy lies at higher frequencies than the call's major energy, the zone of masking was small. The 'whup' was predicted to be unrecognizable over 400m range at depth and 1km range in the surface channel, using the upper audiogram envelope. With the lower envelope, masking occurred over 1km range at all depths.

A behavioral reaction was modelled over 2km range at depth and 7km range in the sound channel, plus at localized convergence spots beyond that. Given that the disturbance threshold was a broadband sound pressure level, the extent of the zone of disturbance is independent of the audiogram envelope used.

For the upper audiogram envelope, nowhere was Capelin loud enough to cause a TTS of 12-18 dB. With the lower audiogram envelope, a TTS of 12-18 dB was modelled over 550m range at depth and 1km range in the near-surface sound channel after 30-50 minutes of exposure. The TTS occurred at 2-3kHz, where Capelin is loudest and the audiogram after Houser *et al.* is most sensitive. A small TTS of 4.8dB was modelled over 1km range at all depths using the upper audiogram envelope; and over 20 km range at depth and 45km range in the sound channel using the lower audiogram envelope, after 20 minutes of exposure. At close ranges, TTS was modelled at frequencies between 100Hz and 10kHz. At the longest ranges, TTS would happen only at 2-3kHz. These threshold shifts are fully recoverable within less than 24 h. It is usually assumed that animals will try to avoid noise that causes even a small TTS. The studies on TTS showed that animals were reluctant to station in front of the TTS inducing transducer. It is, however, unknown how effectively a humpback can determine the direction to the sound source. If humpback whales have poor directional hearing abilities, then they might not be able to leave the zone of TTS within the TTS-inducing time frame.

An effect called masked TTS will likely reduce, perhaps prevent humpback whales from a TTS around Capelin. In the presence of two noises, a low-level ambient background noise and a high-level TTS-inducing noise, the level of measurable TTS decreases as the ambient level increases [Parker *et al*. 1976]. In humans, TTS is reduced by about 5dB if ambient noise is about 20dB above audibility at the TTS-inducing frequency [Humes 1980]. For humpback whales under typical ambient noise conditions in Glacier Bay, ambient noise is about 20dB above the upper audiogram and over 40dB above the lower audiogram at 2-3kHz. Using the data from Kastak *et al*. [1999], a TTS of 4.8dB was modelled where the octave band levels of the noise reached 60-75dB sensation (energy above the audiogram). Considering the masking effect of ambient noise, there would be no TTS unless the octave band levels were more than 75dB above the audiogram. Using the upper audiogram envelope, ambient noise of 20dB sensation at 2-3kHz would reduce the TTS ranges such that a small TTS would commence at 100m from the source (Fig. 15). For the lower audiogram envelope, ambient noise is more than 40dB above audibility, exhibiting an even greater masking effect on TTS, reducing the TTS ranges even further.

The zone of PTS extended over 1km for the upper audiogram envelope and 20km at depth, 45km in the sound channel for the lower envelope. The whales would have to be exposed to the corresponding sound levels of boats for 8h every day for many decades before the modeled PTS would emerge.

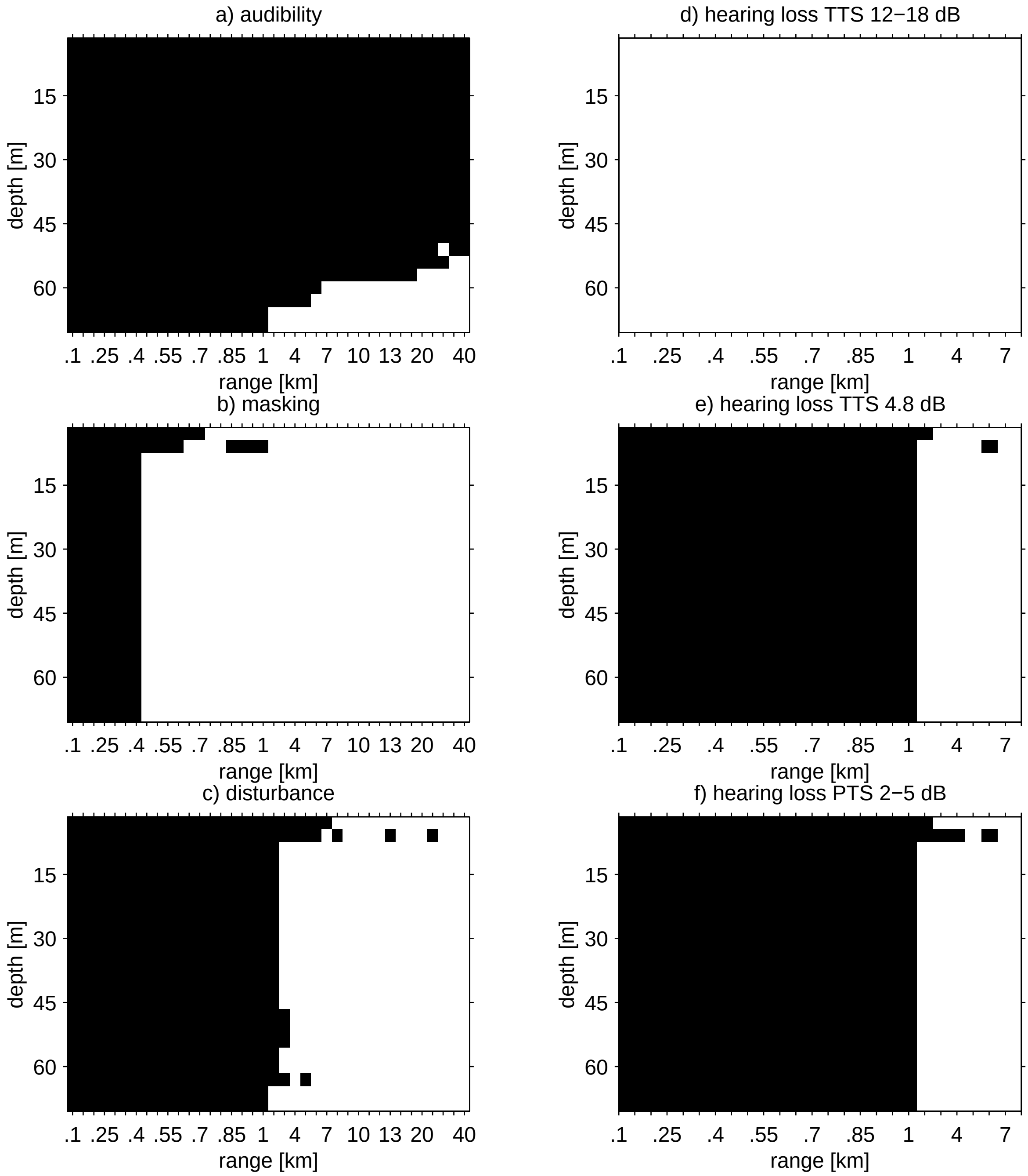

Figure 13: Bioacoustic impact of Capelin on humpback whales using the upper audiogram envelope and typical ambient noise. Between 1 and 7km, the bathymetry slopes upwards. Please note the changing x-axis scales. Impact was computed every 50m between 100m-1km range, then every 1km up to 15km range and every 5km beyond.

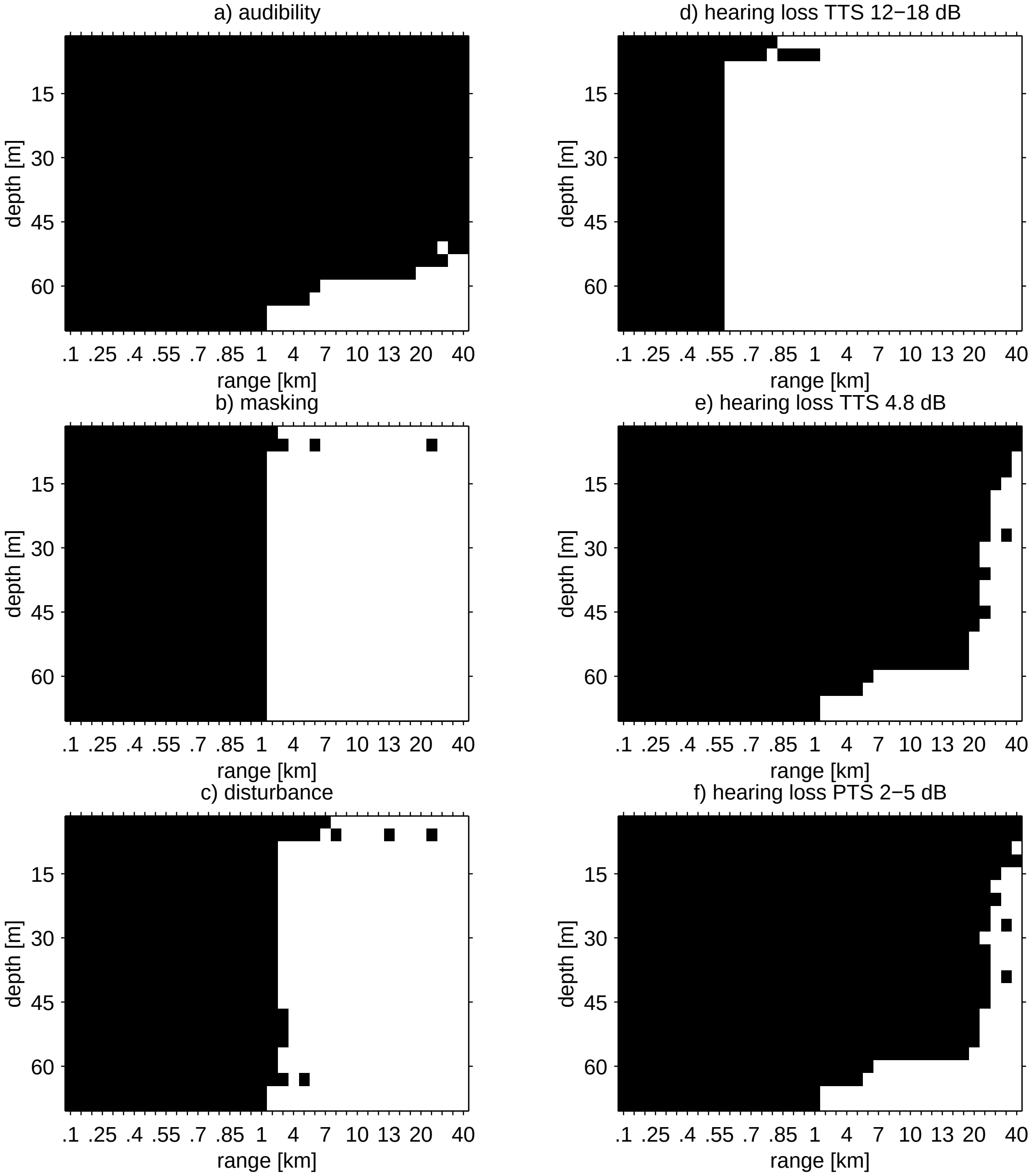

Figure 14: Bioacoustic impact of Capelin on humpback whales using the lower audiogram envelope and typical ambient noise. Between 1 and 7km, the bathymetry slopes upwards. Please note the changing x-axis scales. Impact was computed every 50m between 100m-1km range, then every 1km up to 15km range and every 5km beyond.

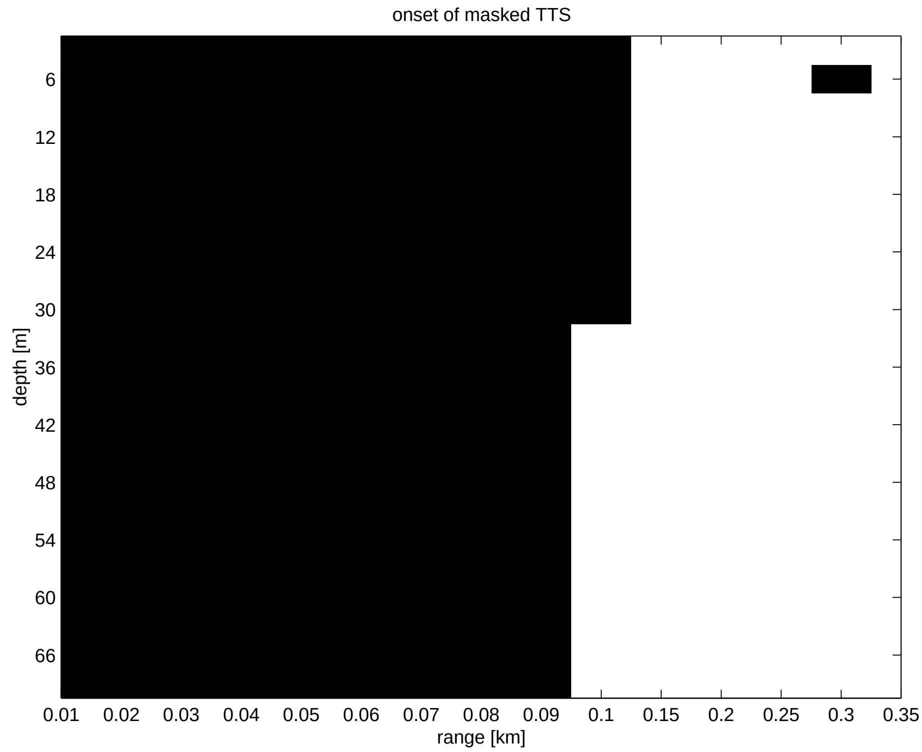

Figure 15: Zone of masked TTS for Capelin in typical ambient noise, upper audiogram envelope.

7.3 Capelin in Quiet Ambient Noise

With both the upper and the lower audiogram envelope, Capelin was modelled audible over all depths out to 40km range and beyond. The frequencies between 600Hz and 3.5kHz remained audible over the longest modelled ranges.

Capelin was predicted to mask the humpback 'whup' over 400m range at depth and about 1km range in the surface channel, based on the upper audiogram envelope. This is the maximum extent of masking, when the call and the ship noise come from the same direction and when the call is just recognizable in the ambient noise. The range of masking is short, because Capelin's acoustic energy peaks at 2-3kHz, outside the band of maximum energy of the 'whup'. Using the lower audiogram envelope, masking was predicted to occur over 1km range at all depths. Masking was independent of the type of ambient noise, because both ambient noise samples were below or just at the threshold of audibility at the main frequencies of the 'whup' for both audiogram envelopes.

A behavioral response was modelled over 2km range at depth, and 7km range in the sound channel, plus at a few localized convergence spots beyond 7km. This is independent of the audiogram used, because the threshold criterion was a broadband sound pressure level. The criterion was also independent of the type of ambient noise used.

Nowhere was Capelin loud enough to cause a TTS of 12-18dB or greater, based on the upper audiogram envelope. A lesser TTS of 4.8dB was modeled over 1km range after 20 min exposure.It happened at 2-3kHz. This TTS is expected to be recoverable within 24h. Given that the quiet ambient noise is only just audible at 2-3kHz, it is assumed to be unable to mask thus reduce the modelled TTS. For the lower audiogram envelope, a TTS of 12-18dB was modelled over 550m range at depth and 1km range in the sound channel after 30-50 minutes. It happened at 2-3kHz. A TTS of 4.8dB was modelled at the same frequencies over 20km range at depth and 45km range in the sound channel after 20 minutes. With the lower audiogram envelope, the quiet ambient noise lies about 30dB above audibility at 2-3kHz; TTS can therefore be expected to be masked thus reduced, if true audibility lies near the lower envelope.

For a PTS using the upper audiogram envelope, humpback whales would have to remain within 1km range of Capelin or similar boats for 8h per day for many decades. Using the lower envelope, PTS was modelled over 20km range at depth and 45km range in the sound channel, after prolonged exposure. This is most unlikely.

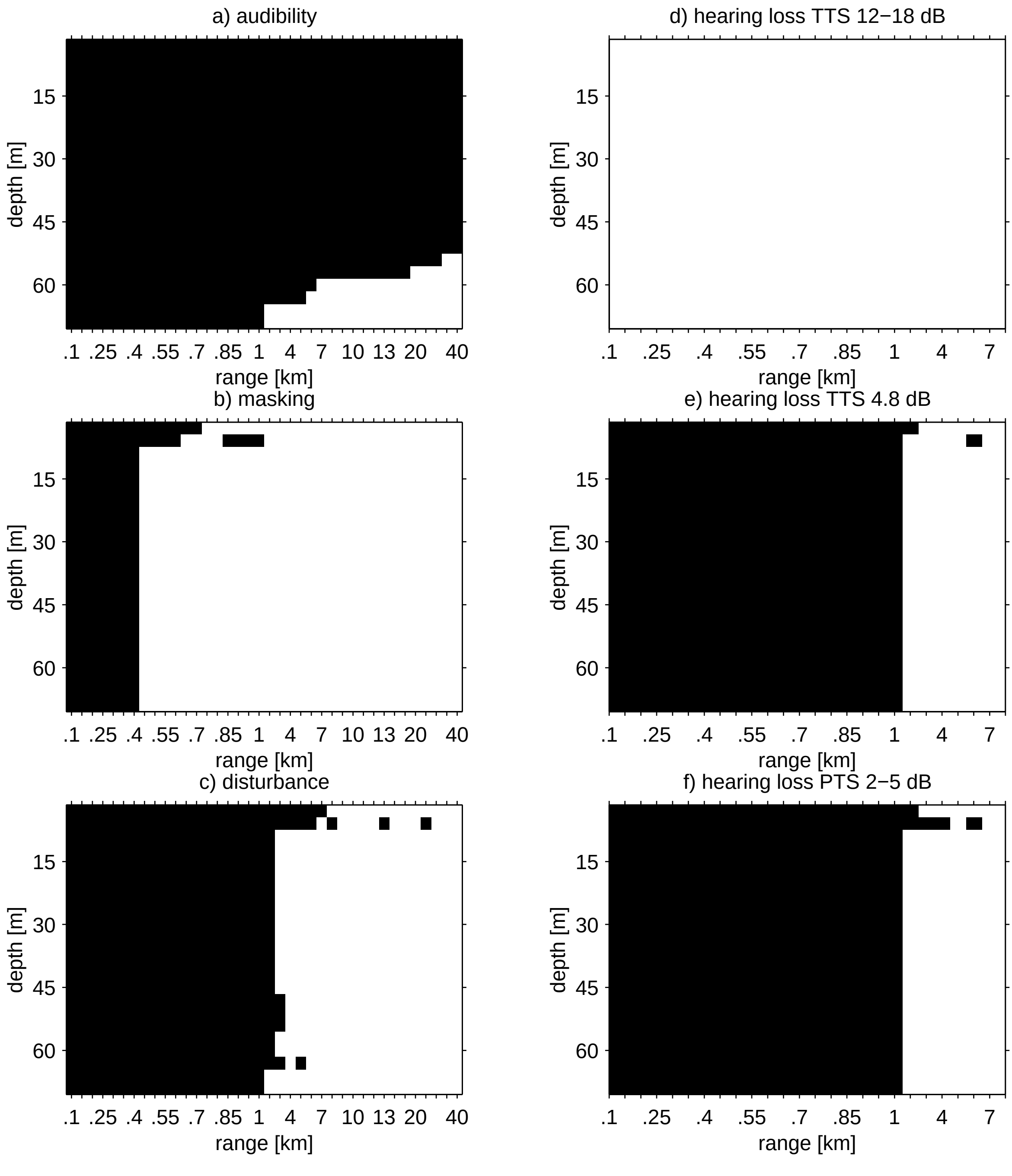

Figure 16: Bioacoustic impact of Capelin on humpback whales using the upper audiogram envelope and quiet ambient noise.

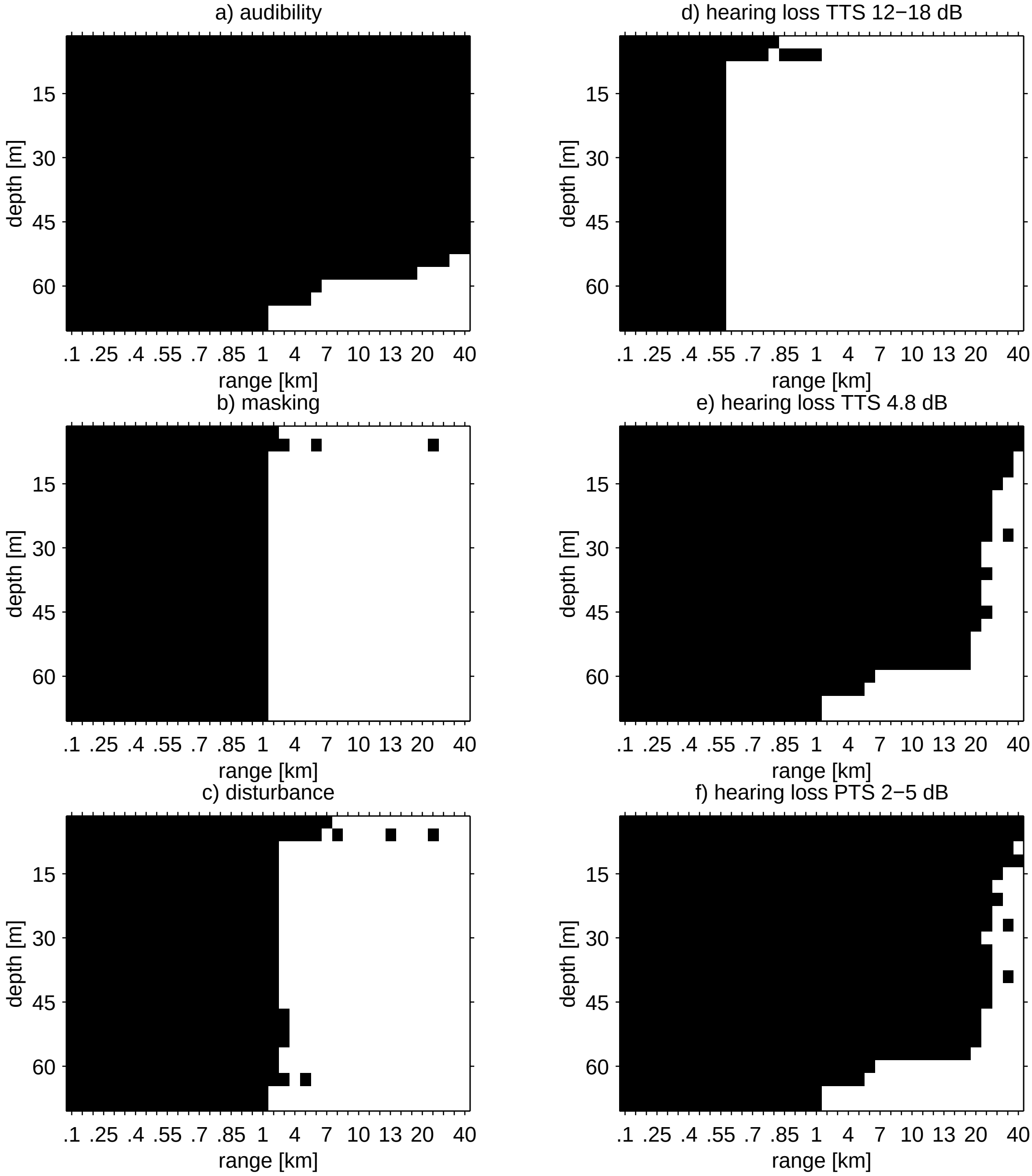

Figure 17: Bioacoustic impact of Capelin on humpback whales using the lower audiogram envelope and quiet ambient noise.

7.4 Cruise Ship in Typical Ambient Noise

The cruise ship was modelled audible over all depths out to ranges of 40km and beyond for both audiogram envelopes. At about 2-3km range, the high frequencies of the cruise ship spectrum dropped below audibility. At 40km range, only energy below 600Hz remained audible.

Masking of the humpback 'whup' also occurred over all depths and ranges modelled for both audiogram envelopes. The main energy of the cruise ship spectrum lies at the main frequencies of the humpback 'whup'. Therefore, the zone of masking is fairly large compared to the zone of masking for Capelin.

A behavioral response was predicted over 10km at depth and beyond 40km range in the sound channel. This zone is independent of the audiogram used, because the response criterion was a broadband sound pressure level.

For the upper audiogram envelope, a TTS of 12-18dB was modelled over 30m range and 48m depth after 30-50 min; it occurred only in the bandwidth of 80-100Hz. For the lower envelope, a TTS of 12-18dB was modeled over 80m at all depths; it occurred at 80-100Hz and at 1-6kHz. However, at 1-6kHz, typical ambient noise is about 20dB above audibility. It can thus be expected to reduce the amount of and the ranges of TTS by masking. For the upper envelope, a TTS of 4.8dB was modeled over 4km range at all depths and 50km range in the sound channel, after 20 min exposure. Near the ship, TTS occurred at all frequencies below 6kHz, at the longest ranges only the band between 80-100Hz was affected. For the lower envelope, a TTS of 4.8dB was modelled over 9km range at all depths and beyond 50km in the sound channel. It occurred at 80-100Hz as well as 1-6kHz at these long ranges. Again, the presence of typical ambient noise will result in a masked TTS, preventing a TTS at 1-6kHz altogether. In the 80-100Hz band, however, ambient noise is not loud enough to reduce or prevent TTS.

Using the upper audiogram envelope, a PTS of 2-5dB was modelled over 4km range at depth and about 50-55km range in the sound channel after prolonged exposure of 8h/day for 50 years. With the lower envelope the PTS zone extended to 11km at depth and beyond 55km in the sound channel.

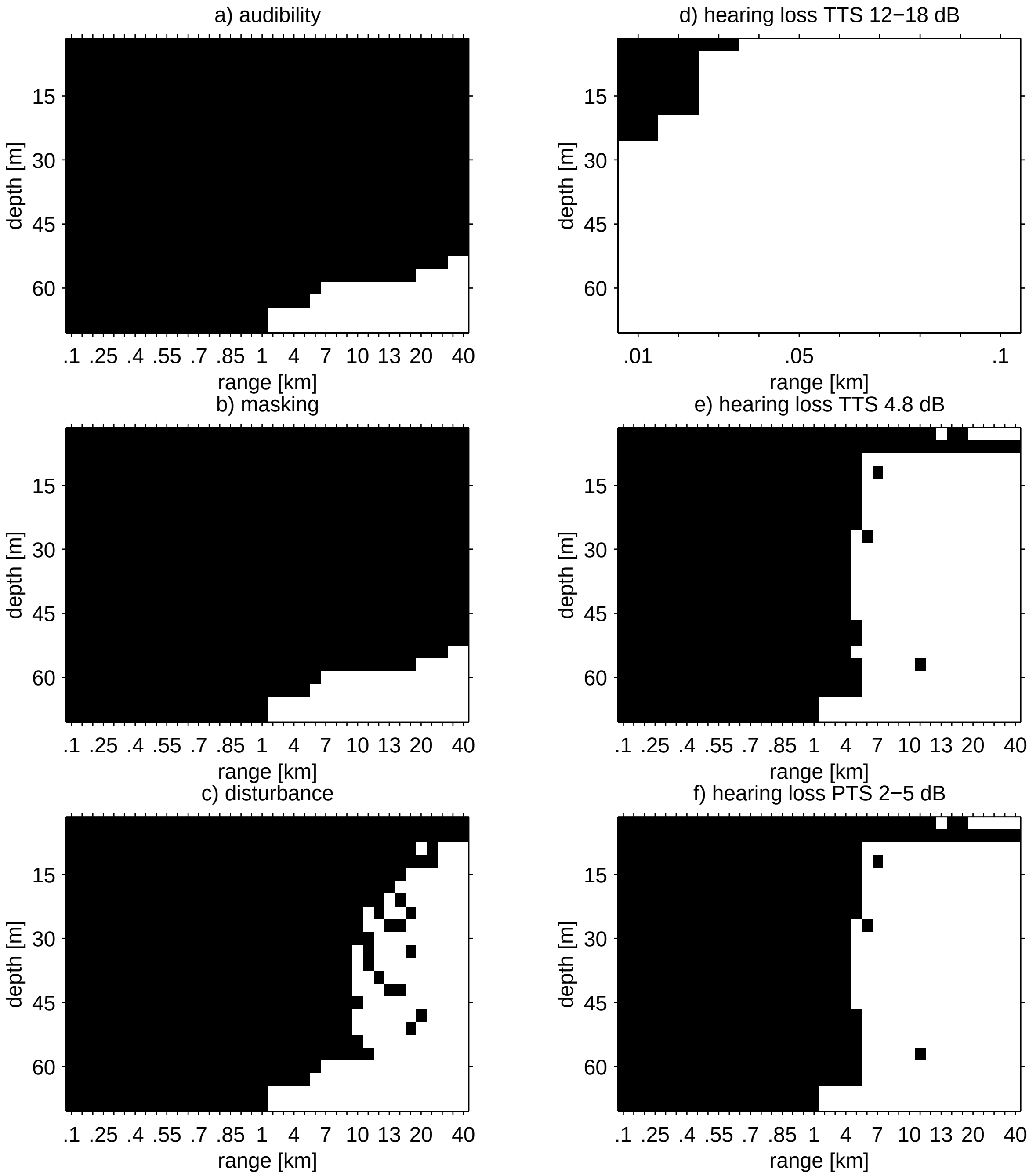

Figure 18: Bioacoustic impact of the cruise ship on humpback whales using the upper audiogram envelope and typical ambient noise.

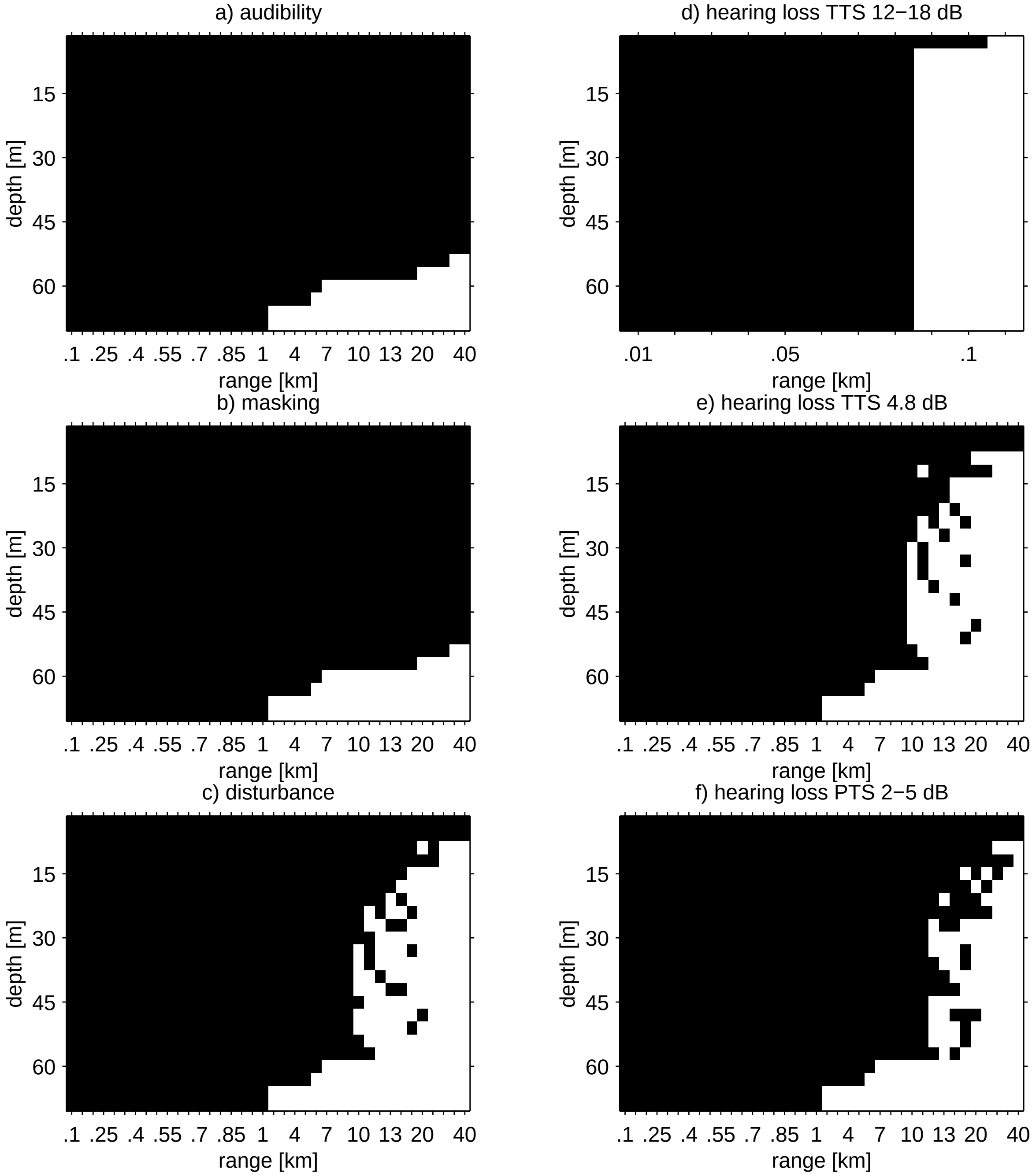

Figure 19: Bioacoustic impact of the cruise ship on humpback whales using the lower audiogram envelope and typical ambient noise.

7.5 Cruise Ship in Quiet Ambient Noise

The ship was modelled audible over all depths and beyond 40km range for both audiogram envelopes.

Given that the frequency band of main energy of the ship noise overlaps with the frequencies of main energy of the humpback 'whup', the zone of masking was large: > 40km range for both audiograms.

The criterion for behavioral reaction was independent of the audiogram used. The zone of behavioral response extended over 10 km at depth and beyond 40km range in the near-surface sound channel.

Using the upper audiogram, a TTS of 12-18dB was modelled after 30-50 min exposure within 30m range and 48m depth. It happened at frequencies between 80-100Hz. A TTS of 4.8dB was predicted over 4km range at depth and about 50km range in the sound channel, after 20 min. At close ranges to the ship, it happened at all frequencies below 6kHz, at the long ranges it happened only at 80-100Hz. Using the lower audiogram envelope, a TTS of 12-18dB was modelled over 80m range at all depths. It happened at 80-100Hz as well as 1-6kHz. However, given that even the quiet ambient noise lies 20-30dB above audibility at 1-6kHz for the lower audiogram, TTS at these frequencies would be masked thus reduced. A TTS of 4.8dB was modelled over 9km range at all depths and beyond 50km in the sound channel. It occurred at 80-100Hz as well as 1-6kHz at these long ranges. Again, the presence of typical ambient noise will result in a masked TTS, preventing a TTS at 1-6kHz altogether. In the 80-100Hz band, however, ambient noise is not loud enough to reduce or prevent TTS.

Using the upper audiogram envelope, a PTS of 2-5dB was modelled over 4km range at depth and about 50-55km range in the sound channel after prolonged exposure of 8h/day for 50 years. With the lower envelope the PTS zone extended to 11km at depth and beyond 55km in the sound channel.

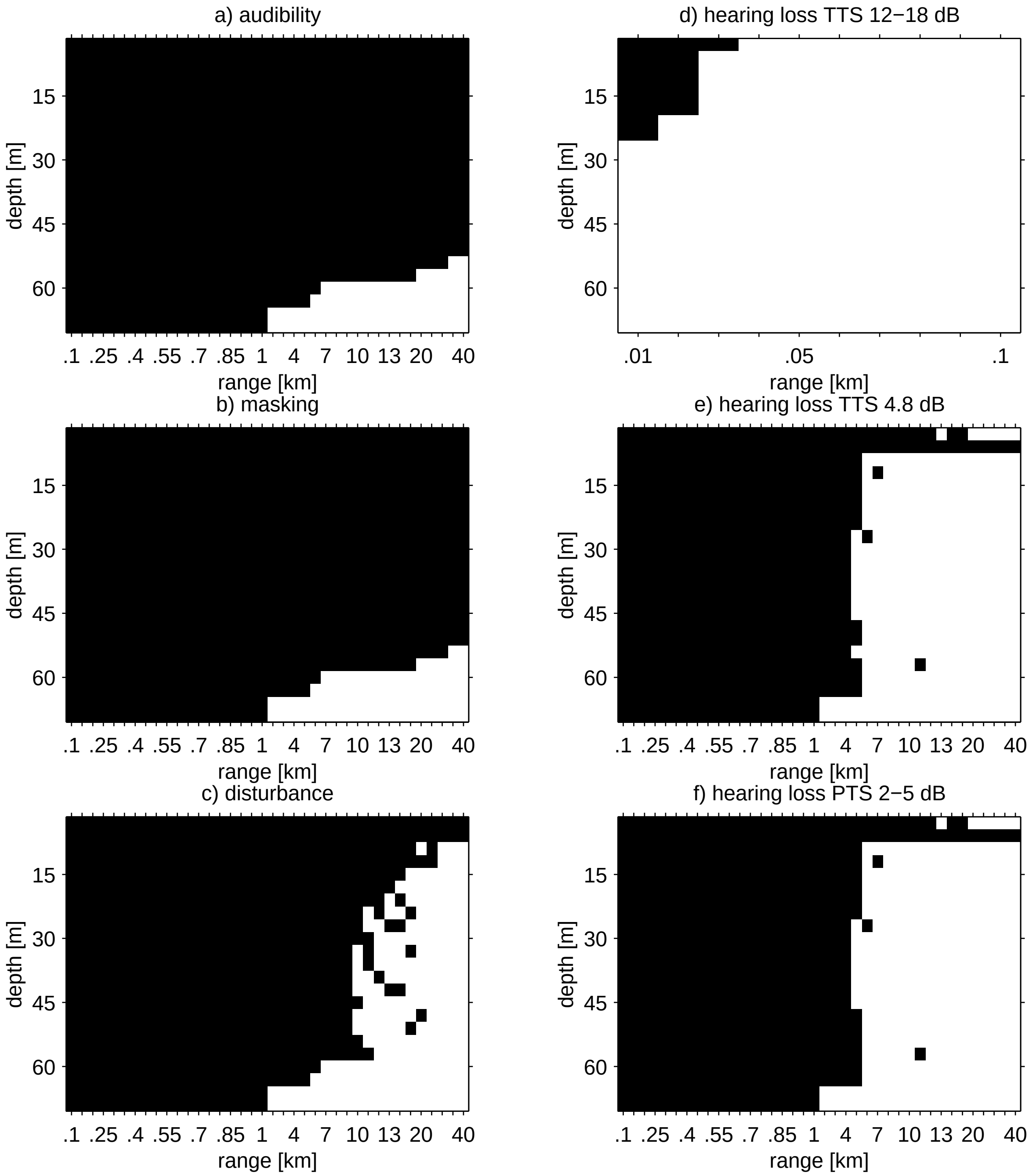

Figure 20: Bioacoustic impact of the cruise ship on humpback whales using the upper audiogram envelope and quiet ambient noise.

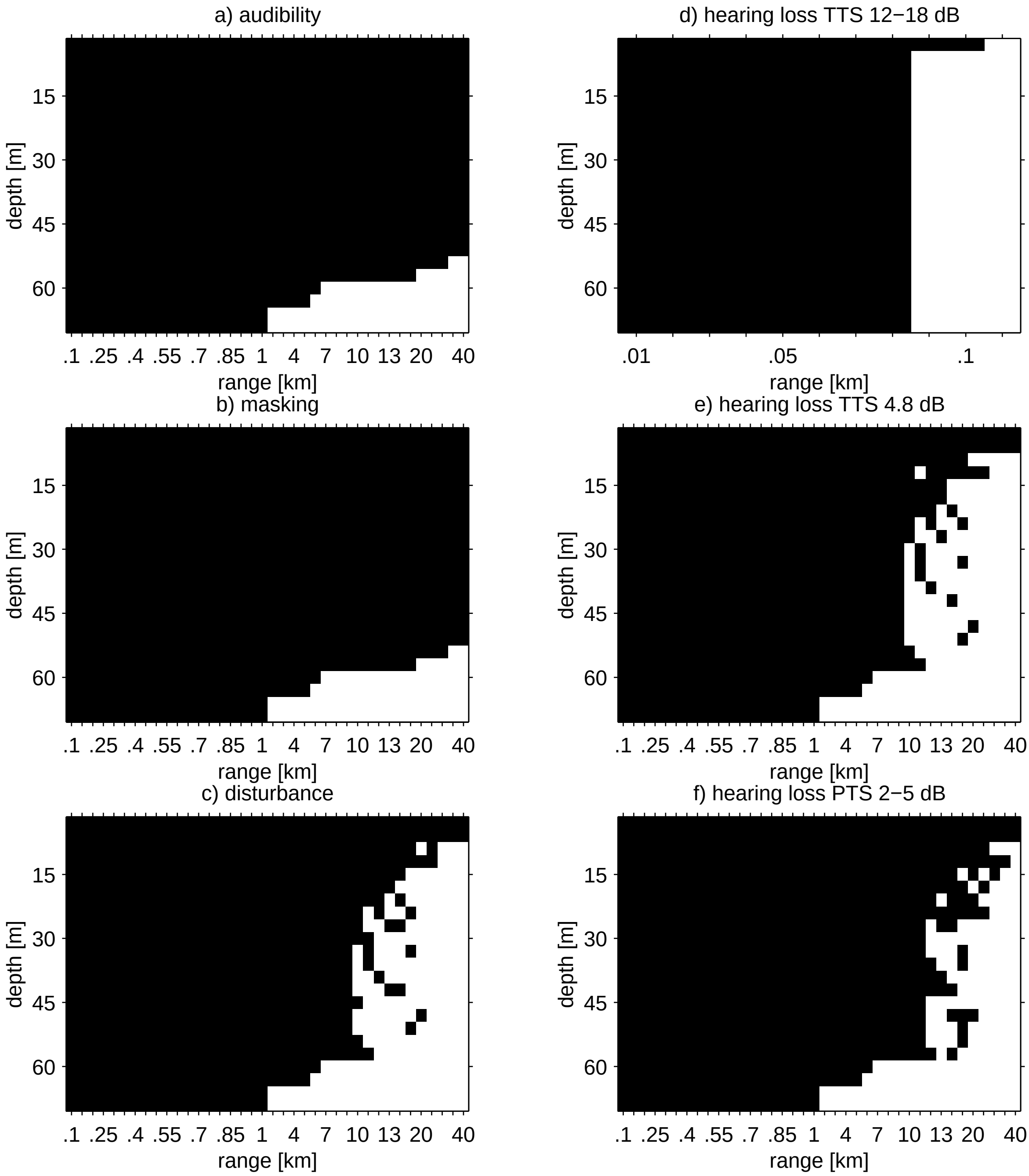

Figure 21: Bioacoustic impact of the cruise ship on humpback whales using the lower audiogram envelope and quiet ambient noise.

8. SUMMARY and DISCUSSION

Bioacoustic effects of two boats, a National Park Service boat Capelin and a cruise ship, on humpback whales were assessed in Glacier Bay, Alaska. The assessment was carried out using a software package that models sound propagation through the ocean and predicts zones of bioacoustic impact. With its nearly flat bottom, steep shores, no sediment but acoustically reflective rock, the lower part of Glacier Bay appeared to be a good acoustic waveguide.

It would be advisable to measure transmission loss in the field in Glacier Bay at some stage to confirm the sound propagation results of the current model. In particular for the cruise ship, low frequencies at 80-100Hz had greater impact than higher frequencies. The RAY model used in the current sound propagation model is a high-frequency approximation. At frequencies as low as 80-100Hz, a normal mode model might be a more accurate tool to estimate transmission loss. This would need to be tested experimentally. For the modeling approach, the RAY model is appealing due its ability to handle broadband signals very fast and efficiently.

As nobody has yet measured an audiogram of a humpback whale, an upper and a lower envelope were derived in Section 4.1 and both were used in the current assessment. With the 'true' audiogram assumed to lie somewhere in between the two envelopes, impact ranges are expected to lie somewhere between the two zones reported.

Table 2: Summary of Impact Ranges. R=range, D=depth. Lower and upper impact ranges correspond to the upper and lower audiogram envelope of the humpback whale. For a TTS of 12-18dB to occur, humpback whales would have to remain within the listed ranges for 30-50min; for a TTS of 4.8dB the required exposure time was 20min. MTTS refers to masked TTS where the presence of ambient noise reduces the TTS. For PTS, continuous exposure over 50yrs would be required.
[1)] expected to be reduced considerably due to masking by ambient noise

	Audibility	*Masking*	*Disturbance*	*TTS 12-18dB*	*TTS 4.8dB*	*PTS 2-5dB*
Capelin						
Typical ambient upper & lower audiogr.	>>40km R @ all D	1km R @ 3m D; 400m R deeper	7km R @ 3m D; 2km R deeper	none	(1km R @ all D); 100m R MTTS	1km @ all D
	>>40km R @ all D	1km R @ all D	7km R @ 3m D; 2km R deeper	1km R @ 3m D; 550m R deeper[1)]	45km R @ 3m D; 20km R deeper[1)]	45km R @ 3m D; 20km R deeper
Quiet ambient	>>40km R @ all D	1km R @ 3m D; 400m R deeper	7km R @ 3m D; 2km R deeper	none	1km @ all D	1km @ all D
	>>40km R @ all D	1km R @ all D	7km R @ 3m D; 2km R deeper	1km R @ 3m D; 550m R deeper[1)]	45km R @ 3m D; 20km R deeper[1)]	45km R @ 3m D; 20km R deeper
Cruise Ship						
Typical ambient upper & lower audiogr.	>>40km R @ all D	>>40km R @ all D	>40km R @ 3m D; 10km R deeper	30m R, 48m D	50km R @ 3m D; 4km R deeper	55km R @ 3m D; 4km R deeper
	>>40km R @ all D	>>40km R @ all D	>40km R @ 3m D; 10km R deeper	80m R @ all D	>50km R @ 3m D; 9km R deeper	>55km R @ 3m D; 11km R deeper
Quiet ambient	>>40km R @ all D	>>40km R @ all D	>40km R @ 3m D; 10km R deeper	30m R, 48m D	50km R @ 3m D; 4km R deeper	55km R @ 3m D; 4km R deeper
	>>40km R @ all D	>>40km R @ all D	>40km R @ 3m D; 10km R deeper	80m R @ all D	>50km R @ 3m D; 9km R deeper	>55km R @ 3m D; 11km R deeper

Audibility

Both boats were audible to humpback whales everywhere within the modelled region of the lower Glacier Bay, for both audiogram envelopes and both types of ambient noise. In the near-surface sound channel, audibility can be expected to extend well beyond the modelled region. Below the sound channel and at times when there is no sound channel, audibility would likely not extend much beyond the modelled region.

Masking

The zones of masking were maximally large, because the worst case was modelled here. The model assumed that two communicating animals were furthest apart, such that they could just hear each other in the presence of ambient noise and absence of boat noise. Therefore, a faint boat noise already masked the signal. Furthermore, signal and noise were modelled to come from the same direction. If humpback whales have directional hearing capabilities at the frequencies of the boat noises and the 'whup', then masking ranges will be reduced. Unfortunately, nothing is known about directional hearing in humpback whales.

The 'whup' had most of its acoustic energy at around 30-40Hz. Capelin was very quiet at these frequencies, being loudest at 2-3kHz. Therefore the effects of masking by Capelin on the humpback 'whup' were small, the ranges of masking were short. The cruise ship had most of its energy at low frequencies and thus interfered with the 'whup' to a much larger degree.

With both types of ambient noise being below or just at the threshold of audibility at the 'whup' frequencies (for both audiogram envelopes), the zone of masking was independent of the type of ambient noise used. The zone of masking was larger for the lower audiogram envelope as compared to the upper audiogram envelope.

Masking would be “biologically significant” if the animals’ biological fitness was reduced (decreased rate of survival and reproduction). One would need to understand the function of humpback calls in Glacier Bay fairly well in order to discuss the importance of masking. If communication plays an important role in foraging or mating, it is conceivable that prolonged masking could affect survival. 'Prolonged' in this sense would at least have to cover an entire season. It is thus most unlikely that either boat could cause a biologically significant degree of masking. In fact, there have not been any studies world-wide able to show the biological significance of masking. The main difficulty is to isolate the effects of masking from other environmental or man-made effects, and the long-term monitoring required to document a decreased rate of reproduction.

Behavioral Response

The 125dB criterion for the ignition of a behavioral response was a broadband sound pressure level from boats that had earlier been linked to the onset of breaches, lunges and head slaps by humpback whales in Glacier Bay. The criterion was hence independent of the particular audiogram and independent of the type of ambient noise. The zone of disturbance was greater for the cruise ship than for Capelin, because of the great sound pressure level of the cruise ship.

It is important to note that the word 'disturbance' is used to indicate a behavioral response of any type. The negative connotation that 'disturbance' often has is unwanted here.

The biological significance of behavioral disturbance is still unknown. If, e.g. feeding is disrupted, will animals simply go somewhere else to feed, or do they incur a reduced energy intake? Temporary behavioral responses are usually not 'biologically significant' (affecting survival). Animals would have to be repeatedly disturbed during important behavior (e.g. nursing, mating, foraging) or be permanently scared away from critical habitat for the effects to be biologically significant. However, so far no long-term study (monitoring e.g. reproductive rate, mortality, habitat avoidance etc.) has been able to isolate vessel or other industrial noise effects from other environmental effects, such as climate change or prey availability.

Hearing Damage

Both Capelin and the cruise ship were loud enough to cause a TTS in humpback whales according to the model. Obviously, for the lower audiogram envelope the zone of TTS was larger than for the upper envelope. Capelin caused the strongest TTS at 2-3kHz; the cruise ship caused the strongest TTS at 80-100Hz.

Typical ambient noise is nearly 20dB above audibility at 2-3kHz, using the upper audiogram envelope. Using data from humans, the presence of ambient noise reduces the amount of TTS of the main noise source. This effect is called 'masked TTS'. If the same effect occurs in humpback whales, then the amount of TTS (or the range of TTS) of Capelin would be reduced under typical ambient noise conditions. Using the lower audiogram envelope, typical ambient noise is even louder and TTS is expected to be reduced even further. The Glacier Bay sample of quiet ambient noise is only just audible using the upper audiogram envelope; it would thus not be able to reduce TTS from Capelin. If the true humpback audiogram, however, lies near the lower envelope, then quiet ambient noise would also reduce TTS from Capelin.

At the frequencies of 80-100Hz where the cruise ship causes a TTS, neither ambient noise is loud enough to reduce the amount of TTS from the cruise ship. This is the case for both audiogram envelopes.

According to the model, humpback whales would have to remain within the 4.8dB-TTS-zone for 20 min to lose 4.8dB sensitivity. They would have to remain within the 12-18dB-TTS-zone for 30-50 min to lose 12-18dB sensitivity. Both TTS levels are assumed to be fully recoverable within 24h. One might expect that animals, given the chance, would avoid noise sources before they became loud enough to cause physiological damage. The studies on TTS quoted in this report support this argument. The marine mammals exposed to TTS inducing noise levels showed signs of distress even at low-level noise causing only a small TTS. It was therefore concluded that animals would try to avoid sounds even if they only caused a small TTS. A question that remains to be answered is how effectively humpback whales can determine the direction of low-frequency sound and thus avoid the source.

As discussed in the section on masking, marine mammals use acoustics for communication, navigation and foraging. Given the importance of hearing to marine mammals, hearing impairment (certainly in the permanent case) likely affects survival. Neither boat was loud enough to cause a PTS under realistic exposure conditions. PTS can occur after brief exposure to very loud sounds and after prolonged exposure to quieter sounds. In terrestrial mammals, for a once-off exposure to cause a PTS, the sound would have to be at least 155dB above the audiogram [Kryter 1985]. Applying the same criterion to humpback whales, nowhere were the boats that loud. To cause a PTS after prolonged exposure, humpback whales would have to remain within the modelled PTS zones around Capelin and the cruise ship (or similar ships) for 8h/day, 5 days/week over 50 years. This is most improbable. It would be interesting to measure and assess summed noise levels of a number of vessels in the same area and to estimate noise exposure statistics for humpback whales throughout the year.

It is important to point out that ambient noise in Glacier Bay lies well above the lower audiogram envelope. If the true humpback audiogram was lying near the lower envelope, then the sensation levels of ambient noise would constantly be high. Ambient noise would limit the audibility of biological, natural and man-made sounds. Ambient noise would add to the masking of anthropogenic noise. Ambient noise would even mask TTS. This situation is quite different from those one commonly encounters with odontocetes or pinnipeds, where ambient noise is hardly audible to them. In bioacoustic impact assessments for those animals, ambient noise appears to play a minor role. With baleen whales, on the other hand, ambient noise appears to be a crucial factor in all the various effects, and the processes by which ambient noise affects the masking, disturbance and hearing damage due to anthropogenic noise are not at all understood. This stresses yet again the importance of obtaining a baleen whale audiogram. If it lies near the upper envelope used here, then it lies near ambient noise levels and the 'additional' effects of ambient noise might be negligible. If it lies considerably below ambient noise levels, then a whole new field for bioacoustic research opens up; masking, disturbance, TTS, all will have to be 'revisited' using two simultaneous noises: an anthropogenic noise and a prevalent ambient noise.

The results of the current modelling exercise should not be used for any environmental decision-making. The motivation for the study was merely exploratory. No audiogram has ever been measured in humpback whales. There is no information on critical bandwidths in humpback whales. No calibrated received sound levels causing hearing damage in humpback whales have ever been measured. The entire model is based on a transfer of data from odontocetes, pinnipeds and terrestrial mammals to humpback whales. The feasibility and accuracy of such an interspecies transfer is highly debatable. There is no data backing it up.

The only species-specific adjustment made during the data transfer was that all acoustic thresholds were normalized by the corresponding species' audiogram (i.e. sensation levels were used rather than absolute sound pressure levels) and then re-applied to the expected humpback audiogram. The humpback audiogram itself was derived. The shape and location of the audiogram is essential in each of the modelled effects. The importance of obtaining a real humpback audiogram can thus not be stressed enough.

Having said all that, the study should be seen as an indicator for what type of bioacoustic information is lacking and to point out areas where more research is needed.

Acknowledgements

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